This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2805804, IEEE Access

An Energy-Aware and Void-Avoidable Routing Protocol for Underwater Sensor Networks

Zhuo Wang, Guangjie Han, Hongde Qin, Suping Zhang, Yancheng Sui

Abstract—Underwater sensor networks (UWSNs) is facing a great challenge in designing a routing protocol with longer network lifetime and higher packet delivery rate(PDR) under the complex underwater environment. In this paper, we propose an energy-aware and void-avoidable routing protocol (EAVARP). EAVARP includes layering phase and data collection phase. During the layering phase, concentric shells are built around sink node, and sensor nodes are distributed on different shells. Sink node performs hierarchical tasks periodically to ensure the validity and real-time of the topology. It makes EAVARP apply to dynamic network environment. During the data collection phase, data packets are forwarded based on different concentric shells through opportunistic directional forwarding strategy (ODFS), even if there are voids. The ODFS takes into account the remaining energy and data transmission of nodes in the same shell, and avoids cyclic transmission, flooding, and voids. The verification and analysis of simulation results show that the effectiveness of our proposed EAVARP in terms of selecting performance matrics in comparison to existing routing protocols.

Index Terms—underwater sensor network; routing protocol; energy-aware; void-avoidable

1 Introduction

UWSNs have lately been suggested as a potent means of supporting aquatic applications ranging from environmental monitoring to intrusion detection [1-3]. It is used in environmental, industrial and military domains for applications that vary in monitoring, navigation, surveillance and tracking, etc. [4-5]. Submarine observation system (SOS) is one of the most important premises of marine exploration, development and utilization of submarine resource. The main task of SOS is to explore the influence of the unknown world, submarine resources and human activities on the ocean. There are characteristics of high energy consumption, high-latency and low-bandwidth in the UWSNs. UWSNs is facing a great challenge in designing a routing protocol with power, topology, scalability, addressing technology, robustness, etc. [6].

Some researchers may modify existing terrestrial routing protocols in mobile underwater networks to support any cast routing by assigning a single virtual node ID to all sonobuoys [7]. Acoustic communication has large latency, low bandwidth and high error-rate which have to be considered in underwater modeling [8]. In UWSNs, communications have to be done through acoustic channels, because electromagnetic radio signals attenuate quickly. The signal propagation speed in the acoustic channel is m/s. This huge propagation latency has great impact on networks protocol design. The bandwidth of an acoustic channel is low (up to 20 kbps), and the error rate is high [9]. Many traditional network protocols for terrestrial sensor networks are infeasible for UWSNs. In addition, time synchronization and location services based on geo-routing protocols are often not available in UWSNs. The mobility of sensor nodes in such three-dimensional context results in dynamically changing network topologies, which compounds the design of networking protocols and algorithms for UWSNs [10].

Autonomous Underwater Vehicle (AUV) has a wide range of applications in marine geoscience, and is increasingly used in the scientific, military, commercial, and policy sectors [11]. The most common AUV configuration is a torpedo-like vehicle with a streamlined body which has a propeller and control surfaces at the stern [12]. Another configuration is a glider (e.g., Sea gliders [13]) that uses small changes in its buoyancy in conjunction with wings to make up-and-down saw tooth-like movements. AUV is easier to lose under complex underwater environment, and its mobile speed is very slow. Unlike AUV, underwater floats (such as UCSD Drogues and ARGO [14]) primarily use a buoyancy controller for depth adjustments and move passively along with the water current [15].

In [17-18], routing strategies start from the sink on the surface of water to sensor nodes deployed at various depths, and data packets are forwarded from sensor nodes deployed at various depths to sink on the surface of water. The sensor nodes which are closer to the surface of water transmit data packets frequently, and that is the problem of hot zone. The routing protocols lead to the problem of more excessive energy consumption, longer end-to-end delay and heavier node load. There is flooding phenomenon in the process of data forwarding which increases the network load and the

- *Z. Wang and Y. Sui are with the Science and Technology on Underwater Vehicle Laboratory, Harbin Engineering University, Harbin, China E-mail: {wangzhuo, suiyancheng}@hrbeu.edu.cn*
- *G. Han is with the Key Laboratory for Ubiquitous Network and Service Software of Liaoning province, School of Software, Dalian University of Technology, Dalian, China; and the State Key Laboratory of Acoustics, Institute of Acoustics, Chinese Academy of Sciences, Beijing, China. (corresponding author) E-mail: hanguangjie@gmail.com*
- *H. Qin is with the Science and Technology on Underwater Vehicle Laboratory, Harbin Engineering University, Harbin, China; and the Changzhou Key Laboratory of Sensor Networks and Environmental Sensing, Changzhou, China E-mail: qinhongde@hrbeu.edu.cn*
- *S. Zhang is with the College of Computer Science & Technology, Harbin Engineering University, Harbin, China E-mail: 330467760@qq.com*

Manuscript received December X, 2017; revised X .

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2805804, IEEE Access

total energy consumption. As the nodes are affected by the water flow and other factors, the data forwarding process may not find the better node to forward data packet, and which leads to the failure of data transmission and reduces the PDR.

Our goal in this paper is to achieve energy balance distribution, higher PDR, lower latency, longer network lifetime, etc. We propose an energy-aware and void-avoidable routing protocol(EAVARP). EAVARP is designed for a mobile 3D deployment and doesn't require synchronization and/or localization techniques, and it consists of two phases. During the layering phase, concentric shells are built around sink nodes, and sensor nodes are distributed on different shells. During data collection phase, data packets are forwarded based on concentric shells through ODFS, even if there are voids. Our main contributions are highlighted as follows:

- Each sensor node's identification takes into account transmission capacity of parent and brother nodes, so that it provides the efficient routing information. If a sensor node is identified as "11", it will never be selected as relay node.
- The ODFS takes into account the remaining energy of nodes and data transmission in the same shell, which avoids cyclic transmission, flooding, and voids.

The rest of this paper is organized as follows. Section 2 describes related work on routing protocols. Section 3 introduces UWSNs propagation model. Section 4 provides system model of EAVARP. Section 5 discusses the detailed description of EAVARP. Section 6 validates and analyses the performance of EAVARP in comparison to APCRP [17] and E-PULRP [18]. Section 7 concludes the paper and gives future work. Finally, references are given at the end of the paper.

2 Related Work

In this section, we first review some related works on routing protocols in UWSNs, and summarize their advantages, disadvantages and existing problems. In UWSNs, routing protocols can be classified into location-based and location-free routing. However, location services based on geo-routing protocols are often not available in UWSNs. Location-free routing can be classified into layer-based, depth-based, machine-learning-based and cooperative routing.

