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Review of Underwater Communication Routing Protocols

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Abstract

Routing protocol plays an important role in underwater acoustic sensor networks (UASNs). Due to the unique characteristics of the underwater acoustic channel, it is difficult to overcome the negative impacts to provide the reliable routing protocol. The main challenges include long propagation delay, high energy consumption, and low successful packet delivery. At present, there are various routing protocols available, but they are confined to applicable conditions. According to the applicable conditions of routing protocols, we review the main designs of several kinds of routing protocols for UASNs in this paper. We analyze and conclude their characteristics and give research direction in the future.

Keywords

Underwater acoustic sensor networks, Routing protocols, Deep learning.

1. Introduction

UASNs have advantages to explore the underwater environment. It uses routing protocols to plan the most convenient path to deliver packets from the nodes to the sink or floating base station. However, the design of routing protocols meets several challenges in the underwater channel, such as high fading, low transmission speed, and long propagation delay, thus leads to high energy cost and short life cycle time.

In the past decades, various routing protocols have been proposed for terrestrial wireless sensor networks. They are generally divided into proactive and reactive protocols [1][2]. The proactive protocol allows the node to establish and maintain a routing table, which is responsible for reporting its routing information to the network. The routing table is updated corresponding to the changes of the current network state, thus incurs huge signaling overhead and shortens the life cycle of networks. On the other hand, the node in reactive protocol establishes the routing table temporarily to reduce the overhead significantly, which is more suitable for networks with dynamic topology. Nevertheless, data transmission has large delays because of unpredictable route discovery and setup. As a result, the routing protocols of terrestrial communication require an amount of information, thus cannot be applied directly to underwater communication due to severe degradation in UASNs.

A lot of routing protocols are designed to overcome the problems in UASNs. The purpose of this paper is to classify and review these protocols. According to the special problems they solved, we divide the protocols into five categories: mobility, sparse network, dense network, energy efficiency, and intelligent-based protocols. We analyze their design mechanism and summary the main features, and then give the comparison results. Finally, we conclude the developing directions of underwater communication routing protocols in recent years and the future.

2. Uasns Routing Algorithm

2.1 Challenges and classification for Routing Protocols

The environment of the underwater channel is severely worse than that of terrestrial communication. For example, the long propagation delay and high fading limits the energy, and the water wave causes the mobility of the nodes to change network topology. The main challenges faced by routing protocols are concluded in Table I, which should be concerned in protocol design to improve the system performance.

Table I. Challenges of Routing Protocols for Uasns

Challenges	Description
Mobility	the nodes move with water wave and form a dynamic network topology
End-to-end delay	the low speed of sound in underwater causes long propagation delay
Network lifetime	the limited battery capacity and high cost replacement of network affect total network
Energy consumption	the data transmit and reception cause the energy lost
Channel bandwidth	the severely limited channel bandwidth leads to high bit error rate

Conventionally, the routing protocols are classified into many ways to solve varied problems. If we consider the impacts caused by movement, network density, and nodes energy, we are able to classify protocols into supporting mobility routing protocols, sparse network routing protocols, dense network routing protocols and energy efficiency based routing protocols. Further, the rapid development of intelligent algorithm also makes its way into routing protocols designs in recent years. It aims to solve several problems, such as extending the lifetime of the network or reducing energy loss. Therefore, we also address the intelligent based routing protocols in particularly with reinforcement learning (RL). We describe the fundamental mechanism and development of different types of protocols, and then analyze and conclude their features.

2.2 Mobility

As we mentioned, the nodes may move with the flow of water, thus the network topology is dynamic. There are many network applications requiring supporting mobility. Hence, a lot of research focused on studying routing protocols to consider mobility. It mainly includes vector-based forwarding routing protocol (VBF), depth-based routing protocol (DBR) and Hydraulic pressure based routing protocol(Hydro Cast). They can be used to deal with the dynamical topology problem.

2.2.1 VBF

VBF is a location-based routing method that uses vector-based packet forwarding [3]. It connects the source node and its receive node by a pipe, as shown in Figure. 1.

