LEER: Layer-Based and Energy-Efficient Routing Protocol for Underwater Sensor Networks

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Abstract. Radio signals attenuate largely when propagating in water, while optical signals have large scattering in water. Therefore, acoustic signals are used for communication in underwater sensor networks (UWSNs). Data transmission in underwater sensor networks is facing challenges due to the characteristics of underwater acoustic channels. In addition, high energy consumption and long latency bring about increased challenges for the design of routing protocols in UWSNs. In this paper, we propose a routing protocol called Layer-based and Energy-efficient Routing (LEER) Protocol to solve the void area routing problem as well as the long end-to-end delay and high energy consumption problems in UWSNs. In LEER, each node extracts the layer field information from Hello messages received and updates its own layer to avoid the void area problem, and all nodes forward packets to the sink node without the need for full-dimensional location information. Simulation results show that the LEER protocol outperforms the depth-based routing (DBR) protocol in terms of delivery rate and end-to-end delay.

Keywords: Underwater sensor networks · LEER · Layer-based routing · Void area

1 Introduction

Underwater Sensor Networks (UWSNs) are usually deployed in an underwater environment such as the ocean, and promise a broad range of applications such as underwater rescuing, offshore mining, offshore exploration, environmental monitoring, and pollutant content detection [1–3]. In UWSNs, radio and optical signals are not suitable for communication as underwater media. Radio signals attenuate greatly when propagating in water, and thus can only propagate over long distances at ultra-low frequencies (30–300 Hz), which requires large wires and high transmission power. Optical signals have a large scattering in water. Therefore, acoustic signals are used for communication in UWSNs. However, UWSNs using acoustic channels have the characteristics of the high latency, high bit error rate (10^{-3}–10^{-7}), low bandwidth,

J. Zheng et al. (Eds.): ADHOCNETS 2019, LNICST 306, pp. 26–39, 2019.
https://doi.org/10.1007/978-3-030-37262-0_3

multi-path effect, and highly dynamic network topology compared with a terrestrial sensor network using radio signals. In addition, underwater nodes move with water current or other underwater activity, and it is difficult to recharge or replace the batteries in the nodes. Due to these characteristics, existing routing protocols for terrestrial sensor networks cannot be directly applied to UWSNs.

This paper proposes a Layer-based and Energy-Efficient Routing (LEER) Protocol for UWSNs, which is independent of the location information on sensor nodes. LEER is a routing protocol based on the layer, the one-hop delay and the residual energy of the node. A sender node does not need to acquire its location prior to sending data packets. In order to balance the energy-consumption of the sensor nodes and maximize the lifetime of the whole network, a receiving node calculates the waiting time for the forwarding timer expires according to its residual energy and one-hop delay. Moreover, LEER can improve the performance in terms the data delivery rate and end-to-end delay, and can effectively solve the void area routing problem.

The rest of the paper is organized as follows. In Sect. 2, we review related work. In Sect. 3, we present the proposed LEER protocol. In Sect. 4, we evaluate the performance of the LEER protocol through simulation experiments. In Sect. 5, we conclude the paper.

2 Related Work

The uniqueness of the underwater acoustic channel brings about some challenges to the design of a routing protocol for UWSNs. To address the characteristics of UWSNs, a variety of routing protocols have been proposed for underwater communication in the literature [3–7].

In [8], Yan et al. proposed a depth-based routing (DBR) protocol. In DBR, a node needs to know the depth information on its own rather than the full-dimensional position information. Data packets are forwarded from the bottom to the water surface, and only the depth is used as the routing metric. The delivery rate with DBR is relatively high in a dense network than in a sparse network, but excessive redundant forwarding would cause additional energy consumption and packet collision. Moreover, the DBR protocol is likely to route a packet to a void area in a sparse network. In [9], Wahid et al. improved DBR and proposed an Energy-Efficient Depth-Based Routing (EEDBR) Protocol. In EEDBR, the selection of forwarding nodes is based on residual energy and depth of the node, which can balance the energy consumption among sensor nodes. In [10], Wahid et al. proposed a multi-layered routing protocol (MRP). In MRP, super nodes are introduced to enhance the battery life of ordinary sensor nodes and increase the delivery rate for data packets. However, MRP is proposed for a network scenario where sensor nodes are deployed in a two-dimensional space, while in the underwater environment sensor nodes are deployed in a three-dimensional space. In addition, the holding time used in the protocol is not correctly defined.