Layer-based routing includes layering phase and communication phase. During layering phase, different layers are formed around sink node. During communication phase, data packets are forwarded based on these layers. APCRP [17] can adaptively adjust power level of nodes to cater for network mobility. However, the self-adjusting of each node's power level leads to the problem of excessive energy consumption, the non-uniform energy distribution and the shorter network lifetime. E-PULRP [18] implements energy optimization and dynamic routing. It applies to the network environment with a static sink as center. E-PULRP doesn't apply to the network environment with multiple or mobile sink nodes. PULRP [19] is proposed for a 3D UWSN with a uniform distribution of sensor nodes, and it doesn't incorporate energy in the design of the routing protocol. In MRP [20], sender broadcasts data packets, and receiver which Layer ID is less than the senders Layer ID competes for relay node through having higher energy. The super node can overcome voids and responses to the dynamic network topology. However, once the energy of the super node runs out, the local network topology of the node will collapse, and that results in the paralysis of the entire network.

Every node needs pressure gauge to acquire depth information, and relay node for forwarding data is selected based on the pressure information in depth-based routing. In VAPR [16], when sensor nodes send data packets, they are always selecting relay node which is closer to the surface of water. So VAPR leads to excessive energy consumption of some nodes, which results in the non-uniform energy distribution and shortening network lifetime. In [15], when a node fails to send data packets, only the nodes on the surface near void perform the fallback algorithm, which reduces the PDR. OUSCRP [21] applies to a specific network environment, but it does not apply to network environment with multi-mobile sink nodes. EEBET [22] can adjust the node's depth threshold to avoid energy consumption caused by retransmission packets.

Machine-learning-based routing adopts Q-learning technique, which is a reinforcement learning technique that solves decision problems. QELAR [10] can reduce the cost of transmission and computation, which achieves uniform energy distribution and prolongs network lifetime. However, QELAR doesn't apply to large-scale network environment, because convergence speed of iterative learning is very slow, and so that routing selection cannot keep pace with the change of dynamic network topology. MURAO [23] is more robust to changes of network topology, and achieves much higher delivery rates as well as shorter delays. But sensor nodes distribute uniformly in the network, transmission range of each cluster intersects with each other, and at least one node (gateway node) is located in the intersection area. The proposed protocol is based on a distributed machine learning technique, Q-learning, which aims to select the most promising forwarders so as to minimize the end-to-end delay [24-25].

When a node sends data packets, its one-hop neighbor nodes cooperate with each other and send the data packets to the terminal nodes or sink node in cooperative routing. In [26], the routing considers source node's depth threshold, potential relay/destination nodes' depth, residual energy and signal to noise ratio of the link connecting source node with potential relay/destination node as selection parameters. The proposed protocol reduces end-to-end delay and PDR. Co-UWSN [27] is a reliable, energy efficient and high throughput routing protocol. Co-UWSN contributes to sufficient decrease in path-losses occurring in the links connecting sensors in UWSNs and transferring of data with much reduced path-loss. DEAD [28] pay more attention to depth threshold, energy and link quality. But it has retransmission packet. What's more, there is no feedback mechanism to ensure reliable data transmission, so that DEAD increases energy consumption and reduces resource utilization. MobiSink [29], in which the mobile sink nodes move in their own region to collect data packets. In MobiSink, nodes take help of transmission range neighbours to

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2805804, IEEE Access

communicate with sink cooperatively, if sink is out of range. MobiSink achieves higher throughput and extends network lifetime. DEADS [30] doesn't consider the link quality. But it has duplicate and unreliable packet transmission. DEADS increases the propagation delay and packet error rate. SMIC [31] makes efficient use of limited resources through controlling retransmission packet and link quality. SMIC achieves lower energy consumption, higher throughput and PDR. However, SMIC doesn't really avoid flooding and increases transmission delay.

3 UWSNs: Propagation Model

Propagation model includes the following section: energy consumption model and relationship between transmission distance and acoustic pressure.

3.1 Energy Consumption Model

Underwater ambient noise model [32] can be expressed as:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \quad (1)$$

Where, $N_t(f)$ denotes turbulence noise, $N_s(f)$ denotes shipping noise, $N_w(f)$ denotes wind noise, $N_{th}(f)$ denotes thermal noise. f denotes acoustic signal frequency.

Energy attenuation model of underwater acoustic signal [33] can be expressed as:

$$10\log(A(\ell, f)/A_0) = k * 10\log\ell + \ell * 10\log a(f) \quad (2)$$

where, $k * 10\log\ell$ denotes diffusion loss; $\ell * 10\log a(f)$ denotes absorption loss; A_0 denotes a unit normalizing factor that represents fixed losses; $a(f)$ denotes the absorption coefficient and k denotes the spreading factor defined as 1 for cylindrical , 2 for spherical and 1.5 for practical spreading.

The signal to noise ratio at the receiver side can be expressed as:

$$SNR(f, \ell) = P(f) - A(\ell, f) - N(f) + D_I \quad (3)$$

Where $P(f)$ represents the power of receiver side, D_I represents the directivity index of the antenna which is zero for omnidirectional antenna, ℓ represents propagation distance.

Acoustic signal model [34] can be expressed as:

$$S_\ell(f) = SNR(\ell, f)\frac{N(f)}{A^{-1}(\ell, f)} \quad (4)$$

Acoustical power [33] can be expressed as:

$$P(f) = \int_{B(\ell)} S_\ell(f)\,df \quad (5)$$

Where, $B(\ell)$ represents bandwidth of coverage radius ℓ.

Power consumed of acoustic signal [35] can be expressed as:

$$-10\log(\eta P_t(\ell)) = 170.8 - 10\log P(\ell) + DI \quad (6)$$

Where, η is a constant.

The energy consumed of each packet P [17] can be expressed as:

$$E_p(\ell) = \frac{(P_r + P_t(\ell))L}{B} \quad (7)$$

Where, L represents the length of the packet, B represents channel bandwidth (transmission rate), the acoustic power P_r emitted for receiving one bit of information.

3.2 Relationship between Transmission Distance and Acoustic Pressure

Figure 1 illustrates relationship between transmission distance and acoustic pressure. As the acoustic signal intensity increases, the maximum propagation distance starts to increase. Underwater acoustic channel is affected by acoustic path loss, noise, multipath effect and other factors, so that the acoustic signal strength is attenuated by increasing propagation distance. Simulation verification can be based on the relationship between transmission distance and acoustic pressure to set acoustic pressure.

