

A Low Propagation Delay Multi-Path Routing Protocol for Underwater Sensor Networks

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Abstract

The large-scale mobile Underwater Wireless Sensor Network (UWSN) is a useful networking paradigm to explore underwater environments. The characteristics of mobile UWSNs, such as low communication bandwidth, large propagation delay, and floating node mobility are significantly different from wireless sensor networks. In this paper, we propose a new efficient routing protocol, called multi-path routing (MPR) protocol, for UWSNs to improve the transmission delay. Multi-path is utilized during the path construction from the source node to the destination node, which is composed of a series of multi-subpaths. Each multi-subpath is a sub-path from a sending node to its two-hop neighboring node, called receiving node, by one more relay nodes, where these relay nodes simultaneously are neighboring nodes of sending and receiving nodes. Due to the different propagation delay of UWSN, the packet arrival time along the different sub-path is different; thus it may avoid the data collision in the receiving node when receiving different packets from different relay nodes. It surely sends the different packet along different sub-path to significantly improve delay time and packet delivery ratio. Finally, simulation results illustrate the performance achievements of the MPR protocol in improving delay time, packet delivery ratio, throughput and reducing overhead ratio.

Keywords: Underwater wireless sensor network, multi-path, relay, propagation delay, routing.

1 Introduction

UWSN[1] is rapidly increasing interest from scientist and business group, because there are large resources in the sea. As we know, human are not suitable for underwater environment exploration and

deployments cost in underwater based networks is much higher than terrestrial based networks. Typically communicate in UWSN spend about ten thousand dollar. Large surface and deep height result in underwater equipment sparsely deployed [9]. In the past three decade, most applications of UWSN are usually applied for undersea exploration. The UWSN is used to extracting oil or detecting reservoirs from underwater [3]. It is a long-term exploration and typically spends many years to discover resources. For the application of the pollution monitoring, the UWSN also uses for disaster prevention, such as tsunami warning or seaquakes investigation. Besides, the military reconnaissance is also an important application for UWSN. The Navy uses UWSN to perform anti-submarine mission because submarines and mines always cause seriously damage [3].

In the wireless sensor network (WSN) [2], sensor nodes are only restricted to work in low power consumption for power saving. However, the UWSN has more restrictions because of intrinsic properties. The first is the propagation delay. The propagation speed in water (1.5×10^3 m/s) is lower than radio propagation speed (3×10^8 m/s)[13]. Second, the power consumption for underwater WHOI modem and RF sensor is listed in [10]. Underwater sensor nodes mainly use battery power. It is a difficult task to change the battery for sensor node in underwater. The energy efficient communication protocol designing is an important issue to extend the network lifetime. The third is sensor node mobility. The sensor nodes in the WSN are typically static. On the other side, sensor nodes in UWSN usually move at the speed of 3-6 km/h in typical underwater condition due to ocean current [9]. The fourth is the error probability of acoustic channel. Sound propagation is primarily determined by noise, transmission loss, multi-path and Doppler spread. Noise can be classified as man-made noise and ambient noise.

Man-made noise is mainly caused by machinery noise and shipping activity [9]. Ambient noise is related with the background sustained noise emanating from lots of unidentified sources. The level of underwater ambient noise may have large variations upon a change location, time or depth. Finally, Doppler spreading causes degradation in the performance of digital communications. Moreover, transmissions at a high data rate cause many adjacent symbols interferences at the receiver.

As mentioned earlier, many intrinsic properties of acoustic channel are harmful transmission process, such as the long propagation delay; therefore, routing protocols for WSNs can not directly apply to UWSNs. In this paper, we propose a new protocol, called multi-path routing (MPR) protocol, for time efficient, network lifetime extending and scalability in UWSNs. In this work, all the nodes send the data to surface sink when they detect an event in water. Source node divides the data packet into several time slots based on the bandwidth. Then source node uses two-hop transmission scheme to transmit data packet to relay nodes. The contribution of this work is to minimize propagation delay. When a relay node receives packet, it checks transmission scheduling to detect whether there is a collision with other nodes. If there is a collision, the relay node defers appropriate time slots to avoid collision. Otherwise, the relay node transmits packets to the destination.

