Available online at www.ijpe-online.com

International Journal of Performability Engineering

Vol. 13, No. 6, October 2017, pp. 966-974
DOI: 10.23940/ijpe.17.06.p17.966974

Mobile-MultiSink Routing Protocol for Underwater Wireless Sensor Networks

Zhuo Wang[a], Yancheng Sui[a,*], Xiaoning Feng[b], Jiajie Liu[b]

[a]*College of Shipbuilding Engineering, Harbin Engineering University, Harbin 150001, China*
[b]*College of Computer Science and Technology, Harbin Engineering University, Harbin 150001, China*

Abstract

Underwater Wireless Sensor Networks (UWSNs) are increasingly applied to explore underwater environments and resources. Some characteristics of mobile UWSNs, such as energy restriction, low transmission rate, node mobility and multiplicity, affect networks' performance significantly. In this paper, a Mobile-MultiSink (MMS) routing protocol is proposed for UWSNs with multiple mobile sink nodes. In the proposed MMS routing protocol, sensor nodes report events to multiple sink nodes using dynamic routing. There are two phases in this protocol, the layering phase and the construction phase. In the layering phase, each sink node establishes a layered structure, which needs to be refreshed periodically. Taking into consideration that the packet delivery rate (PDR) will reduce because of the mobility of nodes, we stipulate that every sink node should refresh its layered structure every time the PDR comes below a critical value. In the communication phase, the intermediate relay nodes are selected to forward data to the target sink node. This phase contains the selection of target sink node and the selection of relay nodes. We evaluate the performance of MMS using NS-3. Our findings demonstrate that the proposed protocol has better packet delivery rate and lower energy consumption in UWSNs with multiple mobile sink nodes.

Keywords: Underwater Wireless Sensor Networks; routing protocol; Moble-MultiSink (MMS); layered structure; energy consumption

(Submitted on April 29, 2017; Revised on July 12, 2017; Accepted on August 23, 2017)

1. Introduction

UWSNs enable real time monitoring of specific ocean areas with the provision of remote wireless data access. A number of issues need to be addressed while using UWSNs. Different from terrestrial sensor networks, the underwater scenario poses some challenges, like high transmission delay, nodes' irregular movement, varying network topology and frequent loss of connectivity due to underwater currents [1,2,4,10,14,18]. Therefore, conventional routing protocols are not appropriate for UWSNs. Besides, multiple autonomous underwater vehicles (AUV) are deployed to collect data in specific area. Their mobility and multiplicity also bring challenges to the design of UWSNs routing protocol.

According to UWSNs' characteristics, many researchers have been studying UWSNs routing protocol and have obtained achievements [3,5,9,11,12,16,17]. In [7], a novel Path Unaware Layered Routing Protocol (PULRP) was proposed for dense 3D UWSNs. PULRP is proved to have higher PDR compared to the Under-Water Diffusion (UWD) algorithm proposed in [13] and Dijkstra's shortest path algorithm. However, a significant limitation in most underwater sensor nodes is low battery capacity. In addition, the transmission range of each node must be optimized to avoid early node failures due to energy depletion. In [8], an Energy Optimized Path Unaware Layered Routing Protocol (E-PULRP) was proposed. E-PULRP algorithm utilizes energy optimized layered structure to reduce the energy loss. It also restricts transmission distance for further energy optimization in the same way. However, E-PULRP algorithm was suitable for a stationary sink node located at the center of the deployment volume. It cannot be applied to UWSNs with multiple mobile sink nodes.

* Corresponding author. Tel.: +86-186-4638-8495.
E-mail address: suiyancheng@hrbeu.edu.cn.

A MMS routing protocol is proposed by considering the challenges of multiple and mobile sink nodes. We demonstrate its effectiveness through extensive computer simulations. The remainder of this paper is organized in the following manner. Section II detail MMS routing protocol. In Section III, performance evaluation of our proposed method is illustrated. Finally, the concluding remarks are presented in Section IV.

2. Mobile-MultiSink Routing Protocol

MMS routing protocol consists of three parts: energy loss model, layering phase and communication phase. The energy loss model is used to optimize energy consumption in building layered structures. Layered structures are formed around sink nodes and will be rebuilt periodically in the layering phase. In the communication phase, relay nodes are identified to forward the packets from source nodes to target sink nodes.