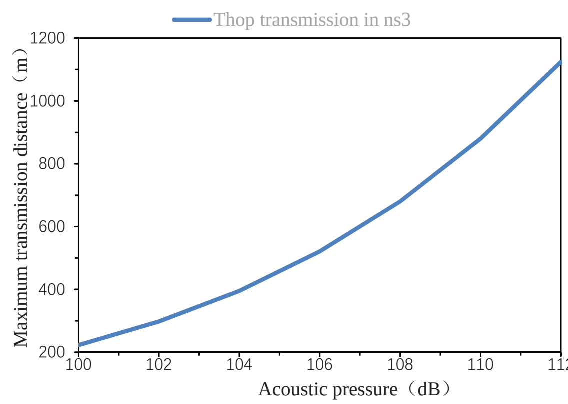


Fig. 1: Relationship between transmission distance and acoustic pressure

4 Network Model

In this section, we first present the terms that will be used for the rest of the paper. Then we present the proposed network model.

The terms are defined as follows:

- Sink node – a node node that has the additional responsibility to collect information from all sensor nodes and send this information to the monitoring center.
- Source node – any sensor node except the sink node.
- Relay node – a sensor node that receives information from a source node or another relay node and forwards this information to the sink node or another relay node.
- Sending node – a source or relay node that is sending information to a relay node or sink node.
- Receiving node – a sink or relay node that is receiving information from a relay or source node.
- One-hop node – a sensor node that is within the transmission range of the sink node.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2805804, IEEE Access

Figure 2 illustrates our proposed network model. The whole network environment consists of two different types of nodes, i.e. ordinary sensor nodes and sink node. The Monitoring center is anchored to the surface of water and collects information from sink node. Ordinary sensor nodes are randomly distributed in underwater and don't need to know their positions. Each sensor node does not need external hardware devices (such as pressure gauge, RSSI [18]) to sense the environment, and has same capability of power, processing and transmitting data. Every sensor node periodically monitors information of interest and stores the information in its buffer or replaces the oldest information with the latest information. The sink node floats on the surface of the water and forwards information to monitoring center by radio transmission.

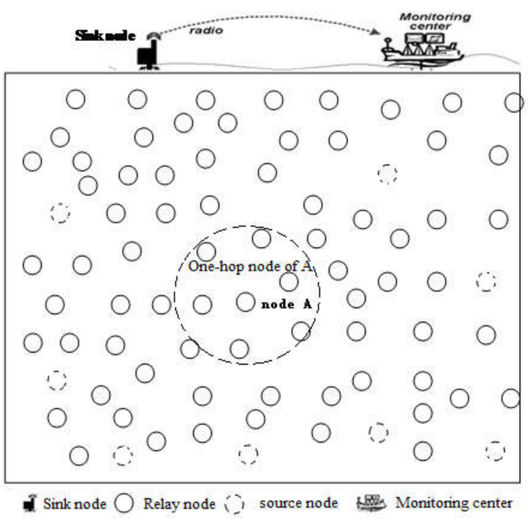


Fig. 2: Network model

5 EAVARP: Energy-Aware and Void-Avoidable Routing Protocol

This section discusses the detail of EAVARP. EAVARP is designed for a mobile 3D deployment and doesn't require synchronization and/or localization techniques. EAVARP includes layering phase and data collection phase. During the layering phase, concentric shells are built around sink nodes, and sensor nodes are distributed on different shells. During the data collection phase, data packets are forwarded based on concentric shells through ODFS.

5.1 Layering Phase

In this section, firstly, we describe the packet structure; secondly, we describe the routing table structure; lastly, the layering phase will be elaborated.

5.1.1 Packet Structure

The packet structure consists of Packet Header and Data, as shown in Figure 3. Packet Header includes Node ID, Source Address, Destination Address, Type, Layer, Identification and Residual Energy, as shown in Figure 4.

Packet Header	Data

Fig. 3: Packet structure

Node ID	Source Address	Destination Address	Residual Energy	Layer	Type	Identification

Fig. 4: Packet header

Where, the Node ID uniquely identifies each sensor node. The Source Address is the physical address of each sensor node. The Destination Address is physical address of sink node or relay node. The Residual Energy represents remaining energy of each sensor node. The Layer is hop count between the sensor node and sink node. The Type includes LAYER_BUILD, DATA_TO_SINK and DATA_COLLECTION. LAYER_BUILD indicates layering packet and is carried out in the layering phase. DATA_COLLECTION indicates data collection signal and is carried out in the data collection phase. DATA_TO_SINK indicates data packet and the packet will be sent to sink or relay node directly. Identification consists of two bits. The first bit indicates whether the parent node of the sensor node has the ability to transmit data packets or not, and the second bit indicates whether the brother node of the sensor node has the ability to transmit data packets or not. "0" represents there is transmission capability, and "1" represents there is not transmission capability.

A void node is defined as a node that does not have sufficient energy for data transmission or an isolated node. A void node also is defined as a node that the parent nodes and the brother nodes are void nodes. A parent node with transmission capacity is defined as a node that has sufficient energy for data transmission and the node that is not void node, identified as "00", "01", or "10". A parent node with no transmission capacity is defined as void node, identified as "11". A brother node with transmission capacity is defined as a node that has sufficient energy for data transmission and the node that the first bit of the node's identification is "0", identified as "00" or "01". A brother node with no transmission capacity is defined as a node that the second bit of the node's identification is "1" or the node that is void node, identified as "10" or "11".

A node identified as "11" will never be selected as relay node, because the node identified as "11" is void node, so that the identification information effectively avoids voids.

5.1.2 Routing Table Structure

Figure 5 shows the routing table structure. Each node maintains a routing table. Routing table includes node ID, Identification, Residual Energy, Layer, Buffer, Timer and Neighbor List. Neighbor list includes node ID, Identification, Residual Energy and Layer.

Node ID	Identification	Residual Energy	Layer	Buffer	Timer	Neighbor List			
						Node1 ID	Identification1	Maximum Residual Energy1	Layer1
						Node2 ID	Identification2	Maximum Residual Energy2	Layer2
						Node3 ID	Identification3	Maximum Residual Energy3	Layer3

Fig. 5: Routing table

Where, Neighbor List stores one-hop neighbor node information; Buffer stores the data detected by sensor nodes or failed to send; Timer periodically controls sensor nodes to monitor the data of interest.

