A Link-State Based Adaptive Feedback Routing for Underwater Acoustic Sensor Networks

Song Zhang, Deshi Li, and Jian Chen

Abstract—**Underwater Acoustic Sensor Networks (UASNs) have recently been attracted significant attention from both academia and industry for resources exploration and for scientific data gathering in underwater environments. The important characteristic of a UASN is that most underwater acoustic sensor nodes have a certain beam width and a three dimension direction, which is ignored by the existing underwater routing protocols. This characteristic will reduce the network connectivity and cause a large number of asymmetric links, so it will lead to sharp decline of the existing protocol performance. We develop a routing protocol to tackle this problem in UASNs. A link detection mechanism is employed to get link state information (symmetrical link or asymmetric link), and an adaptive routing feedback method is adopted to make full use of the underwater asymmetric link and save energy. We propose a time-based priority forwarding mechanism and utilize downstream node table to prevent flooding, and a credit-based routing table update mechanism is adopted to avoid energy consumption caused by frequent update of routing table. The proposed protocol is compared with a representative routing protocol for UASNs. The simulation results verify the effectiveness and feasibility of the proposed protocol.**

Index Terms—**Underwater acoustic sensor networks, routing protocols, beam width, three-dimensional direction, adaptive feedback routing.**

I. Introduction

On THE earth, over 70% of the area covered by water. In order to better explore the vast unexplored underwater areas, the deployment of Underwater Acoustic Sensor Networks (UASNs) has been attracted significant attention recently. UASNs can be widely used in the following areas: pollution monitoring, oceanographic data collection, disaster recovery, navigation and military applications etc [1]–[8].

Routing is a fundamental issue for any network, and routing protocols are considered to be in charge for discovering and maintaining the data transmission routes. Most of the research works pertaining to underwater sensor networks have been on the issues related to physical layer, while issues related to network layer such as routing techniques are a relatively new area. In fact, designing efficient routing protocol in UASNs is very challenging due to the unique characteristics of underwater sensor networks [9]–[10]. First of all, UASNs rely on underwater acoustic communications because radio signals would be rapidly absorbed by water [11]–[12]. And acoustic channels have low bandwidths and long propagation delays features. We need to pay attention to this aspect in the design process. Secondly, most nodes in a UASN may move passively with water currents, resulting in highly dynamic network topology. In addition, a number of autonomous mobile nodes such as underwater robots and Autonomous Underwater Vehicles (AUVs) etc. increase the dynamic nature of the network topology. Therefore, the routing protocol needs to adapt to the highly dynamic topology changes. Thirdly, underwater node localization is a difficult problem [13]–[16]. Thus a routing protocol relying on location information is not a good choice. Fourthly, underwater sensor nodes are usually powered by batteries, which are very hard to recharge or replace in underwater environments. Thus, energy efficiency is another important concern for UASN routing. There are some routing protocols appeared in the existing literatures meet the characteristics discussed above.

However, all the literature ignores another important characteristic in UASNs: underwater acoustic sensor nodes have a certain beam width and a three-dimensional direction. Due to the difference principles, technologies and structures of acoustic transducer or hydrophone [17], the transmitted signal of existing underwater acoustic modem such as the Link Quest's UWM Series [18] is not an Omni-directional signal but a directional signal with a certain beam width. For example, the beam width of UWM Series is 120 degrees (wide beam) and 210 degrees (Omni-directional). Additionally, each underwater acoustic sensor node would head to a random three-dimensional direction. These factors will have great influence on the network connection, such as reducing connectivity, producing large amount of asymmetric links etc. The decline of network connectivity will lead to the decline of the packet delivery ratio. The existence of asymmetric links would cause some routes cannot be feed backed to the source nodes. The existing routing protocols assume the transmitted signal of underwater sensor node is an Omni-directional signal and do not take beam width and three-dimensional direction as constraints. But the beam width and three-dimensional direction of underwater sensor nodes cannot be ignored in the practical applications. If this feature of the UASNs is

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taken into account, the existing protocols could not get good performance or even cannot be used.

In this paper, we propose a novel routing protocol, called Link-state based Adaptive Feedback Routing (LAFR), for UASNs. LAFR taking into account the impact of the beam width and three-dimensional direction of underwater sensors of UASNs and it can make smooth routing feedback in the underwater environment with high proportion of asymmetric links. LAFR utilizes link state information gotten by a link detection mechanism and propose an adaptive routing feedback method to make full use of the underwater asymmetric link, it also uses routing table to save energy. Furthermore, we propose a credit-based dynamic routing update mechanism to avoid the energy consumption of the regularly update routing table. The proposed protocol performance is compared with a representative routing protocol of UASNs in the literature. The simulation results verify the effectiveness and feasibility of the proposed work.

The remainder of this paper is organized as follows. Section II briefly reviews some related work. Section III presents the architecture of the proposed routing protocol. The simulation results are given in Section IV. Conclusion is made in Section V.

II. Related Work

The existing routing protocols for underwater sensor networks [19]–[20], can be categorized roughly into four kinds.

A. Clustering Routing Protocols

It is essential for such protocols to choose the cluster head. Minimum-Cost Clustering Protocol (MCCP) [21] uses a cluster based approach where clusters are formed by computing the following three parameters: total energy required by the cluster members for sending data to the cluster head, the residual energy of the cluster head and its entire members, and relative location of the cluster head and underwater-sink. MCCP can improve energy efficiency and prolong the network life, but it does not support multi-hop routing. Location-based Clustering Algorithm for Data (LCAD) gathering in UASNs [22] divides the entire network into three-dimensional grids and then accordingly selects the cluster head. LCAD can reduce energy consumption during data transmission phase, but its performance depends on grid structure, especially the position of cluster head inside the grid.

B. AUVs Assisted Routing Protocols

AUVs can move without space restriction and can be used as data mules for collecting data. Delay-tolerant Data Dolphin (DDD) [23] exploits mobile node called dolphins to harvest information sensed by the stationary sensor nodes. Multiple-UUV (Underwater Unmanned Vehicles) [24] could be utilized to enhance connectivity with multiple underwater unmanned vehicles. DDD avoids energy expensive multi-hop communication, but it needs enough dolphin nodes to avoid data packets lose, and then cost will become a major issue. In AUV-Aided Underwater Routing Protocol (AURP) [25] the total data transmissions are minimized by using AUVs as relay nodes, and the controlled mobility of AUVs makes it possible to apply a short-range high data rate underwater channel for transmissions of a large amount of data. AURP can achieve high delivery ratio and low energy consumption, but the use of AUVs will produce huge cost.