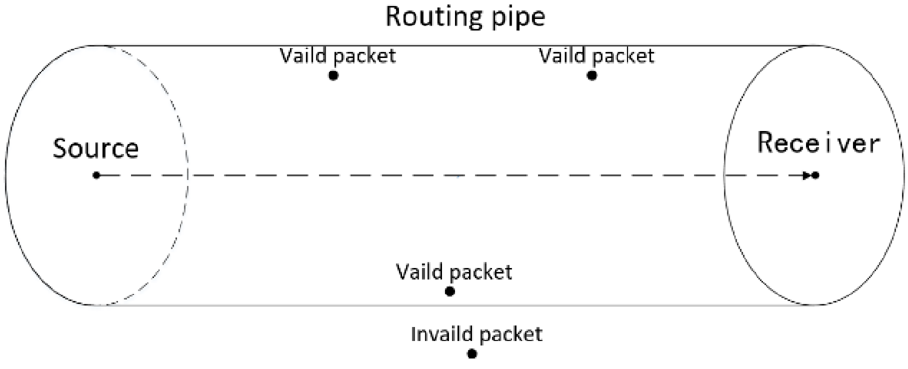

Figure 1. VBF transmission pipe

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Packets within the pipe are permitted to transmit, otherwise, they are invalid. The radius of the pipe is predefined to determine the number of forward nodes [4]. Each packet contains the location information of the source node, receiver node, and forward nodes. The forward node is able to compute its location from the packet information including the previous node's location and arrival angle, thus the mobility can be realized. The node density has an important impact on pipe efficiency, so that the VBF is not suitable to spares network due to an insufficient number of forward nodes.

2.2.2 DBR

DBR takes depth information into account to determine which forward node is effective [5]. The source node broadcasts its message to all neighbor nodes. Each neighbor node computes and compares the depth information. The node whose location is more nearer to the surface than the sender is accepted to forwarding information, otherwise, the packet is dropped [6]. If we deploy many receive nodes on the water surface, it apparently improves the successful delivery rate dramatically. It also is able to reduce the end-to-end delay and energy consumption.

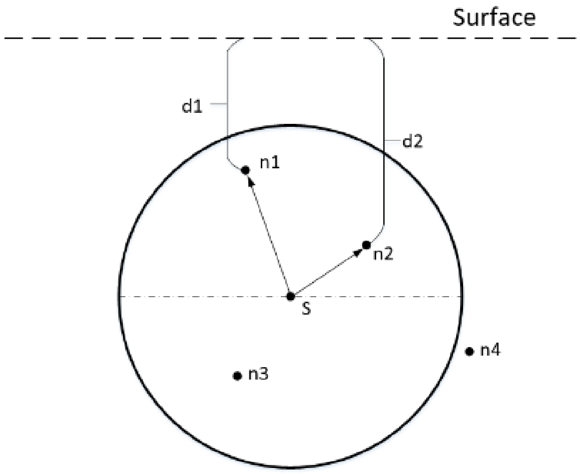

Figure 2. Node selection of DBR

Figure.2 shows the procedure of forward node selection. When the packet is sent from S, the neighbor node $n1$, $n2$ and $n3$ calculate and compare their own depth d with the sender's depth. The result demonstrates that $n1$ has shallower depth than all of the other nodes, thus it is selected as the forward node.

2.2.3 HydroCast

HydroCast is a hydraulic-based routing protocol that finds a forward path according to measured pressure levels [7] [8]. It forwarding the packets with the greedy manner and then selects the node having minor pressure. The protocol also takes channel characteristics into account to select the forward node, aiming to overcome the hidden terminal problem.

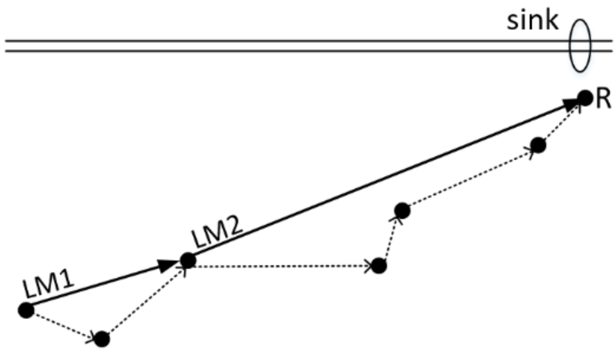

Figure 3. HydroCast recovery mode

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The HydroCast can recover the path for each local maximum node, which ensures the successful delivery. The protocol searches the nodes that have lower pressure (or lower depth) than the local maximum node, and then maintains a recovery path to that node. Figure.3 shows an example. Suppose $LM1$, $LM2$ and $LM3$ are three local maximum nodes and maintain a route to a surface node. It also can switch back to the greedy mode and delivers packets to surface node.

The protocol is able to reduce the co-channel interference, and is efficient to recover the dead end, which outperforms the DBR. However, the length of the route may be long in the sparse network, thus increases the average delay and energy consumption. To deploy fixed nodes in the network is an effective way to cope with this problem.