The Neighbor List is divided into a parent list structure and a brother list structure. There are at most information of two sensor nodes in the parent list structure, and their identification are identified as ″00″ (″01″) and ″10″ respectively. The layer of the two sensor nodes is one less than the layer of the routing table. Parent list structure stores nodes that have maximum residual energy compared with other parent nodes with identification as ″00″ (″01″) and ″10″ respectively. The brother list structure stores at most information of one node, and its identification is identified as ″00″ or ″01″. Its layer is equal to the layer of the routing table. Brother list structure stores node that has maximum residual energy compared with other brother nodes with identification as ″00″ or ″01″. Each node maintains a small amount of neighbor node information to reduce cost of maintaining routing table. It improves the resource utilization. The routing table is always dynamically maintaining the nodes that have the most remaining energy and transmission capability. EAVARP achieves energy balance distribution in the whole network, and reduces the network load and cost of maintaining routing table, and improves the resource utilization.

5.1.3 The detail of Layering Phase

Initialization phase is performed before the layering phase, and the purpose of initialization phase initializes identification, energy, layer, timer and routing table of sink node and sensor nodes. The detail of layering establishment phase is shown in Algorithm 1. Firstly, sink node broadcasts layering packet which contains Node ID, Residual Energy, Identification, Layer and type of layering packet. Secondly, if receiving node receives the packet that type of the packet is LAYER_BUILD and the layer of the packet is less than the layer of the receiving node, the layers of the receiving node will be the layer of the packet increased 1, and the routing table of the receiving node will be updated to store parent node. The parent node has maximum residual energy comparing with other parent nodes with identification as ″00″ (″01″) and ″10″ respectively. The receiving node broadcasts layering packet, after waiting for the time [20]. If the layer of layering packet is equal to the layer of the receiving node, the routing table of the receiving node will be updated to store brother node that has maximum residual energy comparing with other brother nodes with identification as ″00″ (″01″). If the layer of layering packet is more than the layer of the receiving node, the layering packet will be dropped.

During the layering phase, concentric shells are built around sink node, and sensor nodes are distributed on different shells. The phase establishes 3D network concentric shells structure. The sink node performs hierarchical tasks periodically to ensure the validity and real-time of the topology. It makes EAVARP apply to dynamic network environment.

5.2 Data Collection Phase

Sending node sends data packet to sink node or the best relay node based on one-hop neighbor node's identification through ODFS, instead of actually sending data packet or probe packet to select the best relay node, and that aims to shorten end-end delay and avoid voids. Each node's identification takes into account transmission capacity of the parent and brother nodes. If a node is identified as ″11″, it will never be selected as relay node. So that EAVARP effectively avoids voids. The ODFS takes into account the remaining energy of nodes and data transmission in the same shell, which avoids cyclic transmission, flooding, and voids.

The detail of data collection phase is as follows: when receiving node receives data collection signal, it will broadcast the signal waiting for some time. If there is a parent node identified as ″00″ or ″01″ in the node's parent list, the node will send data packets to the parent node directly. If there is only a parent node identified as ″10″ in the node's parent list, the node will send data packets to the parent node directly. If the node's parent list is null and there is a brother node identified as ″00″ or ″01″ in its brother list, the node will send the data packets to the brother node directly. If the node's parent and brother list are null, it will insert the data packets into its buffer or replaces the oldest record with the data packets. The node which receives data packets will become sending node and forward the data packets through ODFS, until the data packets are forwarded to the one-hop node. If the one-hop nodes will detect themselves been within the transmission range of the sink node, they will send their data packets to sink node directly. It avoids the failure of data transmission caused by sink node that moves.

Figure 6 illustrates the opportunistic directional forwarding path (ODFP). The sensor node A starts to send data packets. If parent nodes of A are identified as ″00″ or ″01″, the ODFP will be A-B-C, as shown in Figure 6(a). The reason is that the residual energy of B is more than D. When the residual energy of D is greater than B, the ODFP will be

Algorimth 1:Layering Phase

```
procedure BroadcastLayer (node,packet)
if node ∈ sink node then
    setPacket()
    broadcast packet
end if
end procedure

hearing(packet)
procedure ReceiveLayerPacket(node,packet)
if type of packet is LAYER BUILD
    if type of packet is less than the type of the node then
        the type of node is the layer of packet increased 1
        updateRoutingTable()
        setPacket()
        waitTime(κ)
        BroadcastLayer (node, packet)
    else if type of packet is equal to the type of the node then
        updateRoutingTable()
    else
        drop(packet)
    end if
    end if
end if
end procedure
```

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2805804, IEEE Access

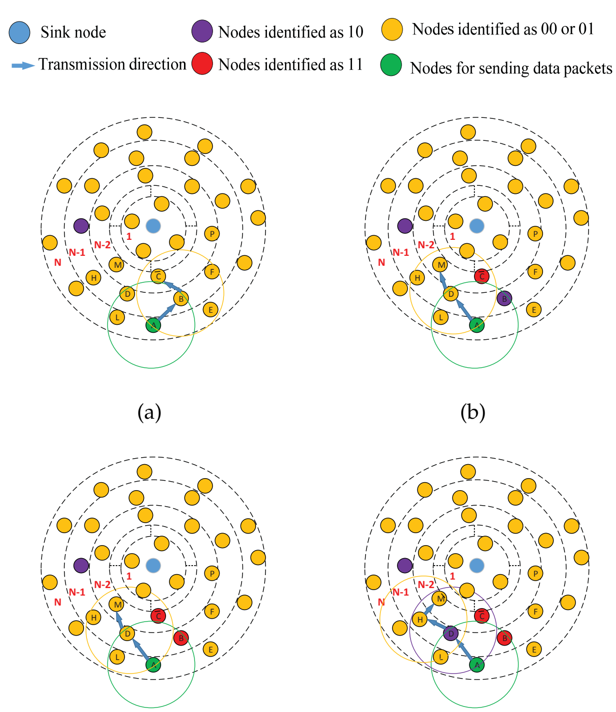
A-D-C. EAVARP makes energy balance distribute in the network. If parent nodes of A are identified as ″00″(″01″) and ″10″, the ODFP will be A-D-M, as shown in Figure 6(b). The reason is that the parent node of B is a void node. EAVARP avoids voids, improves the PDR and reduces the energy consumption. If parent nodes of A are identified as ″00″(″01″) and ″11″, the ODFP will be A-D-M, as shown in Figure 6(c). The reason is that B is a void node. If parent nodes of A are identified as ″10″ and ″11″, the ODFP will be A-D-H-M, as shown in Figure 6(d). The reason is that the parent node(C) of D and the parent node (B) of A are void nodes, but brother node (H) of D is identified as ″00″ or ″01″ to ensure reliable data transmission. If parent nodes of A are identified as ″11″ and brother nodes of A are identified as ″00″ or ″01″, the ODFP will be A-E-F-P, as shown in Figure 6(e). The reason is that the brother node E(L) of A is identified as ″00″ or ″01″ to ensure reliable data transmission and the residual energy of E is more than L. When the residual energy of L is greater than E, the ODFP will be A-L-H-M. If parent nodes of A are identified as ″11″ and brother nodes of A are identified as ″10″ and ″11″, the data packets will be inserted into the buffer of A or replace the oldest record of A, as shown in Figure 6(f).