Du et al. proposed a layer-based adaptive geo-routing (LB-AGR) protocol in [11]. LB-AGR introduces layer-based adaptive geo-routing, downstream directed flooding, and downstream routing, needs the full-dimensional location information on each sensor node.

3 LEER Protocol

In this section, we describe the network model and energy consumption model used in this work, and present the proposed LEER protocol.

3.1 Network Model

We consider a three-dimensional UWSN as shown in Fig. 1. The network consists of a sink node located on the water surface and a number of ordinary sensor nodes distributed in an underwater area. In the network, all sensor nodes are divided into several layers based on the hop-count to the sink. Underwater data transmission is directional from bottom to top, i.e., information such as environmental parameters perceived by underwater sensor nodes is subject to be forwarded to the sink node on the surface. The function of the sink is to receive data from underwater nodes and send the received data to the base station on shore. The function of an underwater sensor node is to collect environmental data in water and forward the collected data to the sink node on the water surface in a multi-hop manner. Moreover, we make the following three assumptions:

(1) Once the sink node is deployed, it's location is fixed;
(2) All sensor nodes have the same functions and parameters (e.g., initial energy, fixed transmission power, transmission radius) except the sink node;
(3) All sensor nodes are randomly and evenly deployed in a three-dimensional underwater area in a layered manner.

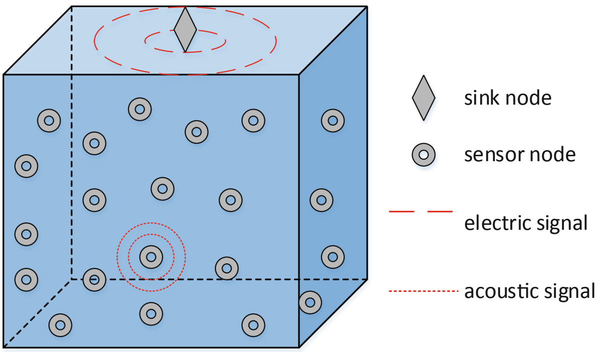

Fig. 1. Three-dimensional UWSNs model

3.2 Energy Consumption Model

In UWSNs, the energy consumption for transmitting data is much larger than that for receiving data. Compared with the energy consumption for transmitting data, the energy consumption for receiving data can be neglected. Thus, in this paper, we define the energy consumption of the whole network as the total energy consumed by all nodes to transmit data. Meanwhile, the energy consumption model proposed in [12] is used as the model. In UWSNs, if the minimum receiving intensity of a signal is P_0 and the signal loss attenuation is $A(x)$, the minimum transmission power P is supposed to be equal to $P_0A(x)$, i.e., $P = P_0A(x)$. According the energy consumption model [12], the attenuation function $A(x)$ is given by

$$A(x) = x^k \partial^x \tag{1}$$

The energy E_l consumed by a sending node to send a data packet of length l to a receiving node is given by

$$E_l = T_{delay} \mathrm{P}_0 A(x) = T_{delay} \mathrm{P}_0 x^k \partial^x \tag{2}$$

where x is the transmission distance between the transmitting node and the receiving node, T_{delay} is the data transmission delay for a node to transmit l bits, k is a coefficient related to the underwater acoustic model, and ∂ is a frequency dependent term. For the coefficient k, when the transmitting area is cylindrical, $k = 1$, when it is sphere, $k = 2$. In general, $k = 1.5$. For the frequency dependent term ∂, it is given by $\alpha(f)$

$$\partial = 10^{\alpha(f)/10} \tag{3}$$

where $\alpha(f)$ is the energy absorption coefficient, whose value can be determined using the expression of Throp, i.e.,

$$\alpha(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f^2} + 2.75 \times 10^{-4} f^2 + 0.003 \tag{4}$$

where, the unit of the absorption coefficient $\alpha(f)$ is dB/km, and the unit of the frequency f is KHz.

