

## Research Article

# An Environment-Friendly Multipath Routing Protocol for Underwater Acoustic Sensor Network

**Yun Li,<sup>1,2</sup> Zhigang Jin,<sup>1</sup> Yishan Su,<sup>1</sup> Ming Yang,<sup>3</sup> and Shenyang Xiao<sup>1</sup>**

<sup>1</sup>School of Electronic Information Engineering, Tianjin University, Tianjin 300072, China

<sup>2</sup>School of Electronic Engineering, Guilin University of Aerospace Technology, Guilin 541004, China

<sup>3</sup>College of Computing and Software Engineering, Kennesaw State University, Marietta, GA, USA

Correspondence should be addressed to Yishan Su; [yishan.su@tju.edu.cn](mailto:yishan.su@tju.edu.cn)

Received 17 October 2016; Revised 27 January 2017; Accepted 8 February 2017; Published 26 February 2017

Academic Editor: Hai-Feng Ji

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Underwater Acoustic Sensor Network (UASN) is a promising technique by facilitating a wide range of aquatic applications. However, routing scheme in UASN is a challenging task because of the characteristics of the nodes mobility, interruption of link, and interference caused by other underwater acoustic systems such as marine mammals. In order to achieve reliable data delivery in UASN, in this work, we present a disjoint multipath disruption-tolerant routing protocol for UASN (ENMR), which incorporates the Hue, Saturation, and Value color space (HSV) model to establish routing paths to greedily forward data packets to sink nodes. ENMR applies the mechanism to maintain the network topology. Simulation results show that, compared with the classic underwater routing protocols named PVBF, ENMR can improve packet delivery ratio and reduce network latency while avoiding introducing additional energy consumption.

## 1. Introduction

Underwater Acoustic Sensor Network (UASN) has attracted much more attentions in recent years, which has wide applications in civilian and military fields, such as coastline surveillance disaster forecast/detection, and military defense [1–3]. In UASN, acoustic communication is considered to be an ideal method for long range communication due to the severe attenuation characteristic of radio wave in underwater environment.

Firstly, low propagation speed results in long end-to-end delay. The propagation speed of acoustic signal in underwater environment is approximately 1500 m/s [4], which is five orders of magnitude less than the radio signal. What is even worse is that the propagation speed varies with the change of water depth, temperature, and salinity. Such uncertainty of delay makes great challenges on the schedule of packet transmission and synchronization of the network.

Secondly, underwater channel is characterized by severe multipath fading and Doppler spread, limited spectrum resource, and high spatial-temporal uncertainty [5]. All these

factors can cause even higher error rate which increases the challenge on reliable packet exchange in UASN.

Finally, in oceans, there exist not only artificial acoustic systems like UASN and sonar systems, but also natural acoustic systems such as marine mammals [6]. All of these systems may share the same water area, which use acoustic signal for sensing, detection, navigation, or communication. Unfortunately, due to the frequency-dependent attenuation feature of acoustic signal in underwater, the available communication frequency is usually from tens of hertz to hundreds of kilo hertz [7], which has been heavily shared by all the existing underwater acoustic systems as shown in Figure 1.

Furthermore, many researchers have proved that anthropogenic noise from artificial acoustic systems will affect marine mammals by causing behavioral responses, hearing injuries, or masking of biological sounds [8–10].

All the features mentioned above impose great challenges to the protocol design on every layer of UASN. Specifically, in routing layer, many proposed routing protocol, such as VBF, DBR dedicated for UASN focus on efficient delivery path design with a consideration of the topology of the network.

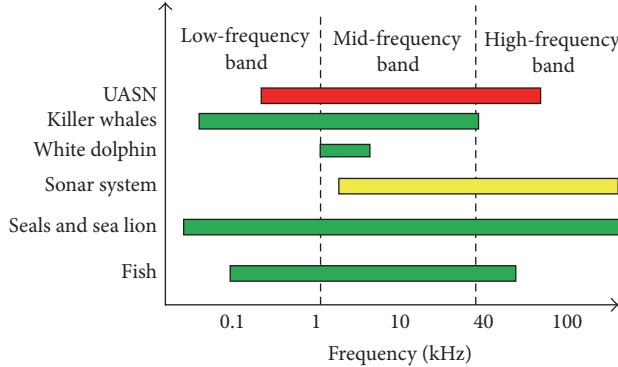


FIGURE 1: Spectrum share in underwater.