6 Simulation Results and Discussions

This section is organized as follows: simulation, performance metrics, results and analysis. We will verify and analyze the performance of EAVARP in this section under NS–3.

6.1 Simulation

In the simulation experiment, 100∼400 sensor nodes are randomly deployed in a 3D monitoring space of $1km \times 1km \times 1km$.



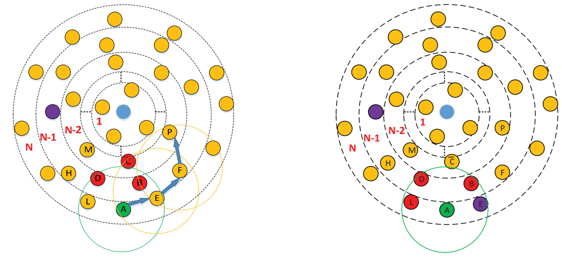


Fig. 6: Opportunistic directional forwarding path. (a) Parent nodes and brother nodes of A are identified as ″00″ or ″01″; (b) Parent nodes of A are identified as ″00″(″01″) and ″10″, and brother nodes of A are identified as ″00″ or ″01″; (c) Parent nodes of A are identified as ″00″(″01″) and ″11″, and brother nodes of A are identified as ″00″ or ″01″; (d) Parent nodes of A are identified as ″10″ and ″11″, and brother nodes of A are identified as ″00″ or ″01″; (e) Parent nodes of A are identified as ″11″, and brother nodes of A are identified as ″00″ or ″01″; (f) Parent nodes of A are identified as ″11″ and brother nodes of A are identified as ″10″ or ″11″.

The maximum width of layer and communication radius is 200m and 250m respectively. Acoustic pressure is set based on the relationship between transmission distance and acoustic pressure. The detailed parameter settings are shown in Table 1.

6.2 Performance Metrics

The total energy consumption, average end-to-end delay, PDR, and network lifetime are important indicators to measure the performance of routing in UWSNs. The performance indicators are defined as follows:

- **The total energy consumption:** The sum of the energy is consumed by all packets in the entire network. Maintaining the routing table in the layering phase also contributes to increasing the energy consumption. The total energy consumption consumed by maintaining the routing table is far less than the total energy consumption consumed by data transmission, so that the total energy consumption don't include this factor in evaluation.
  Total energy consumption can be expressed as:

$$E_{total} = \sum_{j=p}^{0} \sum_{i=n}^{1} E_j (h_i - h_{i-1}) \tag{8}$$

  Where, $h_i - h_{i-1}$ represents the distance between layer $i-1$ and layer i , j represents the last packet, i represents which layer j is.
  The energy distribution in network can be expressed as:

$$a_n = \frac{1}{n_{nodes}} \sqrt{\sum_{i=1}^{n_{nodes}} \left(E_{res}(m_i) - \frac{1}{n_{nodes}} \sum_{j=1}^{n_{nodes}} E_{res}(n_j)\right)^2} \tag{9}$$

TABLE 1: Simulation settings

Simulation Parameters	Values
Transmission model	ns3::UanPropModelThorp
Noise model	ns3::UanNoiseModelDefault
Underwater acoustic channel model	ns3::UanChannel
Consumed energy model	ns3::AcousticModemEnergyModel
Signal to noise ratio model	ns3::UanPhyCalcSinrDefault
Packet error rate model	ns3::UanPhyPerGenDefault
Speed of sound in underwater	1500m/s
Power in received power or idle state	158mW
Transmit power	50W
Bandwidth	80Hz
Network boundary	1km×1km×1km
MAC protocol	CW-MAC802.11DCF
Width of layer	⩽200m
Runtime	1000s
Packet size	64bytes
Size of packet header	13bytes
Initial energy of each node	360J
Transmission radius of sensor nodes	≈250m
Data transmission rate	10kbps
The Number of nodes	100400
The Number of sinks	⩾2
Acoustic pressure of layer	101 dB(μPa)
Acoustic pressure of data transmission	103 dB(μPa)

Where, n_{nodes} indicates the total number of sensor nodes in the network;$E_{res}(m_i)$ indicates residual energy of sensor node m_i; n_j indicates one of the sensor nodes. The larger the difference between the residual energy of a node and the average residual energy of the whole network, the more balanced the energy distribution in the network is, and the smaller a_n is.

- **The average end-to-end delay:** The sum of the time required for all data packets to be received from the beginning of the transmission to the reception by the sink nodes which is proportional to the number of packets successfully received by the sink nodes.
The total time T_i of sensor node sending a packet to sink node can be approximated by the sum of the transmission delay, the propagation delay and the additional delay. The total time T_i can be expressed as:

$$T_i = \sum_{i=n}^{1} \left(\frac{L_{packet}}{B} + \frac{d_i - d_{i-1}}{v} + \varsigma\right) \tag{10}$$

where, L_{packet} indicates the length of data packet, i indicates the layer of sensor node that sends data packet; B indicates bandwidth of channel; $d_i - d_{i-1}$ indicates the distance from layer i to layer $i-1$; v indicates speed of sound in UWSNs(≈1500m/s); ς indicates additional delay.
- **PDRPacket Delivery Ratio:** PDR is the ratio of the data packets received by sink nodes to all data packets sent by sensor nodes.
- **Network lifetime:** The ratio of the total number of energy-exhausted sensor nodes to the total number of all sensor nodes.

6.3 Results and Analysis

Figure 7 illustrates the relationship between the total energy consumption and the number of sensor nodes. The number of sensor nodes increases and the total energy consumption will start to increase. The total energy consumption of APCRP is more than E-PULRP and EAVARP. When APCRP fails to find relay node before sending data packets, it will adjust power level of sensor nodes at high power level, and which increases energy consumption. The collision of packets results in the cross layer node selected as relay node, so that APCRP increases the total energy consumption. The total energy consumption of APCRP and E-PULRP is more than EAVARP. The reason is that sensor nodes broadcast probe packet to find relay node before sending data packets in APCRP and E-PULRP, and which increases energy expenditure. However, EAVARP adopts ODFS to select the best relay node to avoid flooding, so that it decreases energy expenditure. Moreover, EAVARP avoids cyclic transmission to decrease total energy consumption.

