An Energy-Efficient Localization-Based Geographic Routing Protocol for Underwater Wireless Sensor Networks

Kun Hao[1(✉)], Haifeng Shen[2], Yonglei Liu[3], and Beibei Wang[4]

[1] School of Computer and Information Engineering, Tianjin ChengJian University, Tianjin, China
Kunhao@tcu.edu.cn
[2] College of Science and Engineering, Flinders University, Adelaide, Australia
haifeng.shen@flinders.edu.au
[3] School of Electronic and Information Engineering, Tianjin University, Tianjin, China
sanxiong_1@163.com
[4] School of Control and Mechanical Engineering, Tianjin ChengJian University, Tianjin, China
wbbking@163.com

Abstract. An efficient routing protocol for data packet delivery is crucial to underwater sensor networks (UWSNs). However, design of such a protocol is a challenging task due to the characteristics of the acoustic channel used for communication by UWSNs. In this paper, we present a novel energy-efficient localization-based geographic routing protocol EEL, which uses location information and residual energy of sensor nodes to greedily forward data packets to sink nodes. EEL periodically updates the location information of nodes in an UWSN and effectively adapt to the dynamic topological changes of the network. Simulation results show that EEL can effectively locate the nodes and significantly improve the packet delivery ratio and reduce the energy consumption in a routing process.

Keywords: Underwater acoustic sensor networks · Localization
Geographic routing · Energy consumption

1 Introduction

Recently, underwater sensor networks (UWSNs) [1, 2] have received a great deal of attention from the wireless communication and networking communities. This technology is expected to mark a new era of scientific and industrial underwater monitoring and exploration applications, such as oceanographic data collection, disaster prevention, and pollutant content monitoring. As communication in a UWSN is through acoustic waves and high frequency radio waves are strongly absorbed in water, underwater communication has high bit errors, limited bandwidth capacity and high energy consumption. Further because GPS does not work underwater as the radio signals on which it depends cannot penetrate into water, it is non-trivial to obtain the exact location of each node in a UWSN. These issues lead to excessive data retransmission, high energy

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consumption and low packet delivery ratio, which all contribute to the difficulties of designing an efficient and reliable routing protocol for UWSNs.

The routing protocols for UWSNs can be classified into categories of active routing, passive routing and geographic routing [3–5]. A geographic routing protocol is more energy-efficient than an active or passive protocol and thus able to prolong the lifespan of a UWSN as it can reduce flooding by exploiting the location information of sensor nodes, which is getting easier to acquire thanks to the development of localization technology.

The VBF (Vector Based Forwarding) [6] protocol defines a route vector comprising nodes from the source node to the destination node. During a routing process, each node does not save status information; instead it uses a forwarding factor to calculate the suppression time before forwarding is carried out in order to increase network energy efficiency by avoiding unnecessary forwarding, while the routing information is included in each data packet. The data forwarding of VBF is limited to a “virtual pipe”. VBF can take full advantage of the location information for both the source and destination nodes to improve the efficiency of both routing and forwarding, thus saving energy. However, VBF may make local nodes to undertake excessive forwarding tasks, which results in fast energy consumption of these nodes and reduces the lifespan of the sensor network. In addition, the radius of pipe may significantly influence the routing performance.

In DBR (Depth Based Routing) [7], through specialized sensors (such as pressure sensors) that can obtain their own depth information, packets are forwarded from bottom to top with a threshold depth defined to control the efficiency of packet forwarding. The DBR protocol can achieve good performance in dense networks but may cause long transmission delay and high energy consumption in sparse networks.

Clearly the acquisition of location information on sensor nodes is indispensable to geographical routing algorithms. For static networks, nodes are usually deployed at fixed locations and as such the location information is known. However, an UWSN is usually deployed in a dynamic environment where the location information of the nodes has to be provided by a localization algorithm. The nodes on the surface can usually have their position information measured by means of GPS, but the underwater nodes have to be located using measurement algorithms. In Teymorian et al.’s work [8], the authors proposed to transform the three-dimensional underwater sensor network localization problem into its two-dimensional counterpart by using sensor depth information. Cheng et al. [9] proposed a positioning scheme TDOA, a time difference of arrival based localization scheme that does not require synchronizing the time of the nodes. However, a drawback is that it can not locate the nodes that reside outside the enclosed area by four anchor nodes.

This paper presents a novel geographic routing protocol EEL (Energy Efficient Localization-based), which uses location information and residual energy of sensor nodes to greedily forward data packets to sink nodes. Selection of a forwarding node is based on its NADV (Normalized Advancement) determined by its depth difference relative to the sending node and the residual energy of the node. Candidate nodes are sorted according to their NADV, and the node with the highest NADV is selected first to forward data packets. The protocol can periodically update the location information of the nodes in an UWSN and effectively adapt to the dynamic topological changes of the network.