2.1. Energy Loss Model

Underwater communication is severely affected by physical properties like temperature and chemical properties of water, as well as the depth of transceivers. The basic propagation paths between a source and a receiver can be summarized into several forms. Based on these forms, the energy lost can be modeled as follow: For a transmitted energy E_T, the received energy E_R at distance R can be described as:

$$E_R = \frac{E_T}{R^{B/10}10^{(\alpha R+\beta)/10}} \quad (1)$$

B takes values 10, 15 or 20 depending on the type of propagation. β is a constant independent of distance. α is a distance-independent absorption coefficient, which may be a constant or a random variable.

An overview of channel models is available in [15]. According to the reference, we can conclude that a 3D deployment and short-range transmission model with the distance of a few meters can be assumed to have a nearly straight line transmission. In the case of non-straight transmission, we assume that the transmission angle is same as the reception angle of any node. Therefore, the channel can be assumed to be reciprocal for short duration when its condition will not vary significantly [19]. Thus, we define eq. (1) to be the general formula of the energy loss model between underwater transmitters and receivers.

2.2. Layering Phase

In the process of moving, multiple sink nodes collect data in the specific area. The layered structure ensures that the packets are forwarded towards the sink nodes. In layering phase, a set of concentric layers is formed around each sink node. So, a node may be located in different sink nodes' layered structures. The layer formation procedure for a sink node is described below:

- The sink node S is deemed to layer 0 and broadcasts a probe P_0 with energy E_0.
- The nodes that have been layered by sink node s will discard this probe. The other nodes that received this probe with energy at least equal to E_D (the energy threshold) will assign themselves as layer 1 nodes of sink node S. Layer 1 nodes can communicate with the sink node S immediately.
- Layer $k-1$ ($k \geq 1$) nodes broadcast a new probe P_{k-1} ($k \geq 1$) with energy E_{k-1} ($k \geq 1$). If the nodes can receive P_{k-1} and their energy is more than E_D ,they will assign themselves as layer k ($k \geq 1$) nodes. The layer k nodes transmit packet to sink node s with k hops. Then layer k nodes broadcast P_k with energy E_k to build layer $k+1$ of sink node S.

Each sink node builds its own n-layer structure according to energy lost model. All nodes in a particular layer can transmit data to the same sink node through an equal number of hops. The layered structure of one sink node is shown in Figure 1. Each ordinary node may be located in several layered structures of different sink nodes. Network with multiple sink nodes gathering data is shown in Figure 2. We also need to consider several parameters such as probing energy E_n, the energy threshold E_D and the layer width w_l. The probing energy for nodes in layer $l-1$ is related to width w_l of layer l as follow:

$$E_D = \frac{E_n}{{w_l}^{B/10}10^{(\alpha * w_l+\beta)/10}} \quad (2)$$

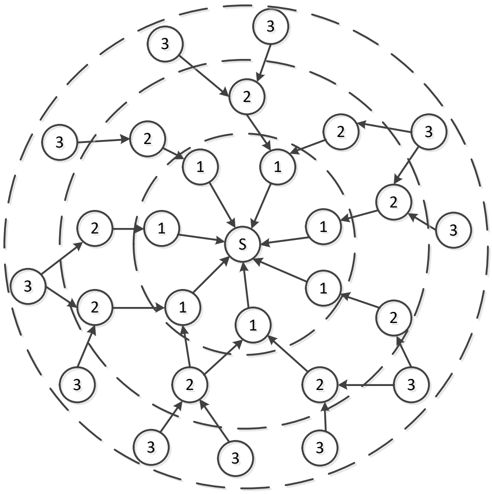

Figure 1. The layered structure of a sink node.

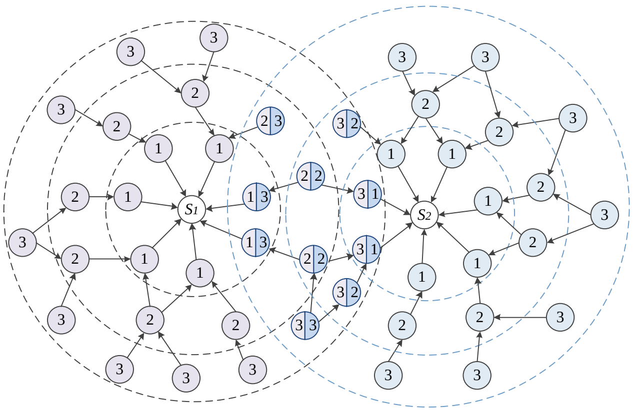

Figure 2. The layered structure of two sink nodes.