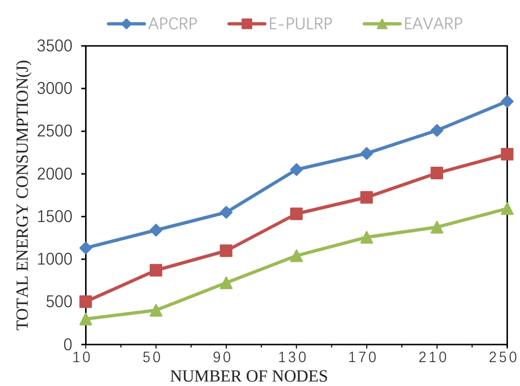


Fig. 7: Total energy consumption

Figure 8 illustrates the relationship between average end-to-end delay and the number of sensor nodes. It can be seen that the average end-to-end delay of APCRP and E-PULRP is longer than EAVARP. In EAVARP, sensor nodes directly send data packets to the reliable relay node by ODFS, so that the average end-to-end delay of sensor nodes is greatly reduced. Moreover, EAVARP avoids cyclic transmission to reduce the average end-to-end delay. When APCRP or E-PULRP cannot find the appropriate relay node before sending data packets, it will broadcast probe packet repeatedly until finding appropriate relay node, and so that the average end-to-end delay of sensor nodes is greatly increased. The average end-to-end delay of E-PULRP is

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2805804, IEEE Access

greater than APCRP. The reason is that E-PULRP broadcasts probe packet repeatedly to find relay node until finding appropriate relay node, but APCRP selects relay node by adjusting sensor nodes at high power levels to decrease the average end-to-end delay of sensor nodes.

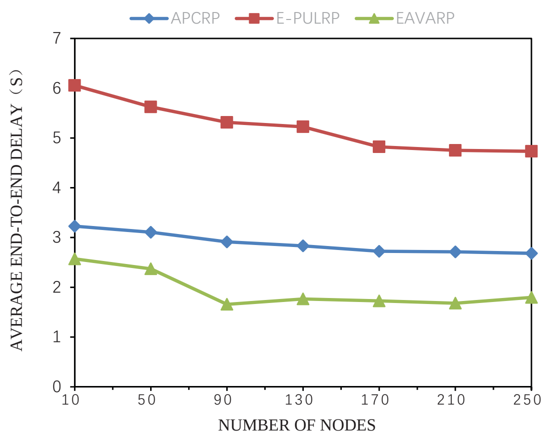


Fig. 8: Average end–to–end delay

Figure 9 illustrates the relationship between death rate of sensor nodes and simulation time. As simulation time goes on, death rate of sensor nodes starts to increase. In APCRP, when the simulation time is less than 1000s, death rate of sensor nodes is faster than E-PULRP and EAVARP. In APCRP, senor nodes do not find relay nodes before sending data packets, their power will be frequently increased until the best relay node would be found. Moreover, the collision of packets will result in the cross layer node selected as relay node in APCRP. The above reasons lead to excessive energy consumption of some nodes and arouse larger difference between the residual energy of some nodes and the average residual energy of the network, so that energy of some nodes are exhausted quickly to make death rate of sensor nodes increase quickly. By the end of 1900s, death rate of EAVARP is less than 20% and network lifetime of EAVARP is higher than that of APCRP and E-PULRP. The reason is that EAVARP takes into account the remaining energy of sensor nodes and avoids cyclic transmission, so that it makes energy balance distribution to extend network lifetime. When the time is gone from 1900s to 2000s, death rate of EAVARP increases exponentially from 20% to 1. At the end of network lifetime, the remaining energy of each node is quickly less than the minimum energy to make network to paralyze in EAVARP. It can be seen energy distribution of EAVARP is more balanced than that of APCRP and E-PULRP.

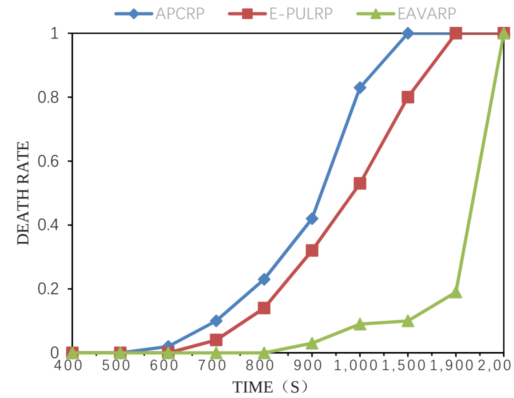


Fig. 9: Death rate

Figure 10 illustrates the relationship between the PDR and the number of sensor nodes. As the number of sensor nodes increases, the PDR starts to increase. When the number of sensor nodes reaches a certain level, the PDR starts to decrease. When the number of sensor nodes is less than 90, the PDR of APCRP is higher than that of E-PULRP and EAVARP. The reason is that APCRP applies to the sparse environment by adjusting each node's power at high power level, and so that APCRP improves the PDR and also mitigates the influence of voids in UWSNs. When the number of sensor nodes is more than 90, the PDR of EAVARP is higher than that of the other two routing. Each node's identification takes into account transmission capacity of parent and brother nodes in EAVARP, and which avoids voids to improve the PDR. Furthermore, EAVARP takes into account data transmission in the same shell and avoids cyclic transmission to improve the PDR.

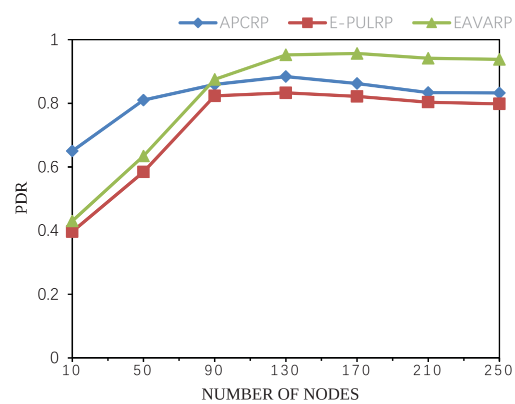


Fig. 10: PDR

7 Simulation Results and Discussions

In this paper, we have presented the EAVARP for UWSNs. EAVARP includes the layering and data collection phases. Concentric shells are built around sink nodes, and sensor nodes are distributed on different shells in the layering phase. EAVARP ensures the validity and real-time of the topology and applies to dynamic network environment. Each node's identification takes into account transmission capacity of parent and brother nodes, and which avoids

voids and provides the efficient routing. EAVARP adopts ODFS in data collection phase. The ODFS takes into account the remaining energy of nodes and data transmission in the same shell, which avoids cyclic transmission, flooding and voids. Moreover, EAVARP makes energy balance distribute in the network to extend network lifetime.