Most of the existing routing protocols rely on the single path from source node to the destination for packets' delivery. However, the single path strategy is fragile since it may be interrupted by other acoustic systems which are located in the interference area. To improve the reliability of packet delivery while avoiding interference with marine mammals in underwater environment, in this paper, we propose a novel Environment-friendly Node-disjoint Multipath Routing protocol for USAN, named ENMR. In ENMR, to deal with the possible link disconnecting caused by nodes' mobility or marine mammals' interference, more than one node-disjoint link is provided to improve the reliability of forwarding packet. The node-disjoint routing protocol is a disruption tolerant scheme by providing a redundant path for forwarding packets. The proposed ENMR protocol applies HSV (Hue, Saturation, and Value) color space model to establish multipaths. Based on HSV model, the ENMR protocol can create a numeric tuple for each link and map these tuples into 6 basic planes, which corresponds with 6 different color spaces and then 6 different paths. In the ENMR protocol, two paths out of six are chosen as the forwarding paths, which is a tradeoff between network's reliability and efficiency. The selection of paths also considers the existence of marine mammals to avoid possible interference with them.

The contributions in the paper are highlighted as follows. Firstly, we propose a node-disjoint multipath scheme based on HSV color space model for reliable packet forwarding from source to sink. Secondly, by obtaining geographical location information of marine animals, ENMR protocol can be friendly with marine animals as well as forwarding packets reliably.

The rest of this paper is organized as follows: in Section 2, we review the related works on routing protocols in underwater acoustic networks. Color model is described in Section 3. In Section 4, we propose a novel node-disjoint multipath scheme named ENMR. In Section 5, we provide simulation results and analysis on the performance of ENMR. Finally, our main conclusions and future works are drawn in Section 6.

## 2. Related Works

In this section, we will review related works on routing protocols in UASN.

The existing routing protocols for terrestrial sensor network can be classified into proactive routing, reactive routing, and location-based routing. The same classification is applied in UASN. However, routing protocols designed for terrestrial sensor networks cannot be directly applied in UASN due to some unique characteristics such as long propagation delay, high mobility, limited bandwidth, and energy-constraint.

Vector-Based Forwarding (VBF) protocol, proposed by Wu and Sun [11], is a kind of greedy routing dedicated to underwater acoustic network. In VBF, nodes broadcast packets to their neighbors residing in a constrained "pipe" of a given radius directing to the sink. The pipe surrounds a virtual line (a vector) between the packet source node and the sink. The efficiency of the protocol depends on the critical determination of the pipe radius. If the radius is too small, few or no relay node can be found in the pipe; otherwise, too many nodes might be involved in forwarding packets, which leads to unnecessary energy consumption.

To improve the performance of VBF, Gomathi et al. extended VBF to HH-VBF protocol (hop-by-hop VBF protocol) [12]. HH-VBF changes the direction of the forwarding pipe hop by hop in the entire lifetime. In this way, every forwarding node can make routing decision according to the current local topology information. Although the performance of the network can be improved by dynamically changing the direction of flooding pipeline compared with VBF, HH-VBF has a relatively low performance in sparse network when a constant pipeline radius is set.

Both of VBF and HH-VBF are vulnerable to marine mammals since the transmission only occurs in the "pipe." Once the pipe is blocked by marine mammals, the transmission can be possibly interrupted.

In [13], Coutinho et al. proposed a routing protocol named Focused Bream Routing (FBR) to reduce the unnecessary flooding in the network. In FBR protocol, prior to sending or forwarding packets, nodes gradually increase the forwarding range by adjusting the flooding angle and transmission power levels according to the preregulated angle gradient and power gradient. However, the nodes need to send RTS and receive CTS many times to build routing link and forward data packets. In the process of building links, FBR pays little attention to the changes of network topology resulting from the ocean current. Therefore, FBR would have pretty much energy consumption due to the appearing of marine animals and interference of ocean current.

In [14], Position Vector-Based Forwarding (PVBF) protocol based on geographical location information is proposed. PVBF protocol pays attention to the problem of nodes mobility which is high energy consumption. By calculating the energy consumption of forwarding packets in the whole link, PVBF protocol selects the least energy consumption link to forward packets. However, PVBF protocol may introduce a long time delay. When interference happens, PVBF protocol has to recalculate energy consumption and then again find the new link to forward packets.