In UWSNs, sink nodes should be some autonomous underwater vehicles (AUVs). Because AUVs keep moving at the speed of 0.5m/s~1.5m/s, the transmission from layer 1 nodes to sink nodes could be affected, which causes topology changes and communication failure. We intend to adopt a method in which we refresh a sink node's layered structure periodically to ensure the network can work properly. However, it is inefficient to frequently refresh the layers because of the high price. Therefore, a critical condition is considered to decide whether layered structure should be refreshed or not. The strategy is explained as follow: The sink node can always get information from its neighbors during network is working. Supposed that a sink node builds initial layered structure at the time t and its layer 1 nodes set are N_t. At the time $t'(t'>t)$, the sink nodes' layer 1 nodes set are $N_{t'}$. We can calculate the specific ε, the loss rate of the initial layer 1 nodes. The sink node reinstitutes its layered structure at the moment that the ratio ε becomes larger than a critical value ξ. The re-layering condition is given by:

$$\varepsilon = 1 - \frac{n(N_t \cap N_{t'})}{n(N_t)}, \varepsilon \geq \xi, t < t', 0 < \xi < 1 \quad (3)$$

The estimation of ξ is related to the offset distance of sink node, the distribution of network nodes and the transmission range. The critical value ξ is determined in view of higher PDR and lower energy consumption. The estimation of the critical value is discussed in Section III.

2.3. Communication Phase

The communication phase involves a selection of target sink node and selection of intermediate relay nodes. Each source node should figure out a sink node as destination after its layered structure has been confirmed. Every source node, which is located among several sink nodes' layered structures, should select the most effective route. The selection of this route is according to source node's layer counts. After the target sink node is confirmed, the source node begins to identify relay nodes. The selected relay node should be in lower layers of the target sink node. Then it continues to transmit data in the same way until the sink node received it. For each node (including source nodes and relay nodes), the method of determining the path from source to the target sink node in MMS is divided into two parts.

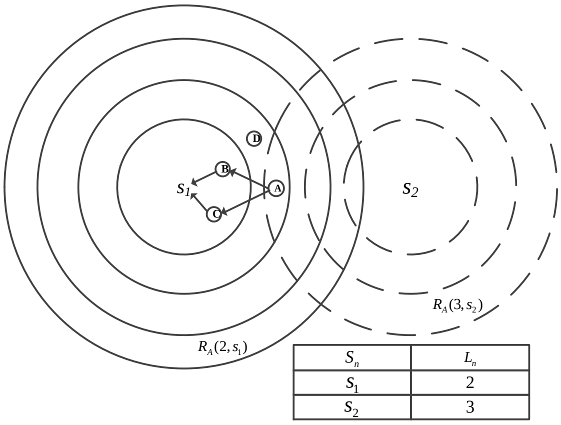

Figure 3. The selection of multiple sinks.

Step1: Node A 's hash set of corresponding relation between sinks S_n and its different layers of S_n is expressed as $R_A(L_n, S_n)$. S_n is the set of sink nodes $s_1, s_2 \ldots s_n$, while L_n represents the set of different sink nodes' layer count $l_1, l_2 \ldots l_n$. In order to reduce path's hop count, node A gives preference to the sink $s_{des}(s_{des} \in S_n)$ whose corresponding l_{des} is the minimum value. Mathematically, the selection of destination sink can be formulated as:

$$s_{des} = GetSink(\min_{l_n \in L_A}(l_1 l_2 \cdots l_n)) \quad (4)$$

The $\min(l_1 l_2 \cdots l_n)$ finds the minimum layer count l_{des}, $s = GetSink(l)$ means extracting mapping sink from one-to-one hash relationship $R_A(L_n, S_n)$ according to the specific l_k. If more than one s_{des} exists after calculating, node A relays one of them randomly. The selection of destination sink node is shown in Figure 3.