According to Eqs. (1)–(4), the transmission distance x is exponentially related to the attenuation factor $A(x)$, and the energy consumption E_l is proportional to the attenuation factor $A(x)$. Therefore, when the frequency is constant, the farther the transmission distance is, the more severe the signal attenuation is, and the more energy a node consumes to send data packets.

3.3 LEER Protocol

The LEER protocol is a routing protocol based on a layering strategy. It introduces a layering algorithm to configure all sensor nodes into several layers, and takes into account the residual energy of a node and one-hop delay in packet forwarding. Moreover, it does not need any location information on each sensor node in the network.

The LEER protocol is divided into two phases. In the first phase, the sink node broadcasts a Hello message to the network. The Hello message contains fields of packet type, source node ID, source node layer and other information. After receiving the Hello message, each underwater sensor node extracts the layer field information contained in the Hello message, updates its own layer and the Hello message, and then continues to broadcast the updated Hello message. In the second phase, each underwater sensor node forwards its perceived data to its upper-layer node until the data is transmitted to the sink node on the water surface. In layering based routing, a packet is not forwarded by the nodes at the same layer of the sender, which reduces much redundancy and energy consumption. At the same time, it effectively solves the void area routing problem because after the network initialization phase, each sensor node will have a upper-layer neighbor node. Thus, the next hop node will always be found for forwarding.

3.3.1 Layering Algorithm

The layering algorithm is used by an underwater sensor node to configure their own layers in the network initialization phase. First, the sink node broadcasts a Hello message to the network, and the sink node sets its own layer to layer 0. When a receiving node receives the Hello message for the first time, it will check the value *L_Snd* of the layer field in the received Hello message, set its own layer to $L\_Rec = L\_Snd + 1$, and start the layer aging timer. Then, the receiving node will update the layer field information of the Hello message with its own layer *L_Rec*, and continue to broadcast the updated Hello message. After the initialization process is completed, the layer of each sensor node will be fixed until the sink node broadcasts another Hello message.

After a sensor node receives a new Hello message. It has to determine whether it needs to update its own layer. When a sensor node which has acquired its layer and its aging timer is not expired receives a Hello message, it compares the value of its own layer *L_Rec* with that of the layer *L_Snd* in the packet. If $L\_Rec > L\_Snd + 1$, the node updates its own layer to $L\_Rec = L\_Snd + 1$, replaces the layer field and the source node ID in the Hello message with its own layer information and the node ID, then broadcasts the updated Hello message. If the aging timer is expired, the receiving node updates its own layer to $L\_Rec = L\_Snd + 1$, and then updates and broadcasts the Hello message. The pseudo code of the layering algorithm is given in Fig. 2.

```
//After receiving a Hello packet
L_self=255;   //Initialization layer of sensor node is 255
L_sink=0;  //The layer of the sink node is a fixed value: 0
IF(PacketType= ="Hello Packet")
  IF(L_self= =255)
    L_self=L_snd +1;   //The new node will update the layer.
  Else
    IF(L_self<=L__snd+1)
      Discard  data packet //Nodes have updated their own layer.
    Else
      L_self=L_snd +1;
      Continue to broadcast Hello packet
    End IF
  End IF
End IF
Exit
```

Fig. 2. The pseudo code of the layering algorithm

Figure 3 illustrates a layering example. In this example, the sink node on the water surface first broadcasts a Hello message to the network. After receiving the Hello message, each receiving node (i.e., *N1*, *N2*, *N3*, or *N4*) extracts the value of the layer field in the received Hello message, which is *L_Snd = 0,* the layer of the sender. Then, each receiving node obtains its own layer value, i.e., *L_Rec = 1*, and updates the layer field of the Hello message with "1", and the source node ID with its ID (i.e., *N1*, *N2*, *N3*, or *N4*), and broadcasts the updated Hello message. After a node (i.e., *N5*, *N6*, *N7*, or *N8*) receives the Hello message from an upper-layer node (i.e., *N1*, *N2*, *N3*, or *N4*), it extracts the value "1" of the layer field in the received Hello message, and then obtains its own layer value "2". Next, the node updates the layer field of the Hello message with "2" and the source node ID field with its own ID (i.e., *N5*, *N6*, *N7*, or *N8*), and then continues to broadcast the updated Hello message.