The Depth Based Routing protocol is presented by Yan et al. in [13]. Each node will forward the data packet it receives only if the depth of the node is less than that of other nodes. Before forwarding the data packet, a node holds the packet for

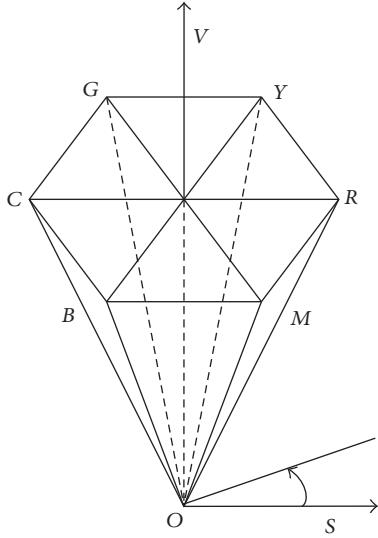


FIGURE 2: HSV color space model.

a time that depends on the difference between its own depth and that of the sender [15]. However, DBR protocol cannot yet take marine animals into consideration. When forwarding packets, DBR protocol may interfere or hurt the sound system of marine animals.

The above-mentioned protocols rely on only single path to forward packets. If the only available link is interrupted, no path can be used to forward packets. Based on the discussion above, we find that few works on multipath routing scheme have been studied for UASN. Driven by this observation, we will propose a novel multipath routing protocol named ENMR protocol, which is able to not only forward packets reliably but also avoid possible negative influence on marine mammals.

### 3. HSV Color Model

The core idea of ENMR is to find two node-disjoint paths for data forwarding. HSV coloring method, which is often used in computer graphics applications, is an effective way to solve this problem. It has three elements named  $H$  (Hue),  $S$  (Saturation), and  $V$  (Value). In numeric  $(h, s, v)$  tuple,  $H$  denotes different colors, valued by  $R$  (Red),  $Y$  (Yellow),  $G$  (Green),  $C$  (Cyan),  $B$  (Blue), and  $M$  (Magenta).  $S$  which is between 0 and 1 denotes color saturation.  $V$  which is between 0 and 1 denotes color brightness. HSV color space is shown in Figure 2.

The model of the color space corresponds to a conical subset in the cylindrical coordinate system, and the top of the cone corresponds to the case that  $v = 1$ .

In a network, each link will be assigned numeric  $(h, s, v)$  tuple based on the HSV model. Then each link will be colored in order to be assigned to different color plane. According to the state of the link, the numeric  $(h, s, v)$  tuple of the link is represented as follows:

$$h_l = H_i \quad (0 \leq i < 6), \quad (1)$$

$$s_l = \frac{m}{k}, \quad (2)$$

$$\nu_l = \frac{\text{HOP}_l}{\text{HOP}_{\text{MAX}}}, \quad (3)$$

where  $h_l$  is one specific color. When transmitting data from  $i$ th node to  $j$ th node, we define  $m$  as the number of successfully received packets in  $j$ th node and  $k$  is a historical statistical value, which is the number of packets sent by  $i$ th node. We propose forward ratio  $s$  as (2) based on  $(m, k)$ -firm constraint model, where  $s$  implies the state of acoustic channel. The closer to 1 the forward ratio is, the better the acoustic channel is. Expression (3) describes the hop number from the source to the sink node.  $\text{HOP}_{\text{Min}}$ , which is statistic in sink node, denotes the minimum number of hops between the destination (sink node) and the link  $l$ , while  $\text{HOP}_{\text{MAX}}$  denotes the maximum number of hops in the whole network. Therefore,  $\nu_l$  describes the distance metric from the output node to the sink nodes via link  $l$ . In the HSV color space with constant  $H$ , the higher  $s$  is, the better the purity of color is, and the lower  $\nu$  is, the darker the color is. Therefore, according to expressions (1) and (2), the color purity would be higher when  $m$  is larger. And the color will be darker when the distance from  $n$ th node to sink node is closer.

According to the above coloring scheme, the numeric  $(h, s, v)$  tuples of different links will map into different color planes according to the different colors  $h_l = H_i$ . Due to different link state (the forwarding ratio and the number of hops between  $l$  and sink), all the links are corresponding to different color purity and shade. Therefore, different links can map into different color planes, which have the same nodes. The same nodes will work as an input node or an output node. This method will realize the separation of multiple paths from the source to the destination.

### 4. Design of ENMR

In this section, we describe the node-disjoint multipath routing protocol based on HSV color space model and REQ-REP mechanism. ENMR protocol can choose reliable route to transmit data.