C. Geographic-Based Routing Protocols

The location information of sensors could be used relay nodes selection. In Vector-Based Forwarding protocol (VBF) [26], it is assumed that each node knows its location already. The packet delivery is guided by a virtual routing pipe from the source to the sink and only those sensor nodes that are in the pipe will forward packets. VBF can reduce network traffics and can easily manage the dynamic topology, but it has much communication overhead and the routing pipe radius threshold which affects the routing performance significantly is difficult to determine. Focused Beam Routing protocol (FBR) [27] assumes that each node in the network knows its own location and every source node knows about the location of the final destination. Nodes that lie within a cone of angle θ emanating from the transmitter towards the destination are considered as the forwarding nodes. FBR can reduce unnecessary flooding, but it is not suitable for sparse environment. Sector-Based Routing with Destination Location Prediction (SBR-DLP) [28] assumes that each node knows its own location information and pre-planned movement of destination nodes. Data packets are forwarded to the destination in a hop-by-hop fashion instead of finding an end-to-end path in order to avoid flooding. SBR-DLP can route a data packet in a fully mobile underwater acoustic network where not only intermediate nodes but also destination can be mobile, but the pre-planned movements of the destination nodes are hard to known. Depth-Based Routing (DBR) [29] needs only the depth information of sensor nodes. When a node receives a packet, it forwards the packet if its depth is smaller than that embedded in the packet. Otherwise, it discards the packet. DBR can handle network dynamics efficiently without the assistance of a localization service and can take advantage of the multi-sink underwater sensor network architecture without introducing extra cost, but it not able to achieve high delivery ratios in sparse areas. Pressure routing [30] proposes the pressure-based routing protocol which is similar to the DBR, just using pressure instead of depth.

D. Special Routing Protocols

This class of routing protocols assumes that the underwater nodes have some special features, for example, Resilient routing algorithm [31] and Temporary Cluster Based Routing (TCBR) [33]. In these protocols, the underwater nodes equipment buoys, ropes, anchors and some other mechanical devices. Nodes fix their own position through the anchors and adjust their depth by buoys. A hybrid underwater sensor network was proposed in [32], in this protocol every node supports both acoustic and radio communication, so they will use acoustic for underwater communication with the neighboring nodes, and radio is used when nodes are on the

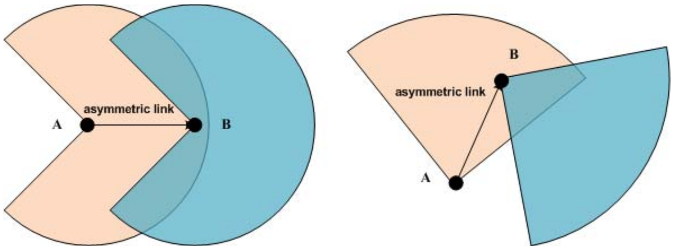

Fig. 1. Illustration of asymmetric link.

surface. Nodes can adjust their position to obtain and optimize the routing. It can achieve high delivery ratio and low energy consumption. However, it will result in a huge manufacturing cost for all nodes equipped with these mechanical devices.

The impact of the beam width and three-dimensional direction of the underwater node to the UASNs have not been considered by the existing routing protocols. In the practical applications, this will bring about the performance of the protocols have a huge impact. We assume that the beam width is θ ($0<\theta<360$), then the communication range of the node becomes $\theta/360$ times when the beam width is not considered. The number of nodes within the communication range of one node becomes less, resulting in the number of links in the network is reduced, so that the entire network connectivity reduced. Further, because of the beam width and three-dimensional directions, the network appears asymmetric links. As shown in Fig. 1 node B is within the communication range of node A, but the node A is not within the communication range of node B, the link between A and B is an asymmetric link. In the existing routing protocols, such as Clustering Routing Protocols and AUVs Assisted Routing Protocols are required interaction information between nodes, the asymmetric link would lead to the asymmetry of information exchange which cause the protocol performance degradation and even failure. Moreover, some routing protocols such as Geographic-based Routing Protocols (VBF, DBR, etc.), the packet delivery rate would be lowered by the significant network connectivity decline and many nodes cannot find the path leading to the sink node.

In our proposed routing protocol, the impact of the beam width and three-dimensional direction of the underwater node would be considered and solved.

III. Link-state Based Adaptive Feedback Routing Protocol

In this section, we introduce the underwater network architecture and analyze the impact on the underwater network which caused by the beam width and three-dimensional direction of the underwater sensor nodes. Then we present our proposed LAFR protocol in detail.

A. Network Architecture and Connectivity Analysis

UASNs consist of a variable number of sensor nodes that are deployed to perform collaborative monitoring over a given volume. Similar to terrestrial sensor networks, for UASNs it is essential to provide communication coverage in such a way

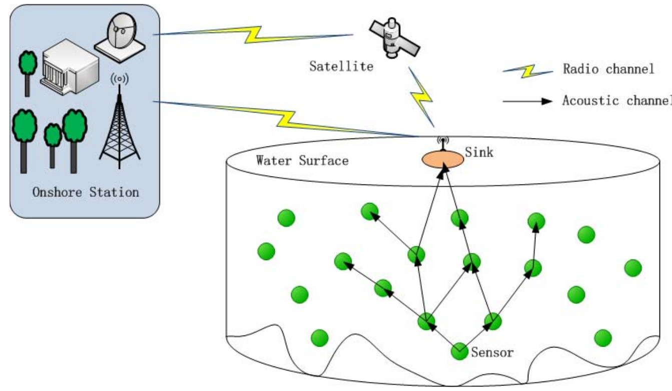

Fig. 2. Illustration of deployment and propagation of an UASN.

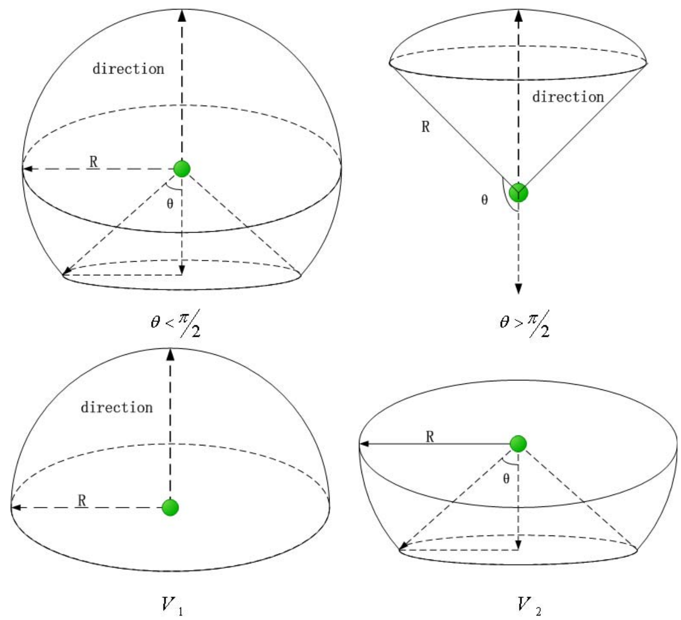

Fig. 3. Illustration of node communication range.