In the near future, the optimal trajectory of sink node can be optimized in UWSNs, and which aims to improve the performance of routing. Moreover, we will propose the best data collection scheme based on multi-mobile sink nodes in a harsh underwater environment.

Acknowledgments

The research is supported by the National Natural Science Foundation of China (51509057, 61572172 and 51779058). It is also supported by National Major Projects "some intelligent control and support software", National Science and Technology Major Project 2015ZX01041101-002 and the Fundamental Research Funds for the Central Universities No.DUT17RC(3)094.

References

[1] Akyildiz, I.F.; Pompili, D.; Melodia, T, "Underwater acoustic sensor networks: research challenges," *Ad Hoc Networks*, 2005, 3, 257-279.

[2] Kong, J.; Cui, J.H.; Wu, D.; Gerla, M, "Building underwater ad-hoc networks and sensor networks for large scale real-time aquatic applications," *MILCOM 2005-2005 IEEE Military Communications Conference*, IEEE 2005, 3, 1535-1541.

[3] Vasilescu, I.; Kotay, K.; Rus, D.; Dunbabin, M.; Corke, P, "Data collection, storage, and retrieval with an underwater sensor network," *International Conference on Embedded Networked Sensor Systems: San Diego, California, Usa*, 2005; pp. 154-165.

[4] Umar, A.; Akbar, M.; Ahmed, S.; Javaid, N.; Khan, Z. A.; Qasim, U., "Underwater Wireless Sensor Network's Performance Enhancement with Cooperative Routing and Sink Mobility," *International Conference on Broadband & Wireless Computing*,2014, 26-33.

[5] Meratnia, N.; Havinga, P. J. M.; Casari, P.; Petrioli, C., "C. CLAM Collaborative embedded networks for submarine surveillance. An overview," *Oceans*, 2011, 1-4.

[6] Kartha, J.J; Jacob, L., "Delay and Lifetime Performance of Underwater Wireless Sensor Networks with Mobile Element Based Data Collection," *International Journal of Distributed Sensor Networks*, 2015, 1-22.

[7] Macker, J., "Anycast routing for mobile services," *Conf.info.sci. & Sys*, 1999.

[8] Cui, J. H., Kong, J., Gerla, M.; Zhou, S., "The challenges of building mobile underwater wireless networks for aquatic applications," *IEEE Network*, 2006, 20, 12-18.

[9] Heidemann J, Ye W, Wills J, Syed, A.; Li, Y., "Research challenges and applications for underwater sensor networking," *Wireless Communications and NETWORKING Conference*, 2006, 1, 228-235.

[10] Hu, T.; Fei, Y., "QELAR: A Machine-Learning-Based Adaptive Routing Protocol for Energy-Efficient and Lifetime-Extended Underwater Sensor Networks," *IEEE Transactions on Mobile Computing*, 2010, 9, 796-809.

[11] Wynn, R.B.; Huvenne, V.A.I.; Bas, T.P.L.; Murton, B.J.; Connelly, D.P.; Bett, B.J.; Ruhl, H.A.; Morris, K.J.; Peakall, J.; Parsons, D.R.; Summer, E.J.; Darby, S.E.; Dorrell, R.M.; Hunt, J.E., "Autonomous Underwater Vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience," *Marine Geology*, 2014, 352, 451-468.

[12] Bellingham, J., "Autonomous Underwater Vehicles (auvs)–Encyclopedia of Ocean Sciences," *Encyclopedia of Ocean Sciences*, 2001, 28, 212216.

[13] Roy, S.; Arabshahi, P.; Dan, R.; Fox, W., "Wide area ocean networks: architecture and system design considerations," *Wuwnet06 Los*, 2015, 25-32.

[14] Gould, D.W.J.; Turton , J., "Argo Sounding the oceans," *Weather*, 2006, 61, 17-21.

[15] Noh, Y.; Lee, U.; Lee, S.; Wang, P., "Pressure Routing for Underwater Sensor Networks," *Vehicular Technology IEEE Transactions*, 2010, 65, 333-347.

[16] Noh, Y.; Lee, U.; Wang, P.; Choi, B.S.C.; Gerla, M., "VAPR: Void-aware pressure routing for underwater sensor networks," *IEEE Trans. Mob. Comput*, 2013, 12, 895908.

[17] Manal Al-Bzoor.; Yibo Zhu.; Jun Liu.; Reda Ammar.; Jun-Hong Cui.; Sanguthevar Rajasekaran, "An adaptive power controlled routing protocol for underwater sensor network," *Int. J. Sensor Networks*, 2015, 18.

[18] Gopi, S.; Kannan, G.; Desai, U. B.; Merchant, S. N., "E-PULRP: Energy Optimized Path Unaware Layered Routing Protocol for Underwater Sensor Networks," *IEEE Transactions on Wireless Communications*, 2010, 9, 3391-3401.

[19] Gopi, S.; Kannan, G.; Chander, D.; Desai, U. B., "PULRP: Path Unaware Layered Routing Protocol for Underwater Sensor Networks," *IEEE International Conference on Communications*, 2008, 9, 3141-3145.

[20] Wahid, A.; Lee, S.; Kim, D.; Lim, K. S., "MRP: A Localization-Free Multi-Layered Routing Protocol for Underwater Wireless Sensor Networks," *Wireless Personal Communications*, 2014, 77, 2997-3012.

[21] Rahman, Z.U.; Ahmad, Z.; Murad, A.; Khan, T., "On utilizing static courier nodes to achieve energy efficiency with depth based routing for underwater wireless sensor networks," *Aina 2016 Conference and Affiliated Workshops: Switzerland*, 2016; pp. 1184-1191.

[22] Javaid, N.; Shah, M.; Ahmad, A.; Imran, M.; Khan, M. I.; Vasilakos, A. V., "An Enhanced Energy Balanced Data Transmission Protocol for Underwater Acoustic Sensor Networks," *Sensors*, 2016, 16, 487.

[23] Hu, T.; Fei, Y., "MURAO: A multi-level routing protocol for acoustic-optical hybrid underwater wireless sensor networks," *IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks*, 2012, 1, 218-226.