The rest of this paper is organized as follows. Section 2 presents a localization model and a NADV link metric model. Section 3 describes the EEL routing algorithm, followed by its performance evaluation in Sect. 4. Finally, Sect. 5 concludes the paper with a summary of major contributions.

2 Localization and Link Metric Models

2.1 TOA (Time of Arrival) Localization Model

The TOA localization [10] method is widely adopted for the positioning of underwater sensor nodes. It measures distance between nodes and can usually achieve higher positioning accuracy than other methods. TOA ranging is a simple form of communication between two nodes, where a timestamp is placed in each frame. The distance between the nodes is obtained through multiplying the signal transmission time by the average propagation speed of the signal. We assume that the depth information of sensor nodes can be obtained through auxiliary means, such as pressure sensors and as such the three-dimensional underwater sensor node localization problem is reduced to a two-dimensional positioning problem in which only three beacon nodes are required to complete a localization process.

Considering three beacon nodes A, B, and C, their position coordinates are denoted (x_a, y_a, z_a), (x_b, y_b, z_b), and (x_c, y_c, z_c) respectively and their underwater acoustic signal transmission time are denoted Δt_a, Δt_b, and Δt_c respectively. The underwater acoustic signal transmission time Δt is subject to time measurement errors, signal reflection, anti-radiation and other unknown factors. For the sake of simplicity yet without losing generality, we assume that the time measurement error follows a Gauss distribution of zero mean, that is $t_n \sim N(0, \sigma_t^2)$. The time measurement error of nodes A, B and C are denoted t_{na}, t_{nb} and t_{nc}. For node U whose position coordinates are (x_u, y_u, z_u) in which z_u is known through pressure sensors, its location is derived through Eq. (1):.

$$\begin{cases} \sqrt{(x_u - x_a)^2 + (y_u - y_a)^2 + (z_u - z_a)^2} = v(\Delta t_a + t_{na}) \\ \sqrt{(x_u - x_b)^2 + (y_u - y_b)^2 + (z_u - z_b)^2} = v(\Delta t_b + t_{nb}) \\ \sqrt{(x_u - x_c)^2 + (y_u - y_c)^2 + (z_u - z_c)^2} = v(\Delta t_c + t_{nc}) \end{cases} \tag{1}$$

2.2 NADV Link Metric Model

NADV (Normalized Advancement) [11] is a link metric model used in multi-hop wireless networks. The purpose of the NADV model is to find an optimal balance between the proximity of the destination and the cost of the link. In this paper, the link cost is the energy consumed by a node to transmit data, while the proximity to the destination is the distance from a transmitting node to the sink node on the surface.

As shown in Fig. 1, node B has a packet to send to node S, which however is not within B's communication range. Therefore B has to rely on its neighboring nodes to relay the packet. Neighboring nodes A and C are both within B's communication range, so the same energy is consumed by B to send data to A or C. However, as the distance from A to S is shorter than that from C to S, B would choose node A to relay data to destination S in order to reduce the number of data forwarding and consequently minimize the energy consumption in the whole data transmission process. Nonetheless, if node A has a higher transmission error rate than C does, it would be more probable for node B to retransmit lost data, resulting in additional power consumption and consequently high link cost. This scenario particularly illustrates the importance of finding a balance between the proximity of the next hop and the link cost.

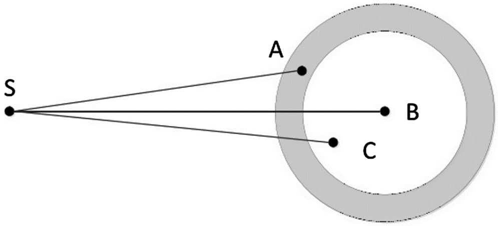

Fig. 1. NADV model diagram

In the NADV model, the distance between the source node B and the neighboring node n relative to the destination node is defined by Eq. (2):

$$\mathrm{ADV}(n) = D(B) - D(n) \tag{2}$$

where D(n) represents the distance from node n to destination node S. The larger ADV(n) is, the closer node n can forward the packet to the target node. Assuming that the link cost from node B to node n is denoted Cost (n), NADV of the neighboring node n represents the distance of transmitting data from node n with one unit energy consumption, which is defined by Eq. (3):

$$\mathrm{NADV} = \frac{ADV(n)}{Cost(n)} \tag{3}$$

Suppose the probability that the data will be successfully passed on to the neighboring node n is., which is calculated using the models described in previous work [11, 12]. If the link cost is expressed by $1/P(n)$, then

$$\mathrm{NADV} = ADV(n) * P(n) \tag{4}$$

3 The EEL Routing Algorithm

In the three-dimensional dynamic network architecture adopted in this paper, the beacon nodes are deployed on the water surface, and their location information is obtained through GPS. The position coordinates of the nodes to be located can be obtained by Eq. (1). According to the different depth of work, location of nodes needs to consider two cases: shallow sea and deep sea. Figure 2 depicts the localization of underwater sensor nodes.