that the whole monitoring area is covered by the sensor nodes, where every sensor node should be able to establish multi-hop paths in order to reach the surface sink. The architecture of an UASN adopted in this work is shown in Fig. 2. Sensor nodes with acoustic modems are randomly deployed in an underwater 3-D area. They can collect data and also help relay data to the sink. One sink node is deployed at the center of the water surface, equipped with both radio-frequency and acoustic modems. In some scenarios, multiple sink nodes are arranged on the water surface. The sink node receives acoustic signals forwarded from the sensors and transmits the packets to the control center ashore through radio-frequency signal.

Now we analyze the impact on the underwater network which caused by the transmit signal beam width and three-dimensional direction of the underwater sensor nodes. As shown in Fig. 3. The coordinates of the underwater sensor node is set to (x_0, y_0, z_0), beam width is $2\pi - 2\theta$, and communication radius is R. When $\theta < \pi/2$, the node communication range can be divided into two parts: V_1 and V_2. V_1 can be expressed by (1), V_2 can be expressed by (2). And the node communication range can be expressed by $V_1 \cup V_2$.

$$\begin{cases} (x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2 \le R^2 \\ z \ge z_0 \end{cases} \tag{1}$$

$$\begin{cases} (x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2 \le R^2 \\ \cos^2\theta\left[(x-x_0)^2 + (y-y_0)^2\right] - \sin^2\theta(z-z_0)^2 \ge 0 \\ z < z_0 \end{cases} \tag{2}$$

When $\pi/2 \le \theta < \pi$, the node communication range can be expressed by (3).

$$\begin{cases} (x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2 \le R^2 \\ \cos^2\theta\left[(x-x_0)^2 + (y-y_0)^2\right] - \sin^2\theta(z-z_0)^2 \le 0 \\ z \ge z_0 \end{cases} \tag{3}$$

In addition, each the underwater sensor node has a random three-dimensional direction. This characteristic could make great influence on the underwater network connection. In order to better analyze these effects, we made a series of simulations to verify that the beam width and direction will cause a decline in the network connectivity and produce asymmetric links. The simulations here are performed using the MATLAB due to MATLAB can easily analyze the links in the network. In our simulations, 50 nodes are randomly deployed in a 500 m × 500 m × 500 m 3-D area and the communication radius is 300 m. These values used here can be set arbitrarily, just ensure the communication radius not greater than the radius of the simulation scene. We reference some simulation parameters in literature [28], such as the range of the simulation scene. We refer to the performance indicators of the existing underwater acoustic modem such as the Link Quest's UWM Series [18]. The beam width of UWM Series is 120 degrees (wide beam) and 210 degrees (Omni-directional). So we chose 210 degrees and 120 degrees as typical beam width in the simulations. In the simulations, we assume that there are no obstructions in the environment. And we did not take into account other factors that may affect the links in the network, such as fish, boats, etc.

Fig. 4–6 show the network connectivity when the beam width is 360 degrees, 210 degrees and 120 degrees, respectively. In these figures, blue line represents the symmetric link while red line represents asymmetric link. There are no asymmetric links when the beam width is 360 degrees. In contrast, the number of symmetrical links becomes fewer when the beam width is 210 degrees. There are almost asymmetric links in the network when the beam width is 120 degrees. It can be seen that the underwater network connectivity changes a lot and a large amount of asymmetric links are produced when we take into account of the beam width and three-dimensional direction of the underwater sensor nodes.

Fig. 7 is a schematic diagram of the proportion of asymmetric links with different beam width. It can be seen that when communication blind angle is 120 degrees (beam width is $360-120=240$ degrees) the proportion of asymmetric links is over 80%. So asymmetrical links hold a dominant position in underwater networks, the routing protocol needs to take full advantage of underwater asymmetric links for communication. Fig. 8 shows that the total links number decreases with the increase of communication blind angle. From these figures, we can see a significant decline in network connectivity due to the

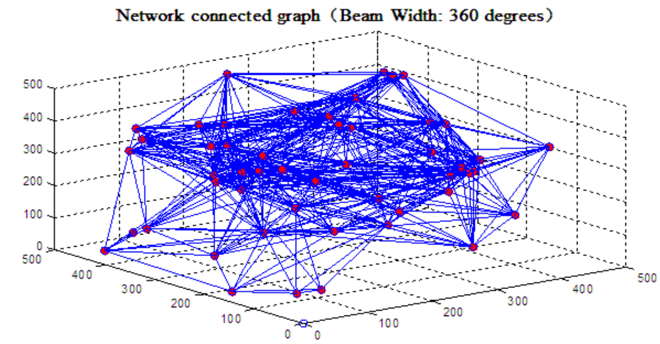

Fig. 4. Network connectivity with 360° beam width.

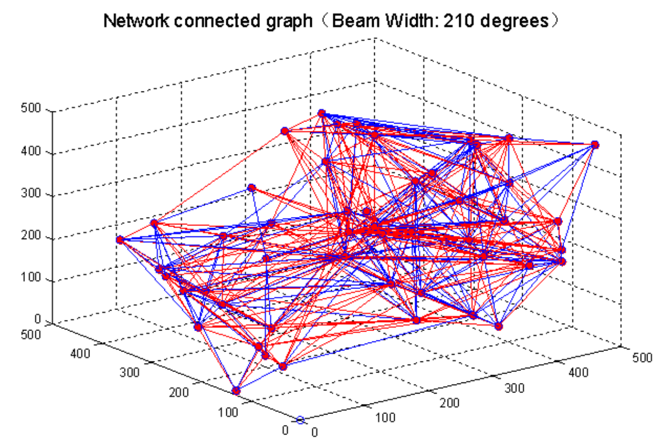

Fig. 5. Network connectivity with 210° beam width.