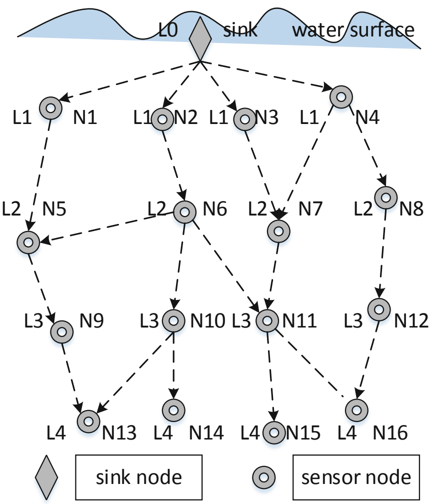

Fig. 3. Layering example

3.3.2 Routing Protocol

In the routing protocol, a receiving node determines whether it is supposed to participate in forwarding a data packet by calculating the forwarding probability. The forwarding probability depends on the one-hop delay and the residual energy of the node. In order to forward the data packet to the sink node along a low-delay path, one-hop delay is considered in calculating the forwarding probability. A waiting time is introduced based on the forwarding probability before the data packet is forwarded. Thus the probability that node k forwards a data packet is given by

$$P_k = \alpha(1 - \frac{Del(k)}{Del_{\max}}) + \beta(\frac{E(k)}{E_{ini}}) \tag{5}$$

where, α and β are weight coefficients that meet $\alpha + \beta = 1$, $Del(k)$ is a one-hop delay from a transmitting node to the receiving node k, Del_{max} is a predefined maximum one-hop delay, $E(k)$ is the current residual energy of the receiving node k, and E_{ini} is the initial energy of the node. The weighting coefficients α and β can balance the effect of the minimum delay path and that of the high residual energy. According Eq. (5), the forwarding probability is proportional the residual energy of the node, and inversely proportional to one-hop delay. The more residual energy the receiving node has, the smaller the one-hop delay, and the higher the forwarding probability of the receiving node.

Each receiving node starts a timer after receiving a data packet. The timeout value set by the timer is based on the forwarding probability. The higher the forwarding probability, the earlier the node timer expires. The timeout value T_{out} of the receiving node k timer is defined as

$$T_{out} = \sqrt{\frac{1}{P_k}} \times Del_{\max} + Rand() \tag{6}$$

where Del_{max} is the predefined maximum delay in one hop, and $Rand()$ is a random time interval between 0 and 1. Supposing that two nodes have the same remaining energy and one hop delay, their timers may expire at different time, and the two nodes will randomly forward the data packet to reduce the redundant packets.

Figure 4 gives an example to illustrate the role of a timer. In this example, node A receives the data packet P_1 sent by the source node. In this case, node A first calculates its own forwarding probability, and then calculates the timeout value of its timer based on its forwarding probability and starts the timer. After the timer expires, node A immediately forwards the data packet P_1. Meanwhile, node B also receives the same data packet P_1 sent by the source node. Similarly, it first calculates its own forwarding probability, and then calculates the timeout value of its timer based on the calculated forwarding probability and starts the timer. During the waiting period, if node B hears the data packet P_1 forwarded by node A, node B will stop its timer and discard the packet P_1. If node B does not hear the data packet P_1 sent by node A during the waiting period, which implies that node B is not within the transmission range of node A. In this case, node B will also forward the data packet P_1 when its own timer expires. Since the proposed protocol is based on flooding, it belongs to multi-path routing rather than single-path routing. Therefore, each node will forward a data packet immediately when its timer expires. It is equivalent to the case where multiple receivers quasi-simultaneously forward the same data packet.