Step2: The procedure of determining the path from node A in layer l_{des} to the sink node s_{des} in MMS is described as:

- Node A selects its relay nodes that could reach s_{des} from routing table. The relay nodes' layer count of s_{des} should equal to $l_{des} - 1$.
- Node A broadcasts a control packet, which contains the source ID, packet ID and the next relay node information N_A.
- Once receive the control packet, the nodes in N_A begin to forward the data packet. Other nodes discard this packet. If node B successfully became relay nodes of A, it will analogically determine its next relay node. By this analogy, the data can be transmitted forward to sink node.

3. Simulation Experiments

In this section, extensive simulations have been carried out to evaluate the performance of the proposed MMS routing protocol. For visual display, we use the Network Simulator version 3(ns-3) [6] to present the results of our experiments. Table 1 exhibits the configuration of the simulation environment. The values of each parameter are set according to the underwater situation and the configurations are set according to reference [8]. Underwater sensor nodes are randomly deployed with a distance no more than 2000m in the three-dimensional volume. Multiple sink nodes keep moving at the speed of 1m/s among normal nodes. The experiment is set up so that each sensor node in the network generates a single packet periodically. All packets are transmitted to the sink nodes. In this experiment, to illustrate our proposed MMS routing protocol, E-PULRP algorithm and PULRP algorithm are applied to similar situation for comparison.

Table 1. Configuration of simulation environment

Parameters	**Values**
R_{max}	2000m
B	20
α	0.7
β	0
Run time	2000s
No. of sinks	3
Packet size	50bytes
Initial Energy(per node)	12000W
Data transmission range	5000m
Data transmission rate	120bps
Node density	2× 10-9~3.2× 10-6/m3
No. of nodes	50~100
Speed of sink node	1m/s

The remainder of this section is divided into two subsections. In the first subsection, we demonstrate the superiority of our MMS routing protocol with the two routing algorithms. In the second subsection, we discuss the boundary value, which is the maximum ratio of lost nodes of a sink's initial layered structure. The critical value determines when to refresh layered structures of sink nodes.

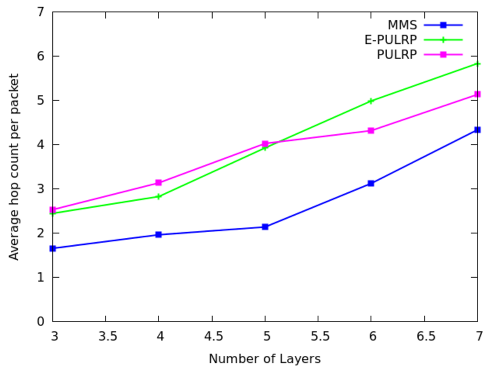

Figure 4. The average hops of successful packet delivery for three protocols with different layers.

We consider PDR, energy consumption and the hop count as performance metrics. Through the experiments, we found that the distribution density of nodes within limit makes little difference to results. So, we use the average results with different density.

3.1. Performance comparison

We set that the whole network has sink nodes and normal nodes. All sink nodes are randomly deployed in the 3D water area. The speed of sink nodes is set as 1m/s. To compare MMS routing protocol with E-PULRP algorithm and PULRP algorithm, we have considered numerous metrics, as follows.

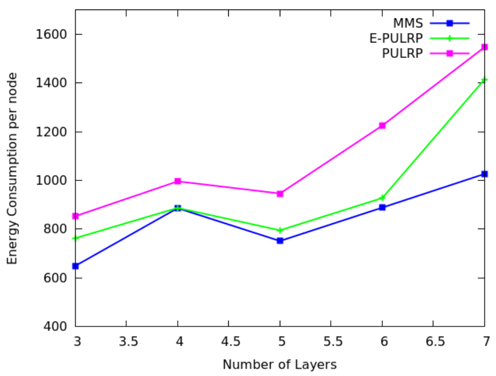

Figure 5. The average energy consumption of nodes for three protocols with different layers.

Figure 4 depicts the average hop count of each packet from source nodes to sink nodes. It can be observed that the E-PULRP and PULRP algorithm suffer from a greater hop count compared with the MMS. The hop count of each packet depends on the layer count of its source nodes. In addition, it should be noted that, in our proposed method, source nodes select destination in term of its minimum layer count in different sink nodes' layered structures. But E-PULRP and PULRP algorithm send data in term of their initial layered structure. Therefore, in MMS protocol, source nodes select the shorter path to send data, which reduce the hop count to a certain extent.