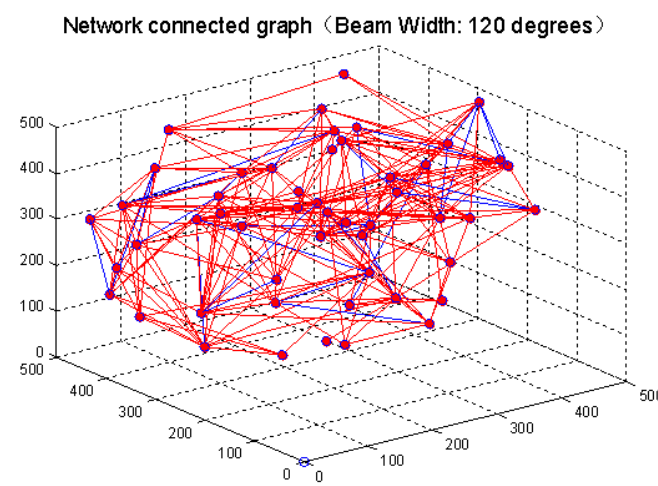

Fig. 6. Network connectivity with 120° beam width.

beam width and three-dimensional direction of the underwater sensor nodes. This would cause the decline in the number of paths between the sensor node and the sink node.

Existing routing protocols have not take into account the impact of the beam width and three-dimensional direction of the underwater sensor nodes to the underwater network topology. The emergence of asymmetric links and the decline of the network connectivity will lead to a decrease in the performance of existing protocols such as lower packet delivery rate. Some

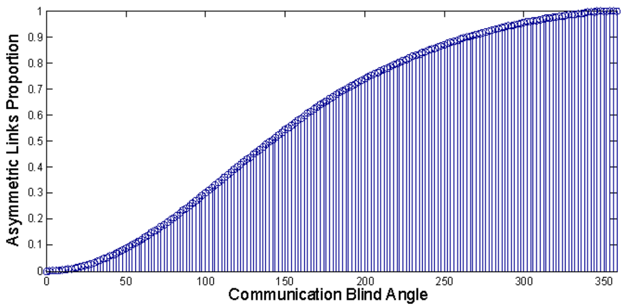

Fig. 7. Proportion of asymmetric links with different beam width.

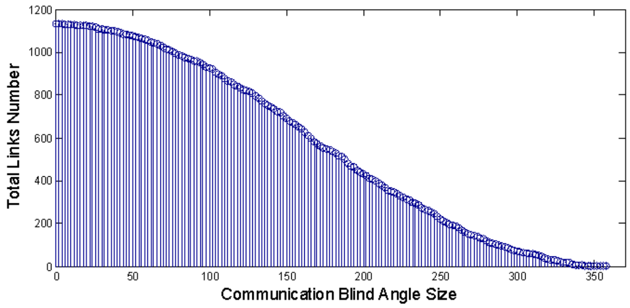

Fig. 8. Total number of links with different beam width.

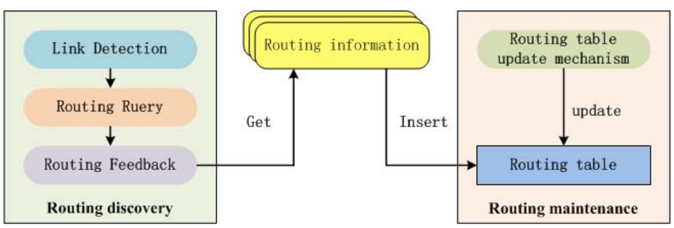

Fig. 9. Architecture of the proposed routing protocol.

existing protocols even failure when take into account the impact of the beam width and three-dimensional direction. The simulation results in section ¢ô can indicate the performance of existing protocols would decrease when take into account the impact of the beam width and three-dimensional direction.

B. Protocol Overview

Underwater sensor networks emerges a large number of asymmetric links due to the beam width and three-dimensional direction of the underwater sensor nodes. Therefore, how the sink node feedback routing information to the sensor node is becoming a difficult problem. Fig. 9 shows the architecture of the proposed LAFR protocol. LAFR is a table-driven routing protocol, which consists of two parts: routing discovery and routing maintenance. The part of routing discovery contains the following three mechanisms: Link Detection, Routing Query and Routing Feedback. Routing maintenance is completed by the routing table update mechanism. LAFR overcome the routing feedback problem in the underwater environment with a high proportion of asymmetric links.

In the LAFR protocol, sensor nodes initiate routing query to get its own routes and added to the routing table, and then send data packets according to the routes in the routing table.

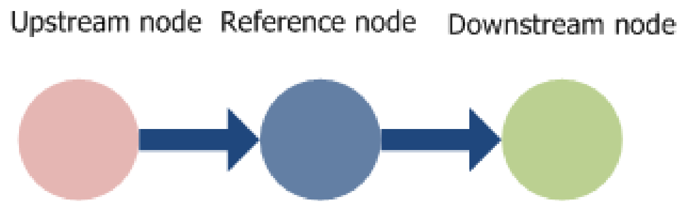

Fig. 10. Illustration of upstream node and downstream node.

Fig. 11. Link detection message format.

We propose a link detection mechanism to get link state information (symmetrical link or asymmetric link). During the routing query process we propose a time-based priority forwarding mechanism and utilize downstream node table (introduced in Link Detection) to prevent flooding and save energy. Then we propose an adaptive routing feedback method, the sink node adaptively select a feedback manner (path inversion method or reverse routing search method) according to the state of links in the routes. This method could effectively feedback the routes to the sensor node and save energy. At last, a credit-based dynamic routing update mechanism has been adopted to avoid energy consumption caused by frequent update of routing table. Some mechanisms such as utilize downstream node table, adaptive routing feedback method and credit-based dynamic routing update mechanism are all not appeared in the current other protocols. It can be said that the protocol proposed in this paper is an originality protocol proposed for underwater environment. In the following paragraphs, we will introduce the details of these mechanisms.

C. Link Detection

The symmetrical links and asymmetric links exist simultaneously in UASNs. Link state information has played an important role in our LAFR protocol such as help sink node adaptively select a feedback manner. In order to get the link state information (symmetrical link or asymmetric link) we propose a link detection mechanism.

We introduce the concept of the upstream node and downstream node. As shown in Fig. 10: select a reference node, upstream nodes data can one-hop to reach the reference node, nodes can directly receive the data of the reference node is the downstream nodes.

All nodes in the network are equipped with an upstream nodes table and a downstream nodes table. Nodes update the upstream and downstream nodes table by sending Link Detection messages. Link Detection messages sent periodically by the nodes, and the transmission period T is set according to network size. The Link Detection message format in our protocol is illustrated in Fig. 11. The message header contains message type and sender ID.