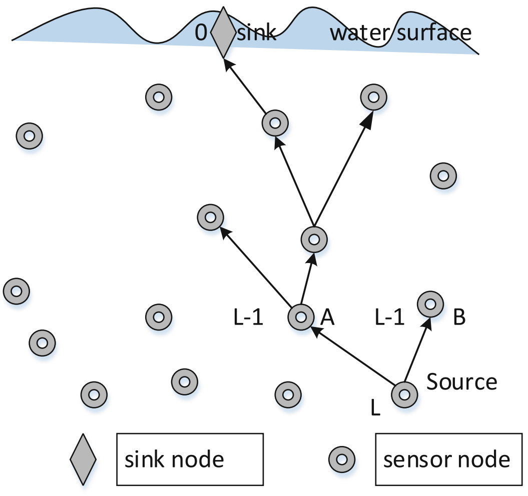

Fig. 4. Example of the role of a timer

3.4 Void Area Routing Problem

In DBR and other greedy routing protocols for UWSNs, a void area is unavoidable when data packets are forwarded in a sparse network. Taking Fig. 5 as an example. After node *N8* receives a data packet, there is no node closer to the sink node to forward the packet upward. In this case, the upper area above node *N8* is called a void area.

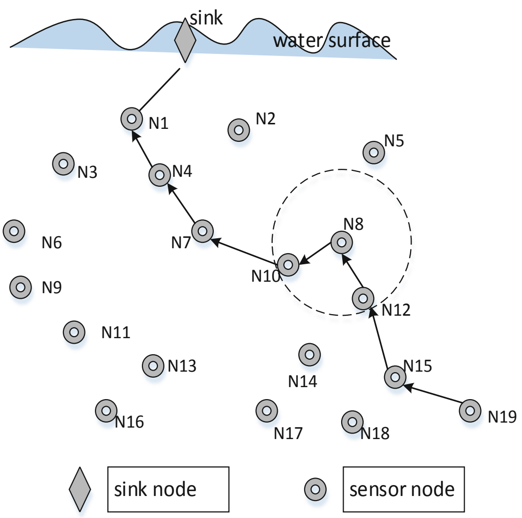

Fig. 5. Void area routing example

The LEER protocol can effectively solve the void area problem. In the LEER protocol, each sensor node knows its own layer in the network initialization phase. When underwater sensor nodes transmit data packets to the sink node, those nodes participating in data forwarding have obtained their own layers. In another word, a forwarding node has at least one upper-layer neighbor node. In this case, there is no void area problem with the LEER protocol. Unlike the DBR protocol, which allows a sensor node to forward data packets only in the direction close to the sink, the LEER protocol allows a sensor node to first determine whether the layer meets the requirements, and then sets the timeout value of its timer based on the forwarding probability.

Figure 6 illustrates the layer of each sensor node in the network after the network initialization phase. It is seen that the path for source node *N19* to the sink is N19→N15→N12→N10→N7→N4→N1→sink. By using the LEER protocol, the void area problem in the upper area of node N8 is completely avoided.

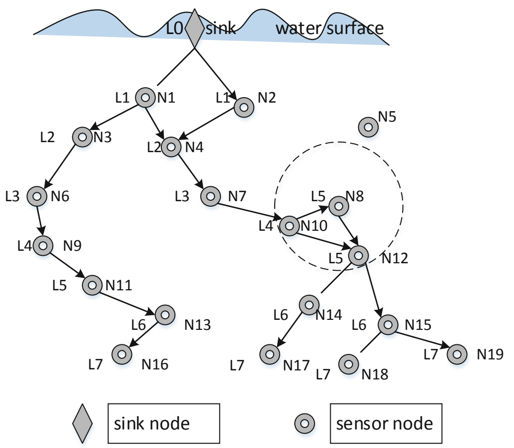

Fig. 6. Illustration of avoiding a void area based on layered routing

4 Performance Evaluation

In this section, we evaluate the performance of the proposed LEER protocol through simulation results.

4.1 Simulation Parameters

The simulation experiments were performed using NS-3. In the experiments, we consider a multi-hop layered network scenario composed of 70 sensor nodes and one sink node. A static sink node is deployed on the water surface. Other sensor nodes are randomly deployed in a three-dimensional region of 1500 m × 1500 m × 2500 m. The MAC layer protocol uses Aloha protocol. The size of a data packet is 134 bytes. The initial energy of all sensor nodes is set to 1000 J. The energy consumed by a node when sending, receiving, and idle is 0.1 J/packet, 0.05 J/packet, and 0.001 J/packet, respectively. The network is divided into three layers, which means that a data source node has at most three hops to the sink node. The simulation parameters are given in Table 1.