The rest of this paper is organized as follows. Section 2 reviews related works. Section 3 define the architecture model, channel characteristics, and describes the basic idea of our scheme. Section 4 present the MPR protocol, performance analysis is discussed in section 5. Finally, section 6 concludes this paper.

2 Related Works

Existing routing protocols on the terrestrial-based sensor network are classified into proactive routing protocols, reactive routing protocols, and geographical routing protocols. As mentioned above, terrestrial-based routing protocols are unsuitable for UWSN because they focus on stationary networks and incur long delay time and vast initial flooding overhead. In addition, GPS (Global Positioning System) does not work accurately in UWSN. Recently, some routing protocols are specifically designing for UWSN, which are divided into three major types of routing protocol for UWSN as follows:

Lee *et al.* [11] proposed a new architecture to use large number of unmanned low-cost sensor node to

locally monitor and report non-accessible underwater event in real time. Author proposed a UWD (Under Water Diffusion) which uses no proactive routing message exchange. Lee *et al.* exploit dynamic unicast-based path management technique to reduce on demand flooding and random node mobility.

Gopi *et al.* [8] proposed a PLURP (Path aware Layered Routing Protocol for underwater sensor networks), a novel on the fly routing algorithm. To solve multipath or loss of connectivity problem, PULRP find the path on the fly because it does not need much information such as fixed routing table, localization synchronization process etc. First, source send the PULRP use flooding message to find the next hop to transmit packet in next layer, the optimal next hop decide by sensor node residual energy.

Domingo *et al.* [5] proposed a GPS free clustering scheme for underwater routing protocol, while GPS system is unsuitable in underwater environment. In this system, assume all the sensor node always has data transmit to sink. Every sensor node first use the self battery information to estimate whether it could become cluster head and each non-cluster head decides to which cluster it belongs by choosing the cluster head that required the minimum communication energy. Time compensating technique solve that underwater communications in different cluster member could overlap message at the cluster head due to long propagation delay, only cluster head can compute this value. Once cluster get all information, it start to arrange member transmission order by propagation delay.

Seah *et al.* [17] developed multipath virtual sink architecture for harsh underwater environment. To solve the bottlenecks happen around the sink node region, including sensor node, because they are usually transmission data. In this architecture the author propose a virtual sink, which sensor node can transmit data to one or more sink to increasing reliability and consider as retransmitting a packet simultaneously instead of sequentially. Besides, use of spatially diverse paths also reduces the probability of contention. In this scheme each node can record it received the hop count update, therefore, a node send can send packet any one of sink nodes that it is connected to.

Xie *et al.* [19], proposed a vector based forwarding protocol. The entire sensor nodes know the surface sink position, it can be seen that forwarding process is building a routing pipe, which call the routing vector. Each packet carries the position of the sender, forwarder and target. The packet forwarding is according to the path between the source and the target. Because the limitation of sensor node transmission range, only the sensor nodes that are

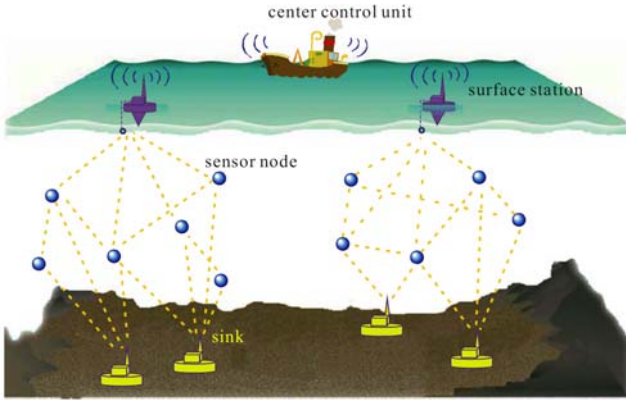


Figure 1: System model

within a range R of the vector will forward packet. Every possible forwarder node estimates the desirability factor to decide suitability to be a forwarder node and this factor can achieve energy, multi path elimination. Nicolaou *et al.* proposed HH-VBF in [14] overcome two major problems in [19]. First, due to a single pipe between source and destination, cause too small data delivery ratio for space networks. Second, because limitation of pipe radius, too sensitive to routing pipe radius threshold. In this paper, authors propose every node has its own routing pipe; the maximum pipe radius is the transmission range. In sparse networks, HH-VBF can find a data delivery path as long as there exists one in the network, in other words, it increasing data delivery ratio in sparse network than VBF.