2.3 Sparse Network

The sparse network contains a few nodes and the transmission distances among nodes are relatively long. We discuss hop-to-hop vector-based forwarding (HH-VBF) and adaptive routing protocols in this subsection.

2.3.1 HHVBF

Compared with VBF mentioned in section B, the HHVBF allows the node to make forward decisions adaptively [9]. It creates a pipe for each forwarder. In particular, the redundancy control solves the problem that the nodes cannot be found in the sparse network, thus reduce the negative impact of the pipe radius. Another improved protocol, named reliable HHVBF protocol (RHHVBF), creates a local routing table (LRT) for each node and then selects the optimal neighbor as the next hop by use of cross-layer designing routing algorithm [10]. It averages the energy cost of each node and then extends the lifetime of the network.

2.3.2 Adaptive routing

In an adaptive routing protocol, the node first copies the packet and then passes the copied packet to each node in the path. During this process, the protocol takes advantage of every opportunity to deliver packets to the receiver node [11]. The adaptive routing protocol distinguishes the importance of packets basing on the water quality. The lower the water quality, the higher the importance of packets and the higher the priority. In this protocol, the data success rate is maximized and the transmission delay is minimized. However, the more important the information, the more resources the packet consumes.

2.4 Dense network

The dense network is characterized by intensive nodes deployed in the network area. We introduce the path unaware layered routing protocol (PULRP) and multipath routing protocol (MRP) in this subsection.

2.4.1 PULRP:

PULRP aims to apply in a highly dense underwater 3D sensor network. It is implemented by two stages [12]. The nodes are divided into layers in the first stage. Each layer is formed by a sphere with the center of the sink node. The radius of a sphere is determined by both successfully forward proportionality and packet delivery delay. The second stage performs the selection of intermediate nodes and data transmission from a source node to the end. Compared with VBF, PULRP does not require fixed routing tables, localization, and time synchronization, but its performance is limited significantly by the sphere radius. In particular, the successful packet delivery rate decreases dramatically when the radius approximates one.

2.4.2 MRP

The MRP formulates the route from source to sink node by multiple sub-paths [13]. The paths from the source node to two-hop neighbors are regarded as sub-paths. The source node of MRP first collects delay information from the two-hop neighbors, and then select the relay node according to the delay time. When the relay node receives the packet, it starts to check the data collision

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intermediately. If there exists a collision, the nodes delay a random time to transmit, otherwise, the packets are delivered to the next step.

2.5 Energy Efficiency

Since the energy is limited by the battery, the UASNs requires high energy efficiency to improve the lifetime of the network. We consider energy-efficient depth-based Routing Protocol (EE-DBR) and the directional depth-based Routing Protocol(D-DBR) in this subsection to cope with energy efficiency problems.

2.5.1 EE-DBR

The purpose of EE-DBR is to reduce the redundant forwarding caused by multi-paths [14]. Although it is necessary to add redundancy for robustness, the EE-DBR wants to find an optimal balance between energy cost and system robustness. It exploits Time of Arrive (ToA) ranging method to locate the blind area of the nodes and then prevents the nodes in the blind area to forwarding packets. Figure.4 [14] shows that the calculation of the blind area is determined by the distance dis from source node S to node N, the depth difference of two nodes Δd and the radius R of maximum transmission range.

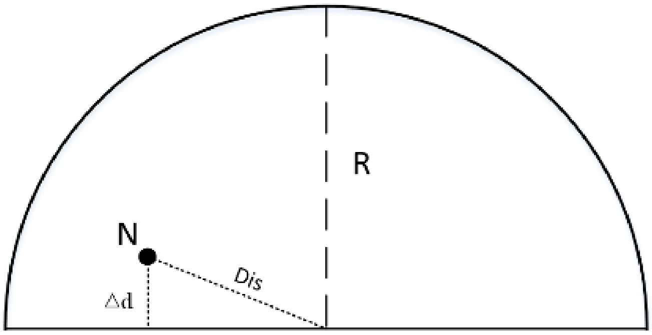

Figure 4. EE-DBR protocol model

Despite using ToA in EE-DBR, it doesn't need an extra transmission for ToA because the ToA's information is added to the existing load. Thus it doesn't increase energy consumption compared with the original DBR. The EE-DBR is not vulnerable to the network density. Therefore, it is able to save more energy than DBR in particularly with the increase of network density.