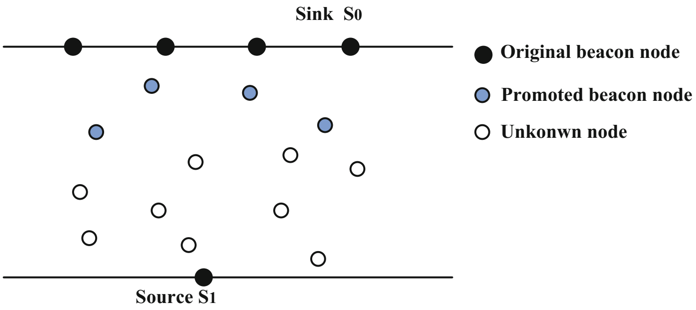

Fig. 2. Schematic diagram of underwater sensor node diffusion localization

When all nodes of a network are working in a shallow sea, any unknown node in the network can communicate directly with at least three beacon nodes to complete its localization. For a node in a deep sea, it has to rely on diffusion localization. In Fig. 2, the original beacon nodes are deployed on the surface of water and periodically broadcast their location information by sending location packets. For an unknown node near the surface of water, its localization starts with the three edge location and after that it becomes a "promoted beacon node". Other unknown nodes carry out localization through original beacon nodes or enhanced beacon nodes before being converted to "promoted beacon nodes". Each beacon node broadcasts its location information to be obtained by an unknown node in the network, which is subsequently transformed into a "beacon node". The localization process proceeds as such until all unknown nodes in the network are identified.

A sensor node can calculate the relative distances between itself and its neighboring nodes through the TOA localization algorithm in order to generate a set of next-hop candidate nodes from which the next hop node is selected for forwarding data packets. In this paper, we improve the NADV algorithm by introducing the residual energy of nodes so that nodes with higher residual energy are more likely to be selected as the next hop, which can balance the energy consumption and extend the lifespan of nodes in the network.

To avoid energy consumed by data wandering between nodes of similar depth, we also define a depth threshold to control the next hop selection as defined in Eq. (5) [13]: if the depth difference is less than the threshold of the neighboring node, only the depth and the depth difference are considered; however if the depth difference is larger than the threshold value of the neighboring node, the residual energy of the node is also considered.

$$\mathrm{ADV}(n) = \begin{cases} |D - D(n)|/R, & |D - D(n)| < \theta \\ |D - D(n)|/R + Energy(n)/E, & |D - D(n)| \geq \theta \end{cases} \tag{5}$$

where D is the depth of the sending node, D(n) is the depth of the neighboring node n, R is the communication radius of the node, θ is the depth threshold, Energy(n) is the residual energy of the neighboring node n, and E is the initial energy of the node. Thus, candidate nodes with higher residual energy have a higher probability to be selected to relay data when they have similar depths. When the neighboring nodes are close to the sending nodes, the distance difference is used as a reference so that short distance relay of data can be avoided as it would generate unnecessary energy consumption. The candidate nodes are sorted according to NADV, and the node with the highest NADV is first selected to forward packets.

4 Simulation Results

To evaluate the performance of the proposed EEL routing algorithm, we compare it with the existing protocols of Flood and VBF using Aqua-Sim [14] as the routing protocol simulator. We randomly deploy 800 sensor nodes in a three-dimensional region of 2000 m * 2000 m * 2000 m and 64 sink nodes at a sea surface region of 2000 m * 2000 m. Each sensor node has an initial energy $E_0 = 100$ J, a transmission range of R = 600 m, a positioning time of 100 s, and a maximum/minimum movement speed of 3 m/s and 0.2 m/s respectively. Assume that the packet size is 100 kB and energy consumption rate of transmitting data is at 60 uJ/bit.

4.1 Effect of the Number of Sink Nodes on Positioning Accuracy

Figure 3 shows the effect of the number of underwater nodes on the average positioning error. With diffusion positioning, unknown nodes may be converted into “promoted beacon nodes” in the process of localization, which consequently increases the intensity of beacons in the network. Therefore, increasing the number of unknown nodes can also improve positioning accuracy. It is worth mentioning that node density may have a negative influence on positioning accuracy, which however is relatively low as compared to the positive influence of beacon intensity.