Fig. 12 shows the Link Detection message processing process. When a node receives a Link Detection message,

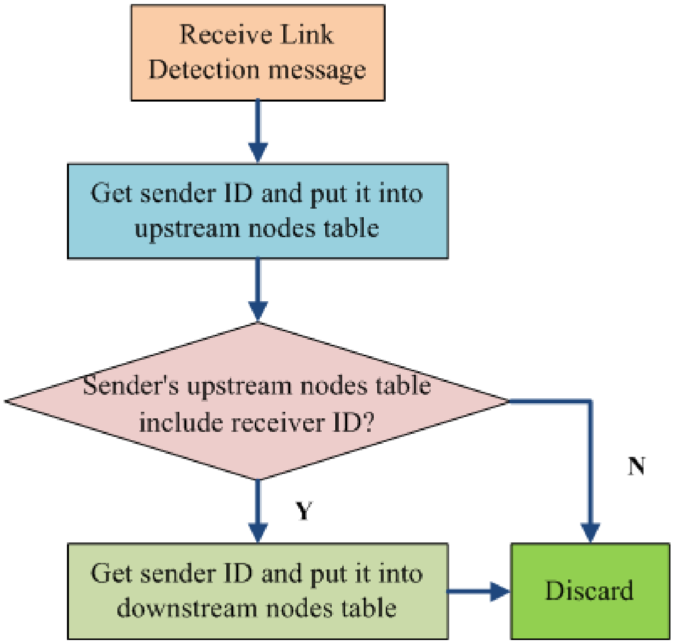

Fig. 12. Link detection packet processing flow.

it first parses out sender ID added to the upstream node table. And then check whether the sender's upstream nodes table contains the receiver ID. We put the sender ID into the downstream nodes table if it contains, otherwise discard the message.

Upstream and downstream nodes table can be represented by an n-bit binary code, where n is the total number of nodes. Assume that P_i is the ith symbol, we use (5) to judge the corresponding node is in the table or not.

$$\underbrace{010100...1101}_{n} \tag{4}$$

$$\begin{cases} P_i\&1 = 1 : \text{ node i in the table} \\ P_i\&0 = 0 : \text{node i not in the table} \end{cases} \tag{5}$$

Link detection is accomplished through the use of the upstream and downstream nodes table. The sender ID will be checked as soon as a node receives data. If the sender ID is included in the downstream nodes table, the link is symmetric link, otherwise it is asymmetric link. It is worth noting: the links between the node and the nodes in the downstream nodes table is symmetric links.

D. Routing Inquiry

If the routing table is not containing required routes, the sensor node will send routing request packets for routing inquiry. The purpose is to find the sensor node to sink node routing. The routing request packet format in our protocol is illustrated in the Fig. 13. The packet header consists of three fields: Message type, Sender ID, and Packet Sequence Number. "Sender ID" is the identifier of the sensor node. "Packet Sequence Number" is a unique sequence number assigned by the sensor node to the packet. Together with Sender ID, Packet Sequence Number is used to prevent duplication of routing request packets forwarding.

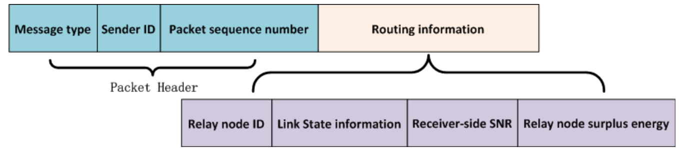

Fig. 13. Routing request packet format.

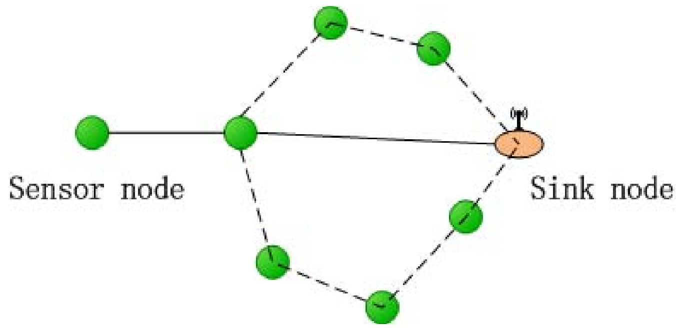

Fig. 14. A scene example.

Routing information can be divided into four parts: Relay node ID, Link state information, Receiver-side Signal Noise Ratio (SNR) and Relay node surplus energy. "Relay node ID" is the identifier of the relay node. "Link state information" is a number to express the symmetric state of the corresponding link: 1 represents symmetric link, 0 represents asymmetric link. "Receiver-side SNR" is the signal to noise ratio of the corresponding relay node side. "Relay node surplus energy" is the residual energy of the corresponding relay node. It is worth noting: "Link state information" must be included in the routing information, because it plays an important role in the latter routing feedback. "Receiver-side SNR" and "Relay node surplus energy" are for routing optimization.

During the routing inquiry process, nodes may repeatedly forwards the routing request packet, resulting in a waste of energy. We propose a time-based priority forwarding mechanism, for the same routing request packet nodes only forward the first received. Nodes through the packet sequence number together with Sender ID to determine whether to receive the same routing request packets. This can effectively prevent the nodes forwarding routing request packets repeatedly and save energy.

In addition, we utilize downstream node table during routing inquiry process. Node checks whether the downstream nodes table contains the sink node to reduce the routing request packet forwarding. As shown in Fig. 14, after the use of the downstream nodes table, the path which indicated by dotted lines will not be found. So this method can conserve energy and avoid finding more long-routing. The sensor nodes even can directly get their own route without routing inquiry when the sensor nodes and sink node are directly connected by a symmetric link.

E. Adaptive Routing Feedback Method

When the sink node receives the routing request of the sensor node, it needs to put the routing information feedback to sensor node. There are two ways for routing feedback:

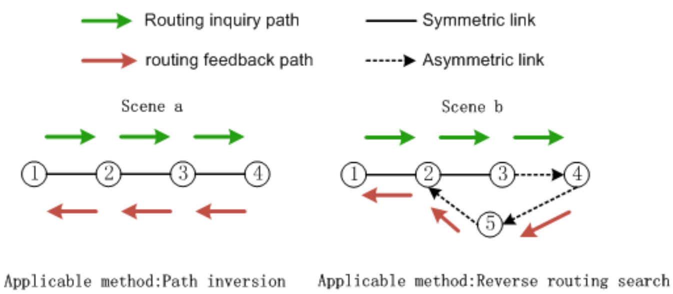

Fig. 15. Illustration of the applicable method in different scenarios.

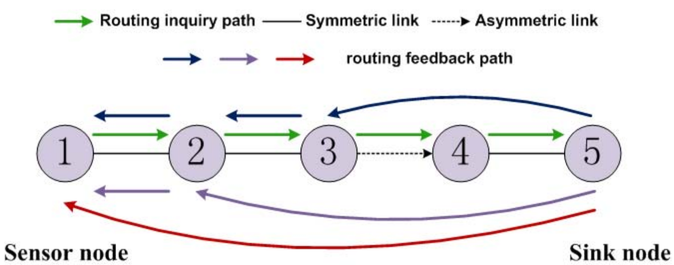

Fig. 16. Illustration of utilize the existing routing information.