2.5.2 D-DBR

D-DBR is a kind of directional routing protocol. The nodes forwarding the packet greedily to upward direction. If there is no receive node, the previous operations are going to be invalid, which is called sink loss. The probability of occurring sink loss is relatively small in most cases, but the performance is degraded significantly when only a single sink exists [15]. The sink nodes in D-DBR are able to broadcast their location periodically. Because they float on the water surface, they have the ability to obtain sufficient power to broadcast the information. Therefore, the D-DBR achieves higher energy efficiency for the underwater nodes compared with the DBR.

2.6 Intelligent-based protocols

Intelligent algorithms are applied widely to cope with the problems occurred in routing protocol in recent years. As an important part of machine learning, the deep learning (DL) has been used to implement protocol in routing layer [16]. For example, the authors in [17] proposed an online learning method based on a deep convolutional neural network (Deep CNN) to control network traffic. Deep CNN improves decision accuracy by learning the routing decision policy. In terms of underwater communication, most of research focused on reinforcement learning (RL), which will be discussed in this part.

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2.6.1 QDTR

The Q-learning-based delay tolerant networking routing protocol (QDTR) proposed a new routing protocol to tolerate long end-to-end delay adaptively [18]. It executes online learning based on Q-learning to deal with the node mobility. The application of Q-learning allows nodes do not exchange control packets before transmission, thus reduce the overhead. As well as, the QDTR can be realized by a distributed manner because the historical data are distributed over the sensor nodes, which also decreases the overhead. The main disadvantage of QDTR is the huge state characteristic required by Q-learning, which may lead to dramatic error.

2.6.2 QELAR

The Q-network-based adaptive, energy efficient, and lifetime-aware routing protocol (QELAR) was designed in [19], which was based on Q-learning algorithm. It combines the idea of both proactive and reactive protocols. The design of Q function takes the energy consumption and residual energy distribution into account to achieve high energy efficiency and uniform energy distribution, thus extends the lifetime of the network. The results show that the application of Q-learning to underwater communication can balance the load of each node and reduce network loss.

2.6.3 DQELR:

As the Q-learning is unstable when the data has a high correlation or the update of Q is small. Hence the deep Q-learning is introduced to solve this problem. The deep Q-network-based energy and latency-aware routing protocol(DQELR) is then proposed [2]. According to the energy and depth of nodes, the DQELR selects the node with the maximum Q value as the forward node, in which the Q value is generated by a deep neural network. The protocol supports multiple policies to decide a new route when the current path breaks, which reduces energy consumption and delay.

3. Comparation and Analysis

According to the classification and discussion in Section 2, we conclude the advantages, disadvantages and suitable scenarios of different routing protocols for UASNs, as seen in Table. II. For different scenarios, the specific protocol can be adopted. For instance, HHVBF is more suitable to overcome the sparsity of the network, and VBF has an advantage to locate the node in a deep water environment.

Table II. Comparison of Different Routing Protocols

Routing protocol	Advantages	Disadvantages	Applicable conditions
VBF	Good transmission efficiency	High cost	Node mobility network
HHVBF	Low radius requirement	Redundant packet	Sparse network
DBR	Low delay and overhead	Susceptible to node density	Node mobility network
EE-DBR	Good robustness	Uneven energy consumption	Energy efficiency
D-DBR	Low delay. Good transmission efficiency	High energy consumption	Energy efficiency
HydroCast	Recovery support	Susceptible to node density	Node mobility network
PULRP	Uniform energy consumption	Susceptible to the radius	Dense network
MRP	Good packet delivery ratio	High energy overhead	Dense network
Adaptive Routing	Good transmission efficiency. Low delay	High resources overhead	Sparse network
QDTR	Save space and time	Take up much time and space	Intelligent network
QELAR	Low overhead. High energy efficiency	Complexity	Node mobility network
DQELR	Low latency. Prolong lifetimes	Data is hard to train	Intelligent network

Although lots of protocols have been studied for UASNs by now, it still has the possibility to improve the performance by further research. Because the underwater environment is pretty complex, the

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application of singular routing protocol is impacted negatively by the changing water flow. Therefore, it is an effective way to study combining the multiple protocols to overcome their shortcomings at the same time, and meet the multiple requirements of underwater communication.

The intelligent-based algorithm is another promising technology for underwater transmission due to its intelligence and self-adaptability. When the characteristic of network changes caused by water, it is hard for nodes to redeploy their routing protocols. However, an intelligent node is able to adjust its own protocol by learning without extra command. Consequently, it is possible to exploit the learning process to satisfy different requirements of an underwater network.

4. Conclusion

We classify the routing protocols of UASNs into five categories in this paper. We review the main methods of each category, and then conclude their key features and applied situations. It shows that the multiple protocols combination and intelligent-based protocols make a promising way to study in the future.

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