**4.1. Network Architecture.** As shown in Figure 3, one sink, which is responsible for collecting data from sensors then transmitting the data to the shore, is deployed on the surface. The sink is equipped with both acoustic and radio-frequency modem. The acoustic modem can collect data from other sensors. The radio-frequency modem is to transmit data to the offshore base station. Sensor nodes are deployed in a three-dimension area. These sensor nodes are responsible for data collection and also relaying data to the sink. Considering the limited transmission range of acoustic signal, we assume that the collected data are transmitted to sink in multiple hops.

Furthermore, we assume that (1) each sensor node knows its own position with many existing self-localization scheme. (2) The link between two nodes is two-way asymmetry. The transmitter of link is called the output node while the receiver is called input node.

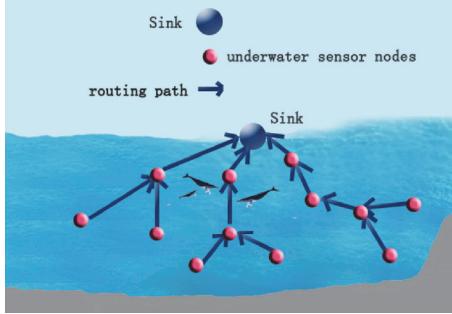


FIGURE 3: Network architecture for UASN.

**4.2. Workflow of ENMR.** ENMR maps links to color planes according to link coloring scheme. Since the color plane is separated from each other, the ENMR can establish multiple disjoint paths. To reduce the impact of nodes' mobility, we also explore a maintaining scheme for the link with a consideration of the link's quality. This algorithm is composed of 3 parts, link color process: links building, and links maintenance. Link color process aims to map links into different color planes. It is a classification method of color planes to build disjoint links. After building disjoint links, we need to apply the maintenance scheme to limit change of network topology.

**4.2.1. Link Color Process.** In this process, with the proposed HSV color theory, each link will be mapped into different color planes. There are two aspects for link color process, named Hue-Assign (HA) process and Reverse Hue-Assign (RHA) process, respectively. HA is the process of color assignment which starts from the sink node. RHA is the process of reversing color assignment. We also have the links which have the same input nodes to be colored with the same color. The whole process is shown in Figure 4.

By link coloring process, all the links will be mapped into different color planes and assigned with numeric  $(h, s, v)$  tuples.

**4.2.2. Links Building Process.** In order to reliably forward data and protect marine animals we need to build disjoint paths. Color classification method is used to build disjoint router. Color classification divides the HSV color planes into two types: Type I and Type II. Type I: the link belongs to one of the color planes, for example,  $h = \text{RED}$ , which has the current output node. Then the current output node belongs to Type I. Otherwise, the color plane Type II color of current output node.

In order to transmit data from source node to sink node, disjoint routers will be selected and the selection process is as follows.

#### Build Disjoint Route to Send Data

**Step 1.** Set Type I and Type II;

**Step 2.**

**If**  $h = H_i$ , **then**  $H_i \in \text{TypeI}$ . The information of the current color plane is encapsulated into the packet and sent to the input node of the link, which is added into preferred link set.

**End if**

**Step 3.**

**If**  $H_i \in \text{TypeII}$ , **then** active the mechanism REQ & REP. Source node broadcast the request (REQ);

**End if.**

**Step 4.**

**If** link is the same color plane, **then**  
Sent response packet (REP) to confirm;

**End if.**

**Step 5.**

**If** links belong to the preferred link set,  
**then** wait for other REP packets;

**Otherwise,**

set the link as the start link and add it to the preferred link set until no new REP.

**End if.**

According to above process we can obtain two schemes to satisfy different requests for reliable data transmission, named the preferred saturation scheme and preferred brightness scheme, respectively. In order to obtain the higher reliable transmission, we select the preferred saturation scheme. That is to say, the next link selected is the link of the best saturation. Otherwise, next link selected is the link of the best brightness.

**4.2.3. Links Maintenance.** The maintenance of node-disjoint multipaths faces huge challenge because of nodes' mobility in UASNs. The maximum mobility speed of sensor node in UASN is around 1-2 m/s. Such mobility of sensor nodes will reduce the delivery rate. According to (2), the link quality is getting lower if " $m$ " is reduced. Therefore, to maintain the network topology, which will be discussed as follows, is of vital importance.