Path inversion and Reverse routing search. Fig. 15 shows the applicable method in different scenarios, node 1 is sensor node and node 4 is sink node. It can be seen that if the routing links are all symmetric links we can take the path reversal method else we take the reverse routing search method.

When the sink node receives the first routing request packet it would wait a period of time to accept different routing information about the same source node. And then integrate these routes to get a route set. If the set contains symmetric route (links in the route are all symmetric links) we reverse the symmetric route to complete the routing information feedback else we send routing request packet from the sink node to find a route to source node.

In the reverse routing search method, we fully utilize the existing routing information. We collect the nodes ID before the asymmetric link of each route in the route set, and then get a node set. In the reverse route search process, we can feedback routing information smoothly as long as find any node in the node set. Fig. 16 is an example for how to utilize the existing routing information, node 1 is the source node and node 5 is the sink node. It is easy to know that the links between node 1 and node 3 are all symmetric links, so we get a node set consist of node 1, node 2 and node 3. As shown in Fig. 16 node 5 which is the sink node could stop forwarding the routing request packet and could feedback the routing information successfully if it finds anyone in the node set. This can reduce the energy consumption. In addition, we also use the downstream nodes table to reduce the number of packet forwarding during reverse routing search process just like routing inquiry process. This can further reduce energy consumption.

F. Routing Optimization and Maintenance

A sensor node may find several different routes to the sink node, and these routes may have different conditions. How to evaluate the routing quality and choose the best route as well as how to maintain routing tables become problems. So we propose a routing scoring mechanism and a credit-based dynamic routing update mechanism to solve these problems.

In the routing inquiry process, we set a signal to noise ratio threshold snr_{th} and a residual energy threshold e_{th}. Nodes which satisfy the conditions (6) and (7) are considered as the forwarding nodes. This guarantees that the quality of the channel and avoid using the node to be depleted as a relay node.

$$snr \geq snr_{th} \tag{6}$$

$$e \geq e_{th} \tag{7}$$

We give each route a score: $k = f\,(e, d, snr)$, "e" represent the average residual energy of all the relay nodes in the routing. "d" represent the total length of the route. "snr" represent the average signal to noise ratio. We calculate these parameters through (8), (9) and (10) respectively.

$$e = \frac{\sum_{i=1}^{n} e_i}{n} \quad \text{n is the total number of relay nodes} \tag{8}$$

$$d = \sum_{i=1}^{n} d_i \quad \text{n is the total number of links} \tag{9}$$

$$snr = \frac{\sum_{i=1}^{n} snr_i}{n} \quad \text{n is the total number of links} \tag{10}$$

We use k_e, k_d, k_s represent the scores of these parameters respectively. The scope of the three parameters are all designed as [0, 2] in order to comprehensive utilization of these three parameters to get the score of route. It is also convenient to use the weight coefficient method to make the score more emphasis on one aspect. They can be calculated by (11), (12) and (13) respectively. Φ_e, Φ_d and Φ_s are score units, Δe, Δd and Δsnr are the corresponding cost of one score unit. The score precision can be adjusted by changing the size of $\Delta e, \Delta d, \Delta snr$ and the corresponding Φ_e, Φ_d, Φ_s. For example: suppose $\Phi_e = 0.01$ and the corresponding Δe, if we set $\Phi_e = 0.1$, the corresponding Δe would be ten times the original one. It is worth noting: we need to select the appropriate size of the parameters to ensure k_s, k_d and k_s in the range of [0, 2].

$$k_e = 1 + \frac{e - e_0}{\Delta e} \times \Phi_e \quad e_0 \text{ is reference value} \tag{11}$$

$$k_d = 1 - \frac{d - d_0}{\Delta d} \times \Phi_d \quad d_0 \text{ is reference value} \tag{12}$$

$$k_s = 1 + \frac{snr - snr_0}{\Delta snr} \times \Phi_s \quad snr_0 \text{ is reference value} \tag{13}$$

Then k can be expressed by (14), it is easy to know that k is in the range of [0, 2]. We can adjust the size of n_e, n_d, n_s (weighting parameters) to make the score more emphasis on one aspect.

$$k = \frac{n_e k_e + n_d k_d + n_s k_s}{n_e + n_d + n_s} \tag{14}$$

Routing score can be obtained by the above formula, each route and its corresponding score is written to the routing table. We propose a routing table update strategy based on reward and punishment mechanism. Node selects the route with the highest score in the routing table to send data packet. The route would be rewarded until the score reaches the upper limit if the data packet is sent successfully. Accordingly, the route would be punished if the data packet is sent failure.

$$\begin{cases} k = k + reward & \text{Data send success} \\ k = k - punishment & \text{Data send failure} \end{cases} \tag{15}$$

In the implementation process reward is much lower than punishment. When the route score is less than the lower limit the route will be deleted from the routing table. The node will re-initiate the routing query if the number of route in the routing table is less than the default minimum number. The default minimum routing number can be developed according to the actual network size.

IV. Simulation Results

In this section, we evaluate the performance of proposed LAFR protocol and compare it with the Depth-based Routing (DBR) protocol [29] which is the representative routing protocol in underwater environment. DBR protocol have better performance in the existing underwater routing protocols, and it is a representative of the underwater routing protocols, so we chose it for performance comparison.

A. Simulation Settings

We evaluate the performance of the proposed work by using a network simulator written by C++. In our simulations, sensor nodes are randomly deployed in a 500 m × 500 m × 500 m 3-D area. One sink is deployed at the center of the water surface. As a result of our simulation for the application of the static waters, so we assume all the nodes are stationary once deployed. Each sensor node has a random orientation and a beam width which can be set in the simulation. The communication range for both the sensors nodes and the sink node is 100 m; the bit rate is 6600bps; and the power consumption for packet sending, receiving are 2w, 0.8w respectively. Each data message packet was 256 bytes long and the data generating rate at the source node is one packet per 30 seconds. Each Link Detection packet was 16 bytes long and its transmission cycle for each node is 5 seconds. The routing request packet (contains the forward and reverse) and routing response packet was 32 bytes long.

B. Comparison With Existing Protocol

Now we compare proposed LAFR protocol with DBR. The DBR protocol is not subject to the effects of asymmetric link and it can effectively route only with depth information. Its performance is better than some other existing protocols such as VBF, the simulation result of the literature [29] can provide data to support it. In the simulation, the beam width of all nodes is set to 210 degrees and 120 degrees, and for DBR, the depth threshold is set to 0.