3 Preliminary

This section presents the system model, contribution and application examples.

3.1 System Model

The architecture of UWSN is illustrated in Fig. 1. The underwater sink node is fixed on ocean floor by anchors or random deployed in an arbitrary location. All of them communicate with each other by using acoustic signals and transmit data through multi-hop routing or direct link to the buoys (i.e. surface station). In addition, they must be able to self-configure to adapt the harsh ocean environment. Underwater sensor nodes are equipped with a limited battery, stay at a certain depth and drift with ocean currents. Buoys are drifting on sea surface and relay the underwater sensor node data to the center control unit (i.e. ship). The function of buoy acts as a gateway between acoustic networks and radio frequency (RF) networks. Precisely, buoys use acoustic signal to collect underwater sensor nodes data and use radio frequency signal to transmit these data to the center control unit or satellite through RF. Mobile equip-

ment under sea surface is an autonomous underwater vehicle (AUV). The capability of AUV includes: (1) An AUV covers large area than static underwater sensor nodes in underwater environment. (2) AUV traveling from node to node crosses all underwater networks like a data mule. When an AUV is deployed in underwater, the center control unit initiates AUV and assigns the task. After that AUV performs the task, the AUV periodically sends report which contains ID, location and underwater information to the center control unit.

3.2 Acoustic Channel Characteristics

The ocean is a timely and spatially varies environment and the characteristics of this environment causes significant challenges to the effective underwater wireless communications systems [20]. The speed in water is increasing with increasing temperature, salinity and depth, directly related to pressure. When the sound speed increases 4 m/s then water temperature arising A_0 . When salinity increases 1 PSU, the sound speed in water increases 1.4 m/s and depth of water increases 1 km, the sound speed increases about 17 m/s [12]. A typical speed of sound in water the ocean surface is near about 1500 m/s to 1520 m/s. The change of temperature is most reason that changes speed of sound in water. This is because salinity effect on sound speed is small. As depth increasing, the pressure of water suffers largest effect on the speed of sound. Such slow propagation speed in water environment cause hardly to deal with mobile sensor node and network topology changes very rapidly. In this paper, we aim at designing a time efficient routing algorithm. Attenuation or path loss occurs over a distance d for a signal frequency f , which is given by [18]:

$$A(d, f) = A_0 d^k a(f)^d \quad (1)$$

where A_0 is the normalizing constant and s is the spreading factor. While $s = 2$ for spherical spreading, $k = 1$ for cylindrical and $k = 1.5$ for the so-called practical spreading. In the water transmission, wave energy may be converted to other forms and absorbed by the medium. The material imperfection is directly controlled by the absorptive energy loss [16]:

$$a(f) = A_1 \frac{P_1 f_1 f^2}{f_1^2 + f^2} + A_2 \frac{P_2 f_2 f^2}{f_2^2 + f^2} + A_3 P_3 f^2 \quad (2)$$

The absorptive energy loss is expressed in dB/km with f in kHz. A_1 , A_2 , and A_3 are constants; the pressure dependences are given by parameters P_1 , P_2 , and P_3 . The relaxation frequencies f_1 and f_2 are

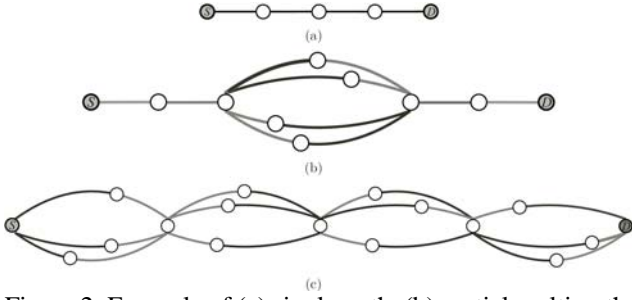


Figure 2: Example of (a) single-path, (b) partial multi-path, and (c) multi-path

described for relaxation process in boric acid and magnesium sulphate, respectively.