#### The Maintenance of Node-Disjoint Multipath

**Step 1.**

Set RDQ is Request Detecting packets, RDP is response packets;

Broadcast RDQ to obtain  $(h, s, v)$ ;

Receive RDP from neighbor nodes

**Step 2.**

**If** the " $m$ " is reduced, **then** the network topology maybe changes; Update  $(h, s, v)$  of the link;

**Otherwise**, the network topology has no changes;

**End if**

**Step 3.**

Delete all links without RDP packets.

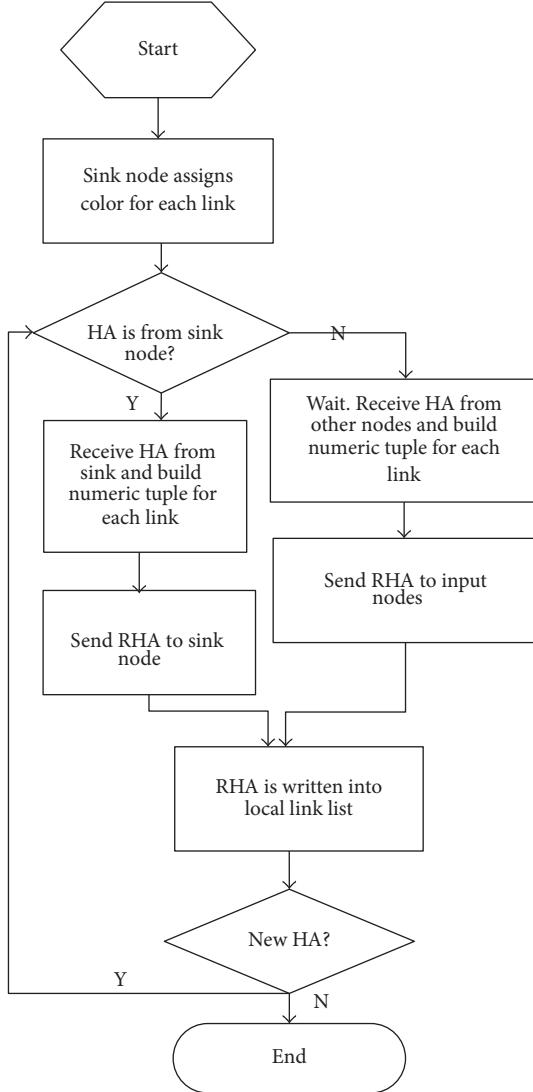


FIGURE 4: The link color process.

Consequently, ENMR can use other disjoint paths to forward data reliably and maintain the network's topology.

## 5. Performance Evaluation

In this section, we will evaluate the proposed routing scheme ENMR and compare it with a classic underwater routing protocol named PVBF in terms of average end-to-end delay and propagation, energy consumption, and packet delivery ratio. PVBF protocol with routing pipe determines to greedily forward data packets to any sink node on the sea surface. Aqua-Sim is chosen to conduct a series of simulations. Aqua-Sim is NS-2 based network simulator applied in underwater network simulation.

We randomly deployed 200 to 1000 nodes in a 3D region of  $20 \text{ km} \times 20 \text{ km} \times 5 \text{ km}$ , which is a sparsely distributed acoustic sensor network. The simulation parameters are shown as follows:

Data transmission rate is 2500 bps.

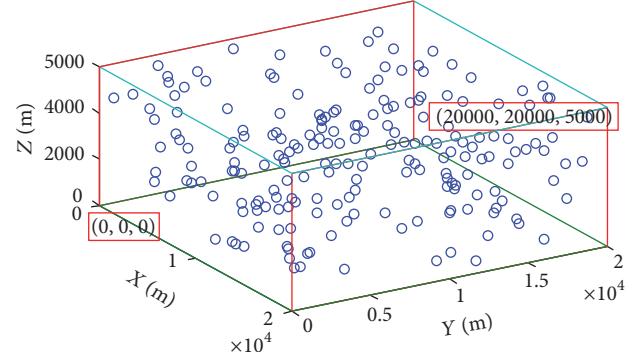


FIGURE 5: Network topology architecture.