Table 1. Simulation parameters

Simulation parameter	Value
Three-dimensional area	1500 m × 1500 m × 2500 m
Number of nodes	21∼71
Communication radius R	1000 m
Initial energy	1000 J
Packet size	134 Bytes
Packet frequency	15 S/packet
Topology	Random uniform deployment

4.2 Simulation Results

In the performance evaluation, we use packet delivery rate, end-to-end delay, and energy consumption as the performance metrics. The packet delivery rate (PDR) is defined as the ratio of the total number of packets received by the sink node P_{sucess} to the total number of packets sent by the source node P_{send}, i.e., $PDR = P_{sucess}/P_{send}$. The end-to-end delay is defined as the time taken to deliver a data packet from a source node to the sink node. Energy consumption is defined as the total energy consumed by all nodes during the simulation time.

In Eq. (5), α and β are weight coefficients, where $\alpha + \beta = 1$. Table 2 gives the average packet delivery rate for each group of the 21 nodes. When the weight coefficients α and β are different, the average end-to-end delay and energy consumption in the network also have some effects, as shown in Figs. 7 and 8.

Table 2. Effect of different α on PDR

α	β	PDR
0.1	0.9	70.67%
0.2	0.8	72%
0.3	0.7	76.43%
0.4	0.6	78%
0.5	0.5	79.33%
0.6	0.4	78.67%
0.7	0.3	73.33%
0.8	0.2	73.33%
0.9	0.1	76%

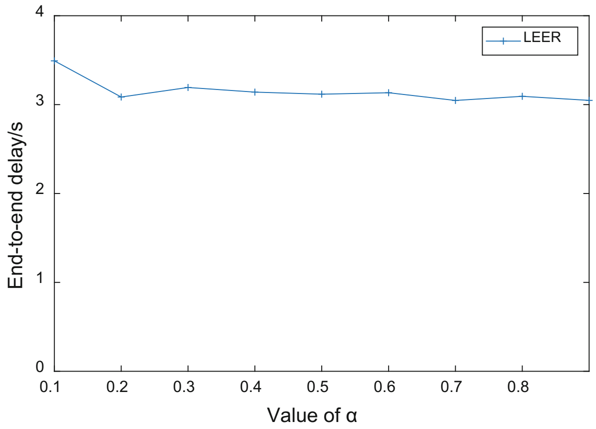

Fig. 7. Effect of different α on end-to-end delay

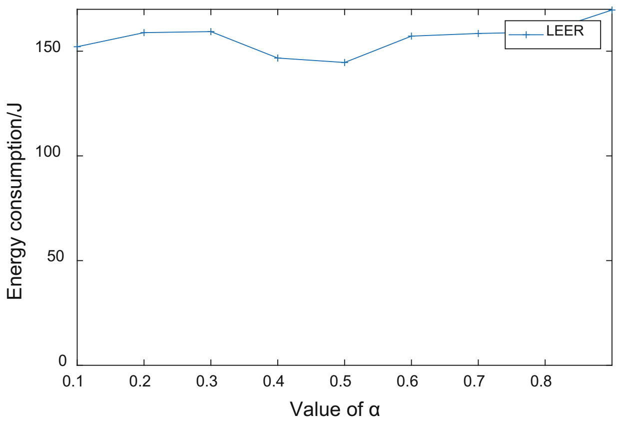

Fig. 8. Effect of different α on energy consumption

In Table 2, it is seen that the highest PDR is generated when the weight coefficient combination is α = *0.5* and β = 0.5. Figure 7 shows the effect of different α on the average end-to-end delay. Figure 8 shows the effect of different α on the total energy consumption in the network. It is observed that the average end-to-end delay decreases with the increase of α.