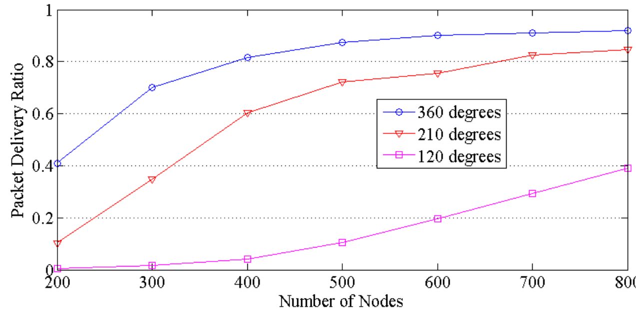

Fig. 17. Packet delivery ratio of DBR with different beam width.

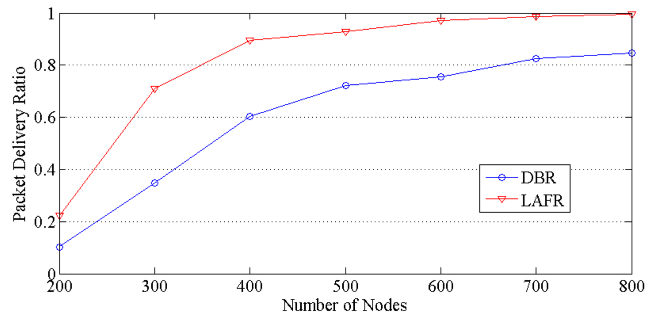

Fig. 18. Packet delivery ratio for LAFR and DBR with 210° beam width.

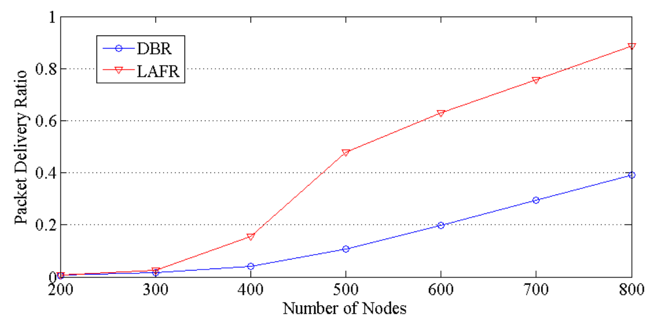

Fig. 19. Packet delivery ratio for LAFR and DBR with 120° beam width.

Fig. 17 shows the packet delivery ratio for DBR scheme with 120°, 210° and 360° beam width. It can be seen that the protocol performance would drop dramatically when taking into account the impact of the beam width and three-dimensional direction. That because using the DBR mechanism may not be able to find a path of a sensor node to the sink node due to the decline of the network connectivity.

Fig. 18 and Fig. 19 show the comparison of packet delivery ratio for LAFR and DBR scheme when the beam width is 210° and 120°, respectively. It can be seen that the LAFR significantly outperforms DBR in terms of packet delivery ratio. As mentioned in Section III, the network connectivity would change a lot when take into account the impact of the beam width and three-dimensional direction. This leads to the decreased performance for DBR. But LAFR can still achieve a high delivery rates. For example, in a network with 800 nodes with 120° beam width, LAFR has a packet delivery ratio of around 90%, which is much higher than 39%, the delivery ratio of DBR. That because the number of links in the network

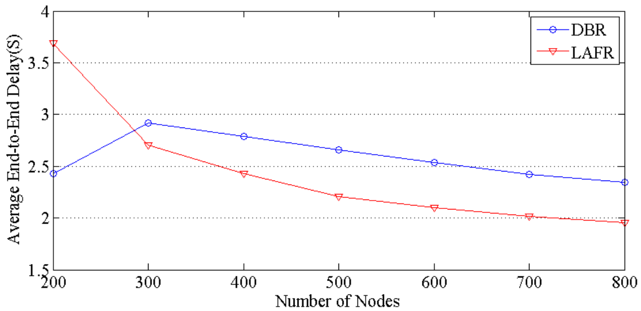

Fig. 20. Average end-to-end delay for LAFR and DBR with 210° beam width.

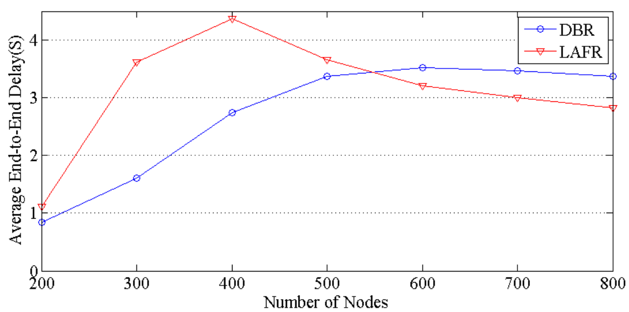

Fig. 21. Average end-to-end delay for LAFR and DBR with 120° beam width.

is drastically reduced with the reduction of the beam width, using the DBR would lead to a lot of nodes cannot find the routing and lead to packet loss.

Fig. 20 and Fig. 21 show the comparison of average end-to-end delay for LAFR and DBR when the beam width is 210° and 120°, respectively. It can be seen that LAFR has a better end-to-end delay than DBR when the beam width is 210°. This is because the holding time required in DBR approach results in higher delay time. In DBR protocol, a node uses holding time to schedule packet forwarding. When a sensor receives a packet from its neighbor sensor, it will wait a period of time to broadcast the packets. DBR uses holding time mechanism to select the neighboring node with the minimal depth to be the first one to forward a packet and prevent other neighboring nodes from forwarding the same packet to reduce energy consumption. In our LAFR protocol we do not use the holding time mechanism. From Fig. 21 we can see that in a network with 200 nodes the average end-to-end delay is very low, when the number of nodes larger than 600 LAFR begins to have a better end-to-end delay than DBR. That because when the beam width is 120° and fewer nodes in the network, the network connectivity is very low, most of the nodes cannot reach the sink node, just a small number of nodes can reach the sink node within a small hop numbers, this led to the end-to-end delay becomes very low.

Fig. 22 and Fig. 23 show the comparison of energy consumption for LAFR and DBR scheme when the beam width is 210° and 120°, respectively. It can be seen that the energy consumption of LAFR is slightly increased when the number of sensor nodes gets larger, owing to the effectiveness of the routing table in the proposed protocol. The more nodes in

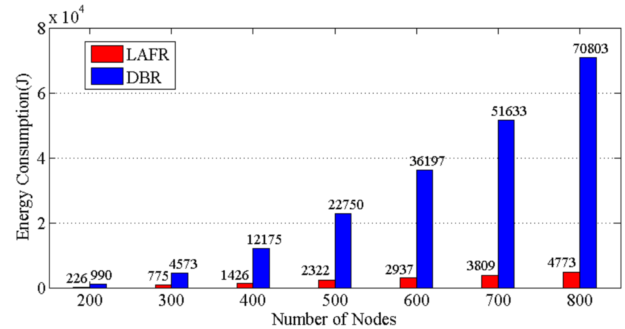

Fig. 22. Energy consumption for LAFR and DBR with 210° beam width.