Figure 5 depicts the average energy consumption of each node in different layered structures. Apparently, PULRP algorithm and E-PULRP algorithm incurs higher energy consumption in each node when compared to MMS routing protocol. The figure presents that the volume of relayed data grows larger as the layers of network increase. In MMS routing protocol, the volume of relayed data is smaller because source nodes choose the shorter path. This can inhibit the growth of the number of intermediate nodes for forwarding data. For other two protocols, the average energy consumption has little difference when the layer number is less than 6, but the gap widens after layer 7.

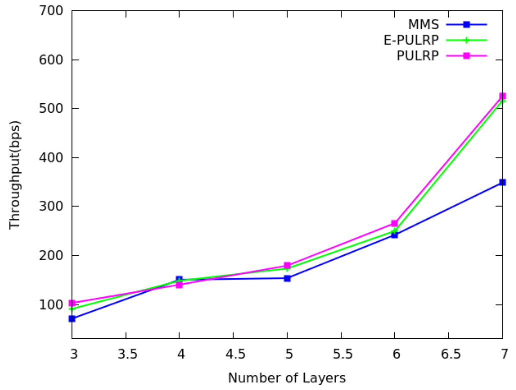

Figure 6. The average networks throughput for three protocols with different layers.

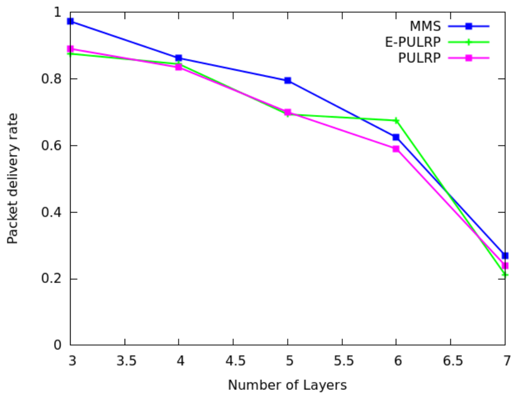

Figure 7. The average networks PDR for three protocols with different layers.

Figure 6 shows the throughput of networks with different layers. It can be observed that the throughput increases as the number of layers comes up. This phenomenon can be explained as follow: The number of relay nodes grows on account of the node density's increasing. They send data packets to sink nodes at a certain frequency, which means that the volume of transmitted data increases at the same time. Compared with E-PULRP algorithm and PULRP, MMS routing protocol inhibits the growth of the whole network volume through selecting paths with less relayed nodes. It is also the reason why the energy consumption of MMS routing protocol is lower than that of E-PULRP algorithm.

Figure 7 shows the tendency of packet delivery rate of different layers. As the layers increase, path reliability decreases owing to many uncontrollable factors (e.g. collision of the data). The number of successfully delivered packets drops off gradually. However, in MMS routing protocols, the closer distance between sources and sinks ensures network's reliability. Therefore, it shows that the performance of MMS routing protocol is slightly better than others.

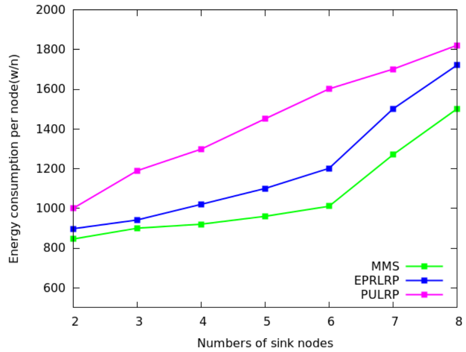

Figure 8. The average energy consumption for three protocols with different number of sink nodes.

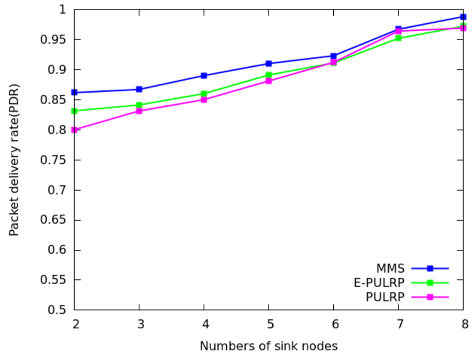

Figure 9. The average networks PDR for three protocols with different number of sink nodes.