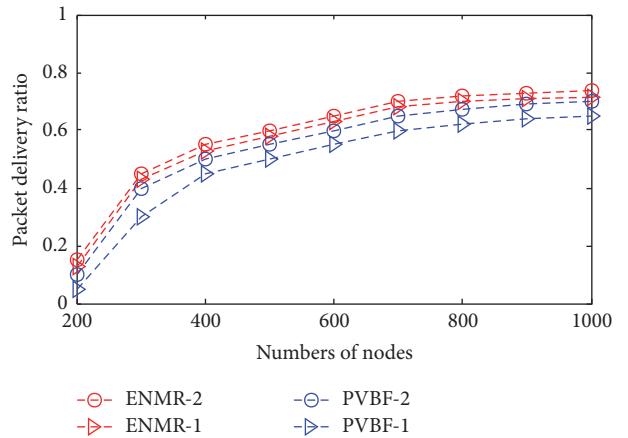


FIGURE 6: Packet delivery ratio versus numbers of nodes.

The number of nodes is 1000.

Maximum speed of node mobility is 2 m/s.

Acoustic signal propagation is 1500 m/s.

The coordinates of the source node are  $(0, 0, 0)$  while the destination is  $(20000, 20000, 5000)$ , which are shown in Figure 5. For ENMR simulation, each node is randomly deployed. During the simulation, the marine mammals are treated as one point in the network topology since many marine mammals' movement is population based. We evaluate the performance of the routing protocols in two different scenarios: with/without marine animals. When marine animals appear, ENMR/PVBF protocol denotes ENMR-1/PVBF-1, while ENMR-2/PVBF-2 denotes the conditions that are not affected by marine mammals.

### 5.1. ENMR Performance in Static Network

**5.1.1. Packet Delivery Ratio.** Figure 6 shows how the packet delivery ratio (PDR) changes with different numbers of nodes. All the simulation results show a similar trend where the PDR grows with the increased number of the deployed nodes. The reason for this trend is that the more nodes are deployed, the less routing voids appear which can lead to packet loss. Furthermore, ENMR generally shows better

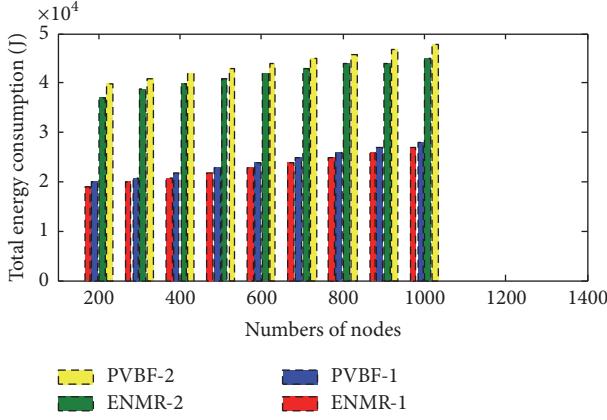


FIGURE 7: Total energy consumption versus numbers of nodes.

performance compared with PVBF. The PDR of ENMR-2 is 73% with 1000 nodes, which is about 12% higher than that of PVBF-2. It is because ENMR offers multiple paths to forward packets. Once the link is interrupted due to the occupation by marine animals, ENMR still has another reliable path to forward packet. Therefore, ENMR shows higher PDR compared with PVBF. In other words, ENMR has a better capacity of disruption-tolerance than PVBF. With the number of nodes varying from 200 to 1000, the packet delivery ratio of ENMR-1 is close to that of ENMR-2. Otherwise, the packet delivery ratio of PVBF-1 is more different from that of PVBF-2. The results illustrate that multidisjoint links have better and stable PDR performance.

**5.1.2. Total Energy Consumption.** The total energy consumption for different number of nodes is shown in Figure 7. From this figure, we observe that when marine animals appear, the energy consumption of ENMR reduces in half because fewer paths are applied to forward packets. However, when there is appearance of marine animals, the energy consumption of PVBF-2 increases twice than that of PVBF-1. The reason is that PVBF protocol needs to spend much energy and time to rebuild the routing pipe to guarantee PDR. Therefore, the simulation shows that ENMR protocol which has disruption-tolerance can protect marine animals and save energy consumption.