[24] Hu, T.; Fei, Y., "An Adaptive and Energy-efficient Routing Protocol Based on Machine Learning for Underwater Delay Tolerant Networks," *IEEE International Symposium on Modeling, Analysis & Simulation of Computer and Telecommunication Systems*, IEEE 2010, 381-384.

[25] Hu, T.; Fei, Y., "An adaptive routing protocol based on connectivity prediction for underwater disruption tolerant networks," *GLOBECOM 2013 - 2013 IEEE Global Communications Conference*, 2013, 65-71.

[26] Umar, A.; Akbar, M.; Iqbal, Z.; Khan, Z. A., "Cooperative partner nodes selection criteria for cooperative routing in underwater WSNs," *National Symposium on Information Technology: Towards New Smart World–wireless Systems & Networks*, IEEE, 2015, 1-7.

[27] Ahmed, S.; Javaid, N.; Khan, F.A.; Durrani, M.Y.; Ali, A.; Shaukat, A.; Sandhu,M.M.; Khan, A.; Qasim, U., "Co-UWSN: Cooperative Energy Efficient Protocol for Underwater WSNs," *International Journal of Distributed Sensor Networks*, 2015, 11, 1-16.

[28] Pervaiz, K.; Wahid, A.; Sajid, M.; Khizar, M.; Khan, Z. A.; Qasim, U.; Javaid, N., "DEAC: Depth and Energy Aware Cooperative Routing Protocol for Underwater Wireless Sensor Networks," *IEEE International Conference on Complex, Intelligent, and Software Intensive Systems*, 2016.

[29] Shah, P.M.; Ullah, I.; Khan, T.; Hussain, M.S.; Khan, Z. A.; Qasim, U.; Javaid, N., "MobiSink: Cooperative Routing Protocol for Underwater Sensor Networks with Sink Mobility," *IEEE, International Conference on Advanced Information NETWORKING and Applications*, 2016, 189-197.

[30] Umar, A.; Javaid, N.; Ahmad, A.; Khan, Z. A.; Qasim, U.; Alrajeh, N., Hayat, A., "DEADS: Depth and Energy Aware Dominating Set Based Algorithm for Cooperative Routing along with Sink Mobility in Underwater WSNs," *Sensors*, 2015, 15, 1445814486.

[31] Sajid, M.; Wahid, A.; Pervaiz, K.; Khizar, M.; Khan, Z. A.; Qasim, U.; Javaid, N., "SMIC: Sink Mobility with Incremental Cooperative Routing Protocol for Underwater Wireless Sensor Networks," *EEE International Conference on Complex, Intelligent, and Software Intensive Systems*, IEEE, 2016.

[32] Yu, H.; Yao, N.; Liu, J., "An adaptive routing protocol in underwater sparse acoustic sensor networks," *Ad Hoc Networks*, 2015, 34, 121-143.

[33] Stojanovic, M., "On the relationship between capacity and distance in an underwater acoustic communication channel," *In The First ACM International Workshop on Underwater Networks: Los Angeles, California, USA*, 2006; Volume 25 , pp. 4145.

[34] Yan, H.; Shi, Z.J.; Cui, J.H., "DBR: Depth-Based Routing for Un-

derwater Sensor Networks," *Lecture Notes in Computer Science*, 2008, 4982, 72-86.

[35] Johannesson, K.A.; Mitson, R.B., "Fisheries acoustics. A practical manual for aquatic biomass estimation," *Fao Fisheries Technical Paper*, 1983.

[36] Guangjie Han, Chenyu Zhang, Lei Shu, Joel J.P.C Rodrigues, "Impacts of Deployment Strategies on Localization Performances in Underwater Acoustic Sensor Networks," *IEEE Transactions on Industrial Electronics*, Vol.62, No.3, pp: 1725-1733, 2015.

[37] Guangjie Han, Jinfang Jiang, Na Bao, Liangtian Wan, Mohsen Guizani, "Routing Protocols for Underwater Wireless Sensor Networks," *IEEE Communications Magazine*, Vol.53, No.11, pp: 72-78, 2015.

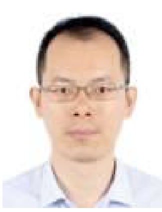
[38] Guangjie Han, Jinfang Jiang, Ning Sun, Lei Shu, "Secure Communication for Underwater Acoustic Sensor Networks," *IEEE Communications Magazine*, Vol.53, No.8, pp: 54-60, 2015.

[39] Guangjie Han, Jinfang Jiang, Lei Shu, Mohsen Guizani, "An Attack-Resistant Trust Model based on Multidimensional trust Metrics in Underwater Acoustic Sensor Networks," *IEEE Transactions on Mobile Computing*,Vol.14, No. 12, pp: 2447-2459, 2015.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2018.2805804, IEEE Access

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.

Guangjie Han (S'03-M'05) received the Ph.D. degree from Northeastern University, Shenyang, China, in 2004. From 2004 to 2006, he was a Product Manager for the ZTE Company. Until 2008, he was a Post-Doctoral Researcher with the Department of Computer Science, Chonnam National University, Gwangju, South Korea. From 2010 to 2011, he was a Visiting Research Scholar with Osaka University, Suita, Japan. He is currently a Professor with the Department of Information and Communication System, Hohai University, Changzhou, China. He has authored over 230 papers published in related international conference proceedings and journals, and holds 100 patents. His current research interests include sensor networks, computer communications, mobile cloud computing, and multimedia communication and security. He is a member of ACM. He received the ComManTel 2014, ComComAP 2014, Chinacom 2014, and Qshine 2016 Best Paper Awards. He has served as a Co-Chair for over 50 international conferences/workshops and as a Technical Program Committee Member of over 150 conferences. He has served on the Editorial Boards of up to 14 international journals, including the IEEE ACCESS, the Telecommunication Systems, the International Journal of Ad Hoc and Ubiquitous Computing, the Journal of Internet Technology, and the KSII Transactions on Internet and Information Systems. He guest edited a number of special issues in the IEEE journals and magazines. He has served as a Reviewer of over 50 journals.



Hongde Qin born in 1976, PHD and professor in naval architecture and ocean engineering of Harbin Engineering University, director of science and technology on underwater vehicle laboratory, his research interests focus on autonomous underwater vehicle technique, offshore structure hydrodynamics and ship strength analysis.

Suping Zhang received her M.S. degree in Computer Science and Technology from Harbin Engineering University, China in 2017. During M.S., her specialization area belongs to Underwater Wireless Network and Communication. Her research interests include underwater location, routing protocols and underwater acoustic sensor networks.

Yancheng 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.