Figure 8 and Figure 9 show the tendencies of PDR and energy consumption with different number of sink nodes. In Figure 8, the average energy consumption of the three protocols grows as the number of sink nodes increases. The increase of the number of sink nodes leads to larger communication data volume for building layered structures. However, MMS protocol is superior to other two protocols because of its shorter delivery path. Figure 9 depicts the PDR of three protocols with different number of sink nodes. It is clear that PDRs of the three protocols increase as the number of sink nodes comes up. Our proposed MMS protocol is better than the other two protocols due to the strategy of selecting the target sink node. Source nodes can delivery data more reliably through MMS protocol. In general, different numbers of sink nodes have little effect on the performance tendency of the three protocols.

3.2. Consideration about the critical value

In this subsection, we consider the influence of critical value ξ. The evaluation of ξ depends on the characteristics of the underwater acoustic communication. Relevant fundamental analysis of ξ has been proposed in Section 2.1. The sink nodes to collect data would be severely affected by ε in our proposed MMS routing protocol. The difference of layer numbers brings about changes in the packet delivery rate of sink node. Therefore, we adopt an experimental approach to estimate the critical value ξ. In Figure 10, the ratio ε varies as the sink node moving. The layer number is set as 3, 4 and 5. It is very evident to see that the packet delivery rate changes little when ξ is no more than 0.5. However, it decreases sharply as ξ becomes greater than 0.5. From the above consideration, we set the critical value ξ as 0.5.

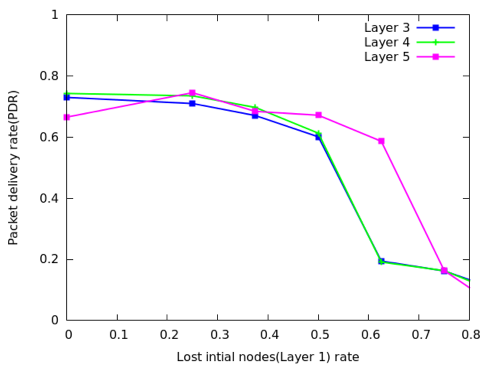

Figure 10. The average networks PDR for three protocols with different number of sink nodes.

4. Conclusions

We have proposed a MMS protocol for UWSNs with multiple mobile sink nodes. It can improve the performance of networks with mobile multiple sink nodes gathering data. Most existing protocols focus on single and stationary sink node. They do not take into account the sink nodes' multiplicity and mobility. This paper specifically describes a routing progress including layer phase and communication phase. The selection strategy of MMS routing protocol can reduce the number of intermediate nodes. It can reduce the average hop count and energy consumption likewise. Its re-layer mechanism enables networks to combat connectivity losses due to the problem of mobility, multipath and energy depletion. With extensive simulations performed, we demonstrate our proposed MMS routing protocol with various metrics. Eventually, it can be concluded that MMS routing protocol achieves better performance for 3D underwater networks with multiple mobile sink nodes.

Acknowledgements

This research is supported by the National Natural Science Foundation of China (51509057 and 61572172). It is also supported by National Major Projects "some intelligent control and support software" and National Science and Technology Major Project 2015ZX01041-101.