**5.1.3. Average End-to-End (E2E) Delay.** It can be seen from Figure 8 that, when the number of nodes varies from 200 to 1000, the average E2E delay of ENMR and PVBF protocol are both decreased. It is because the more nodes are deployed the less routing voids appear which can lead to packet loss. Therefore, the average E2E delay will be reduced. The average E2E delay decreases slowly with the nodes' number varying from 200 to 500, and the trends become almost flat when the nodes' number is larger than 600. The reason is that the number of nodes is large enough to cover the whole space. In general, the average E2E delay is less than PVBR. When nodes number is 400, the average E2E delay of PVBF-2 is 20.5 (s), while the average E2E delay of ENMR-2 is 18.5 (s). Furthermore, when marine animals occupy the channel, the average E2E delay of

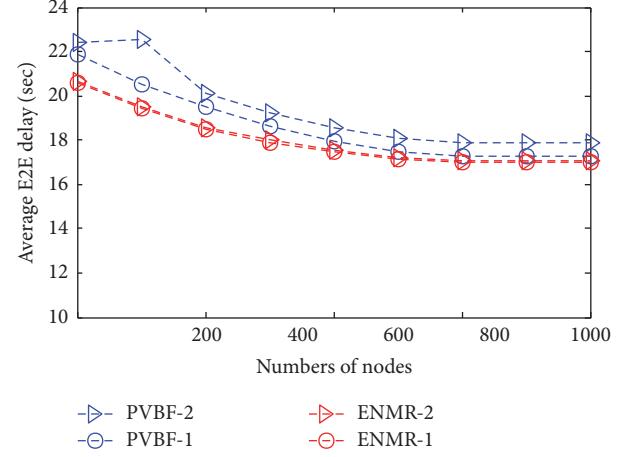


FIGURE 8: Average E2E delay versus numbers of nodes.

PVBF-2 is larger than PVBF-1. When the number of nodes is 300, the average E2E delay of PVBF-2 is 23 (s), while PVBF-1 is 20.8 (s). The average E2E delay of PVBF-2 is larger than that of PVBF-1. It is clear that the existence of marine mammals prolongs the time of packet delivery. Marine animal may interfere with forwarding nodes so that PVBF-2 has to spend more time to restore the routing pipe. Otherwise, ENMR is less affected when marine animals occupy the channel. The main reason is that ENMR has more than one path to forward packets. If the selected path is interrupted, the other path can still be used to forward packets successfully. Therefore, we can see that ENMR has better capacity of disruption-tolerance.

## 5.2. ENMR Performance in Mobile Network

**5.2.1. Packet Delivery Ratio.** To evaluate how the node mobility affects the performance of ENMR, we simulate both ENMR and PVBF with different node speeds from 0 to 2 m/s. Figure 9 shows that the packet delivery ratio of ENMR-1 and ENMR-2 is almost the same for different mobile speeds of nodes. It is because ENMR has a better capability of disruption-tolerance and is little affected by the interruption of the link due to node mobility. Otherwise, the packet delivery ratio of PVBF-1 is higher than PVBF-2 protocol. It is because when the link is interrupted due to node mobility or marine animals, the packet delivery ratio of PVBF will be decreased sharply. Therefore, when the link is interrupted, there are some variations between PVBF-1 and PVBF-2. When the number of nodes is 400, we can observe that the packet delivery ratio of PVBF-2 is 34% at 1.2 s, which is 8% higher than that of PVBF-1. Meanwhile, the packet delivery ratio of ENMR-2 is 50% at 1.2 s, which is 1% higher than that of ENMR-1. This further explains the fact that ENMR protocol has better reliability when the node mobility is taken into account.

**5.2.2. Total Energy Consumption.** Figure 10 shows how the total energy consumption changes with different velocity of nodes mobility. All simulation results show a similar trend where the energy consumption grows with the increase of the

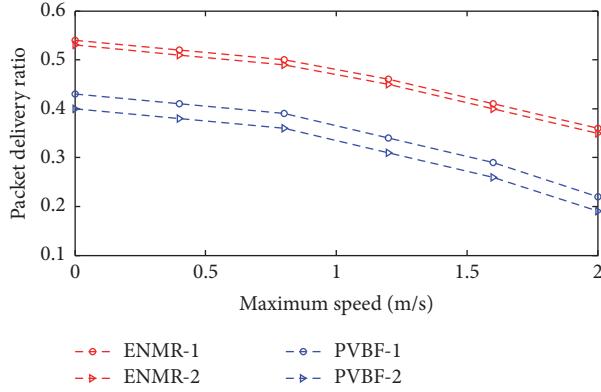


FIGURE 9: Packet delivery ratio versus maximum speed.