Figure 9 shows the packet delivery rates with of the LEER routing protocol and the DBR routing protocol, respectively, when the number of nodes are 21, 31, 41, 51, and 71. It is seen that as the number of nodes increases, the packet delivery rate increases. This is because as the number of nodes increases, the number of candidate forwarding nodes for the next hop increases, which increases the data forwarding success rate. As a result, the packet delivery rate from the source node to the sink node increases. On the other hand, the packet delivery rate with the DBR routing protocol decreases from

70.53% to 43.53% with the number of nodes decreasing from around 71 to 21. This is due to the greedy mode of DBR. When the number of nodes is small, the DBR routing protocol sends data packets to the sink node closer to the water surface in a greedy manner. In this case, the nodes at a deeper layer cannot participate in the forwarding of the data packets, which are more likely to be routed to a void area. As a result, it would results in a low packet delivery rate. In contrast, the packet delivery rate with the LEER routing protocol does not change much as the number of nodes decreases, ranging from 79.33% to 82.33%. This is because the LEER routing protocol is based on a layering strategy, which can avoid the void area problem and achieves a relatively stable packet delivery rate. In addition, it is seen that the packet delivery rate of the LEER routing protocol is better than that of the DBR routing protocol.

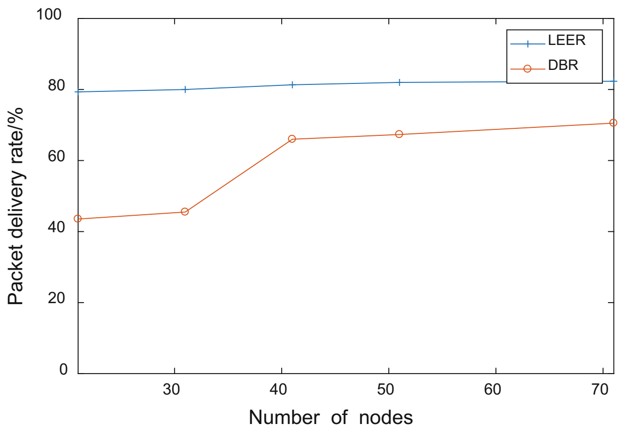

Fig. 9. Comparison in the packet delivery rate

Figure 10 shows the end-to-end delay with the LEER routing protocol and the DBR routing protocol, respectively, when the number of nodes is 21, 31, 41, 51, and 71. It is seen that as the number of nodes increases, the average end-to-end delay with the LEER protocol decreases gradually. This is because with the increase of the number of nodes, the density of nodes in the simulation scenario will increase accordingly. In this case, the number of candidate forwarding nodes will increase, the distance between nodes will decrease, and thus the end-to-end delay will decrease as well. On the other hand, it is seen that the average end-to-end delay with the LEER routing protocol is smaller than that with the DBR routing protocol.

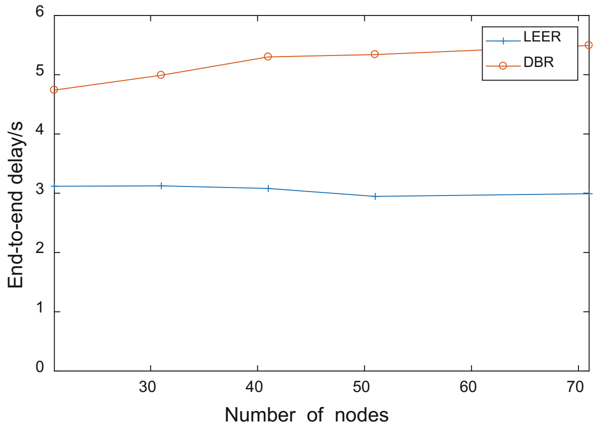

Fig. 10. Comparison in end-to-end delay

5 Conclusion

In the paper, we proposed a LEER protocol for a UWSN based on a layering strategy. The LEER protocol introduces a layering algorithm to configure all sensor nodes in the network into several layers, and takes into account the residual energy of a node and one-hop delay in packet forwarding. Moreover, it does not need full-dimensional location information on each sensor node in the network. To ensure energy balance and prolong the network lifetime, the LEER protocol sets the timer of a sensor node taking into account the residual energy of a node and one-hop delay in data forwarding. By using the LEER protocol, the void area problem can be effectively avoided. The simulation results show that the proposed LEER routing protocol outperforms the DBR routing protocol in terms of the packet delivery rate and average end-to-end delay.

Acknowledgments. This work is supported by the National Natural Science Foundation of China (under grant no.: 61962052), the IoT Innovation Team Foundation of Qinghai Office of Science and Technology, the Key Lab of IoT of Qinghai, Hebei IoT Monitoring Center (under grant no.: 3142016020); and the Key Projects of Hebei Province (under grant no.: 19270318D).

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