References

1. N. Aitsaadi, N. Achir, K. Boussetta and G. Pujolle, "Differentiated underwater sensor network deployment", *OCEANS*, pp.1-6,2007
2. I. F. Akyildiz, W. Su and Y. Sankarasubramaniam, "Wireless sensor networks: a survey", *Computer networks*, vol. 38, no.4, pp.393-422, 2002
3. M. Ayaz, A. Abdullah, "Hop-by-hop dynamic addressing based (H2-DAB) routing protocol for underwater wireless sensor networks", in *Proc. of International Conference* on *Information and Multimedia Technology*, pp. 436-441, 2009
4. M. Ayaz, I. Baig, A. Abdullah and I. Faye, "A survey on routing techniques in underwater wireless sensor networks", *Journal of Network and Computer Applications*, vol. 34, no.6, pp. 1908-1927, 2011
5. J. Chen, X. Wu and G. Chen, "REBAR: A Reliable and Energy Balanced Routing Algorithm for UWSNs", in *Proc. of International Conference on Grid and Cooperative Computing*, pp. 349-355, 2008
6. Y. S. Chen, Y. W. Lin, "Mobicast Routing Protocol for Underwater Sensor Networks", *Sensors Journal*, vol. 13, no.2, pp. 737-749, 2013
7. S. Gopi, G. Kannan., D. Chander, U. B. Desai and S. N. Merchant, "PULRP: Path unaware layered routing protocol for underwater sensor networks", in *Proc. of International Conference on Communications*, pp. 3141-3145, 2008
8. S. Gopi, K. Govindan, D. Chander, U. B. Desai and S. N. Merchant, "E-PULRP: Energy optimized path unaware layered routing protocol for underwater sensor networks", *IEEE Transactions on Wireless Communications*, vol. 9, no.11, pp. 3391-3401, 2010
9. J. M. Jornet, M. Stojanovic and M. Zorzi, "REBAR: A Reliable and Energy Balanced Routing Algorithm for UWSNs", in *Proceedings of the third ACM international workshop on Underwater Networks*, pp. 75-82, 2008
10. D. Kornack and P. Rakic, "Cell Proliferation without Neurogenesis in Adult Primate Neocortex", *Science*, vol. 294, no.5549, pp. 2127-2130, 2001
11. T. Li, "Multi-sink opportunistic routing protocol for underwater mesh network", in *Proc. of International Conference on Communications, Circuits and Systems*, pp. 405-409, 2008
12. W. Liang, H. Yu, L. Liu, B. Li and C. Che, "Information-carrying based routing protocol for underwater acoustic sensor network", in *Proc. of International Conference on Mechatronics and Automation*, pp. 729-734, 2007
13. U. Lee, J. Kong, M. Gerla, J. S. Park and E. Magistretti, "Time-critical underwater sensor diffusion with no proactive exchanges and negligible reactive floods", *Ad Hoc Networks*, vol. 5, no.6, pp. 609-615, 2007
14. T. Liu, Q. Li and P. Liang, "An energy-balancing clustering approach for gradient-based routing in wireless sensor networks", *Computer Communications*, vol. 35, no.17, pp. 2150-2161,2012
15. C. D. Mari, "Overview of channel models for underwater wireless communication networks", *Physical Communication*, vol. 1, no.3, pp. 163-182, 2008
16. N. Nicolaou, A. See, P. Xie, J. H. Cui and D. Maggiorini, "Improving the robustness of location-based routing for underwater sensor networks", *OCEANS*, pp. 1–6, 2007
17. Y. Noh, U. Lee., P. Wang, B.S.C. Choi and M. Gerla, "VAPR: Void-Aware Pressure Routing for Underwater Sensor Networks", *Mobile Computing*, vol. 12, no.5, pp. 895-908, 2012
18. J. Partan, J. Kurose, B. N. Levine, "A survey of practical issues in underwater networks", *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 11, no.4, pp. 22-33, 2007
19. The Network Simulator – ns-3, "http://www.nsnam.org/"

Zhuo Wang received the BS and MS and PhD degree in Computer Science and Technology, all from Harbin Engineering University. She is currently an associate professor in the Department of College of Shipbuilding Engineering, Harbin Engineering University. Her research interests in Autonomous Underwater Vehicle and Underwater Acoustic Networks.

Yanchen Sui received the B.S. degree in naval architecture and marine engineering from Harbin Engineering University in 2016. Now he is studying for his master degree in Design and Manufacture of Marine Structures in Harbin Engineering University, and engaged in the research about communication protocols of Underwater Wireless Sensor Networks and path planning strategies for autonomous underwater vehicles.

Xiaoninig Feng received the BS and MS and PhD degree in Computer Science and Technology, all from Harbin Engineering University. He is currently an associate professor in the Department of Computer Science and Technology, Harbin Engineering University. His research interests in Underwater Acoustic Networks.

Jiajie Liu received her M.S. degrees in College of Computer Science & Technology from Harbin Engineering University at March 2015. Her research interests include Underwater Sensor network Routing method. Now she is working at China Unicom Software Research Institute, Harbin.