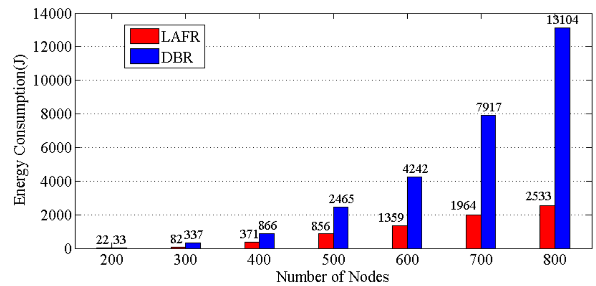

Fig. 23. Energy consumption for LAFR and DBR with 120° beam width.

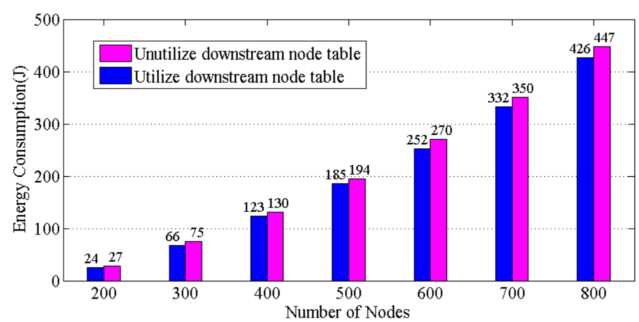

Fig. 24. Energy consumption for whether to utilize downstream node table during routing inquiry process with 210° beam width.

the network, the more energy we save through LAFR. That because routing table is used to prevent diffusion packet when the nodes send data, this will save a lot of energy.

C. Impact of Protocol Mechanisms

Now we examine how the performance of LAFR protocol is affected by protocol mechanisms as follows:

- utilize downstream node table
- utilize routing information during routing feedback process

Fig. 24 and Fig. 25 show the comparisons of energy consumption for whether to utilize downstream node table during routing inquiry process when the beam width is 210° and 120°, respectively. It can be seen that utilize downstream node table could save a part of energy, owing to utilize downstream node table could reduce the spread of the routing request packets in the network. Compare Fig. 24 and Fig. 25 we can see that when the beam width is 210° and 120°, the proportion of

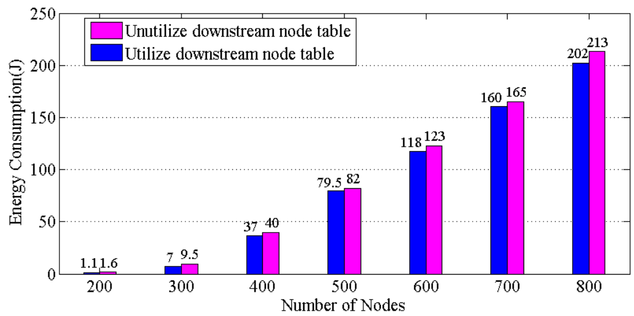

Fig. 25. Energy consumption for whether to utilize downstream node table during routing inquiry process with 120° beam width.

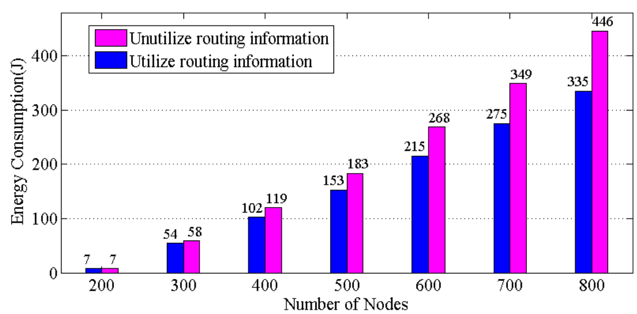

Fig. 26. Energy consumption for whether to utilize routing information during routing feedback process with 210° beam width.

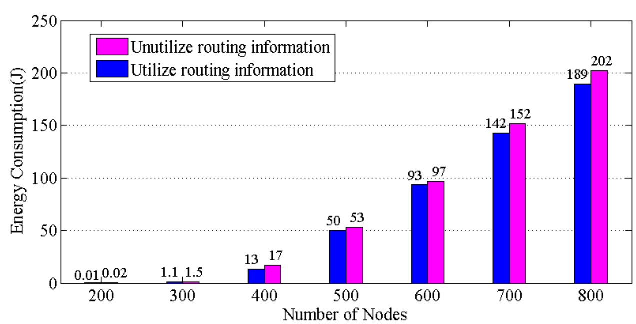

Fig. 27. Energy consumption for whether to utilize routing information during routing feedback process with 120° beam width.

the energy savings is basically the same size. That because regardless of the size of the beam width, utilize downstream node table can only prevent last hop nodes continue to spread the routing request packet, the proportion of the energy savings is consistent.

Fig. 26 and Fig. 27 show the comparisons of energy consumption for whether to utilize routing information during routing feedback process when the beam width is 210° and 120°, respectively. It can be seen that utilize routing information during routing feedback process could save some energy. Compare Fig. 26 and Fig. 27 we can see that we could save more energy with the increase in beam width. That because the proportion of asymmetric links would decline with the increase in beam width. So the send chance of reverse routing request packets would be reduced and the spread of the reverse routing request packets in the network would also be reduced if they have been sent.

V. Conclusion

A link-state based adaptive feedback routing protocol for UASNs is proposed in this work. Different from other underwater routing protocols, out protocol takes into account the impact of the beam width and 3-D direction of the underwater node to the network topology. Link detection mechanism and adaptive routing feedback method are adopted to get data transmission routes effectively, and a credit-based dynamic routing update mechanism is developed to avoid energy consumption caused by frequent update of routing table. In addition, we utilize downstream node table during routing inquiry process and reverse routing search process to reduce the power consumption of the sensor nodes. The simulation results show that the proposed routing protocol can achieve excellent performance in terms of the metrics, the packet delivery ratio, energy consumption, and average end-to-end delay.

In the future, we would consider the routing improvements applied to the high dynamic UASNs. The impacts of mobile sensors and multiple sinks will also be considered in the future work to enhance the practicability of UASNs.

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