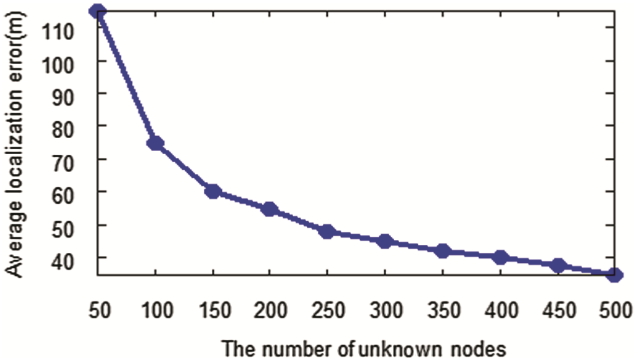

Fig. 3. The influence of the number of underwater nodes on the average localization error

4.2 Packet Delivery Radio

Figure 4 shows the data transfer rate of the three protocols, where the flood routing is optimal, while the packet delivery ratio of EEL is higher than that of the VBF protocol, thanks to the positioning technology used in the protocol. For all the three protocols, with the increase of network nodes, the density of nodes gets higher and as such the distance between nodes becomes shorter, the connectivity rate gets higher, and so does the data delivery rate.

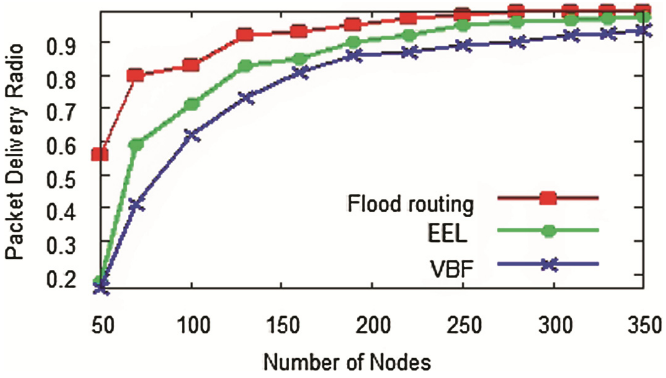

Fig. 4. The influence of the number of nodes on packet delivery radio

4.3 Energy Consumption

As shown in Fig. 5, flood routing has the highest energy consumption, VBF routing performs better than flood routing, while EEL routing performs the best. The total energy consumption in the network includes the energy consumed by the routing process and the energy consumed by the localization process. When the network is sparse, the average energy consumption of the network would be high as the packet delivery rate is low in the routing process and as such the positioning process would dominate the energy consumption. With the increase of the number of nodes in the network, the packet delivery rate in the routing process increases and consequently the average energy consumption decreases. When the number of nodes reaches a certain level, routing instead of positioning becomes dominant in the energy consumption and as such the average energy consumption starts to increase with the number of nodes.

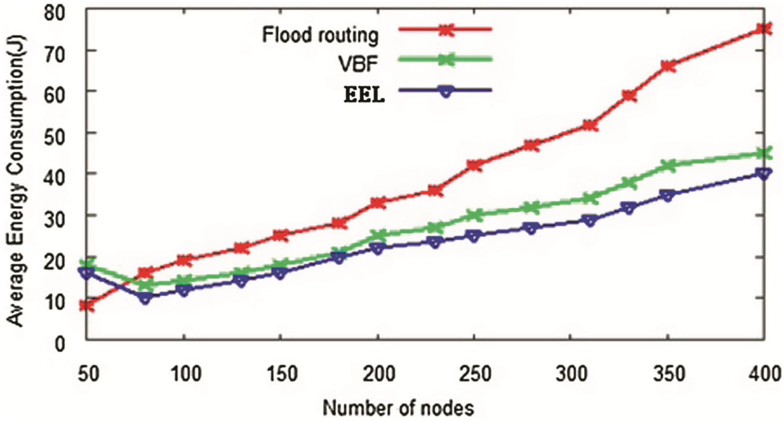

Fig. 5. The influence of the number of nodes on average energy consumption

5 Conclusion

The location and routing issues are two major challenges for UWSNs. In this paper, we have proposed a novel routing protocol EEL using geographic and location information of nodes in a UWSN. Considering the three-dimensional dynamic UWSNs, we have combined these two aspects to design the routing protocol. During the localization process, the diffusion localization can effectively locate the nodes in UWSNs. During the routing process, EEL uses a new greedy approach to deliver packets to sink nodes, thus improving data transmission ratio and reducing energy consumption. However, high energy consumption is a drawback of this algorithm. As future work, we intend to investigate other important geographic routing features, such as average end-to-end delay and average number of candidates, in order to improve the performance of EEL.

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