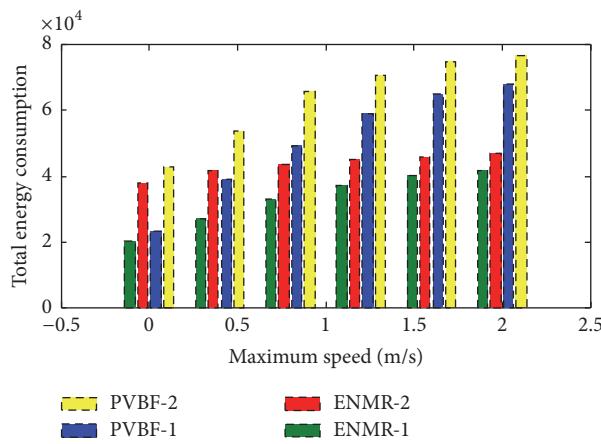


FIGURE 10: Total energy consumption versus maximum speed.

velocity of nodes mobility. Nodes mobility may result in more interruption links and low PDR. In order to guarantee the constant PDR and maintain reliable network topology, it is necessary to consume more energy to improve the delivery rate. ENMR generally shows better performance compared with PVBF. There are few differences between ENMR-1 and ENMR-2. In other words, ENMR protocol has a better capacity of disruption-tolerance than PVBF protocol when marine animals interfere with the network. With increase of the node mobility speed, the energy consumption of PVBF-1 improves 3 times compared to the original. The energy consumption of PVBF-2 increases nearly twice compared to the original, while the energy consumption of ENMR-1 increases less than one time compared with that of ENMR-2.

**5.2.3. Average E2E Delay.** As shown in Figure 11, the average E2E delay of PVBF is larger than that of ENMR. Furthermore, the average E2E delay of PVBF-2 is larger than that of VBF-1. But the average E2E delay of ENMR-1 is almost the same as that of ENMR-2 with the node mobility speed varying from 0 to 2. When node mobility speed is 2 (m/s), the average E2E delay of PVBF-2, PVBF-1, ENMR-2, and ENMR-1 is 27.8 (s), 25.8 (s), 19.7 (s), and 19.6 (s), respectively. It is because the node mobility interrupts the routing pipe so that PVBF

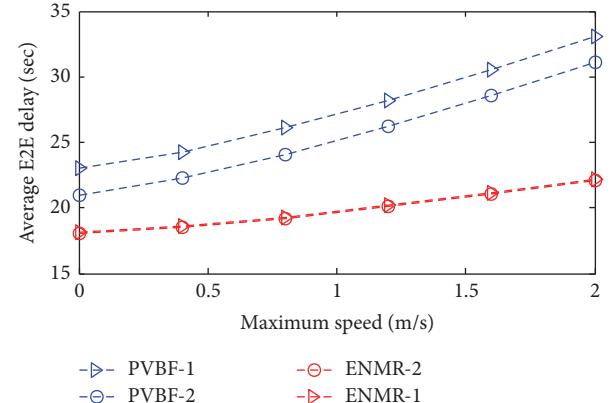


FIGURE 11: Average E2E delay versus maximum speed.

spends more time to rebuild link to forward packets. In comparison, node mobility has less influence on ENMR protocol. It is because ENMR can predict node mobility in advance by mechanism of REQ-REP and ENMR has more paths to forward packets reliably. Therefore, ENMR implies more robustness about the interruption of the link due to node mobility or marine animals. This further shows that ENMR has a better reliability than PVBF.

## 6. Conclusion

We presented ENMR, a disjoint multipath disruption-tolerant routing protocol for UASN in this paper. In order to reliably forward packets, HSV model is applied to build disjoint paths in ENMR protocol. In ENMR, the mechanism of REQ-REP and forward ratio is utilized to maintain the network topology reliable. In general, ENMR can improve the network delivery ratio and while reducing the energy consumption and end-to-end delay. Furthermore, ENMR can effectively forward packets while protecting marine animals. Simulation results show that ENMR can improve packet delivery ratio and reduce network latency while avoiding introducing additional energy consumption.

## Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

## Acknowledgments

This work was supported in part by the following projects: the National Natural Science Foundation of China through Grant 61571318, Qinghai Science and Technology Project 2015-ZJ-904, the Guangxi Nature Science Fund (2015GXNSF AA139298 and 2016GXNSFAA380226), Guangxi Science and Technology Project (AC16380094 and 1598008-29), Guangxi Nature Science Fund Key Project (2016 GXNSFDA380031), and Guangxi University Science Research Project (ZD2014146).

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