3.3 Basic Idea and Challenge

In this section, we introduce the characteristics for (1) single-path and multi-path scheme and (2) sensor nodes affected by ocean current. In Fig. 2, let S denote as the source node, D denotes the destination node. The other nodes are relay node. As shown in Fig. 2(a), there is only one single path between any two nodes. Although the scheme may simplify the routing table and a packet flow path, but single-path is not fault tolerant. In underwater environment, because the propagation delay in any two nodes are different, sensor nodes carry half-duplex omni-directional transceivers and use single-path transmission, In addition, it wastes time for transmission. For multi-path scheme, there are two ways, one is partial as shown in Fig. 2(b) and the other is full multi-path as shown in Fig. 2(c), where there exist multiple paths between source node and destination node. There are two advantages for the multi-path scheme. First, the packet drop rate is decreased and achieved load balancing because data load is distributed over multiple paths. In addition, multi-path increases the battery lifetimes. Second, high network robustness is achieved because multiple same packets are sent by multiple paths [4][7][9]. There two types of multi-path, namely, non-disjoint paths and disjoint paths. Disjoint paths can further classify in two types: node-disjoint paths and link disjoint paths. For the node disjoint paths, they do not use common nodes. For the path disjoint paths, they do not use common links.

In our work, we consider the multi-path routing protocol in UWSN. In Fig. 3, an example for MPR to compare with VBF and H-H VBF [19][14]. Let S denote source node, R_1 , R_2 , and R_3 denote relay nodes, D denotes destination node. Although the route of VBF [19] is similar to trajectory-based forwarding path, each node must know its position and the sink position to construct radius pipe. In

addition every forwarder (i.e. the relay node) needs to use self-adaptation algorithm to minimize node energy consumption and decide next hop transmission. Thus, it wastes many time slots, especially for underwater environment. In Fig. 3(a), VBF increases time slot for self-adaptation algorithm T_{ad} . VBF uses single path to transmit data packet. Assume that source node S chooses R_1 to be forwarder. The path between S and R_1 costs one time slot, and the path between R_1 and D costs three time slots. In single path transmission, each node should wait the entire packet arrived due to half duplex property. Then nodes can transmit to next forwarder. Thus, it increases more delay time for transmission process. In HH-VBF[14], every node owns its pipe. When a receiver receives a packet from the source node or a forwarder, it computes the vector from the sender to the sink. In this way the forwarding pipe change each hop in the network, which call hop-by-hop vector based forwarding. After computing the vector, receiver calculates its distance to that vector. In Fig. 3(b), let CV denote compute vector from source or sender to sink, CDV denote compute the distance to the vector. After that, HH-VBF also use the self-adaptation algorithm T_{ad} qualifies as a candidate forwarder. We also assume we assume source node S choice R_1 be forwarder and observe in Fig. 3(b) HH-VBF need more time to transmit data packet than VBF. In MPR protocol, the multi-path transmission is used by source, relay and destination node. Every data packet is transmitted by different path to different relay nodes. After receiving a data packet, it transmits the packet to next hop in next time slot. In Fig. 3(a), we assume there are three packets the first packet assigned for R_1 and second packet assigned for R_2 , the third packet assigned for R_3 . Once these three relay nodes receive data packets, they send them out in next time slot immediately. Besides, MPR does not need extra information before transmit data packet. As shows in Fig. 3(b), MPR use less time than VBF and HH-VBF.

Here we describe for single-path and multi-path scheme about transmission efficiency. In order to discuss data transmission time precisely, the data have to divide into proper time slot. According to the network bandwidth, the time slot requirement (TSR) can be written as:

$$Time\ Slot\ Requirement(TSR) = \frac{Mount\ of\ data}{Bandwidth\ of\ each\ slot} \quad (3)$$

For the single-path scheme, each node can not receive and send the data at the same time because of its half duplex property.

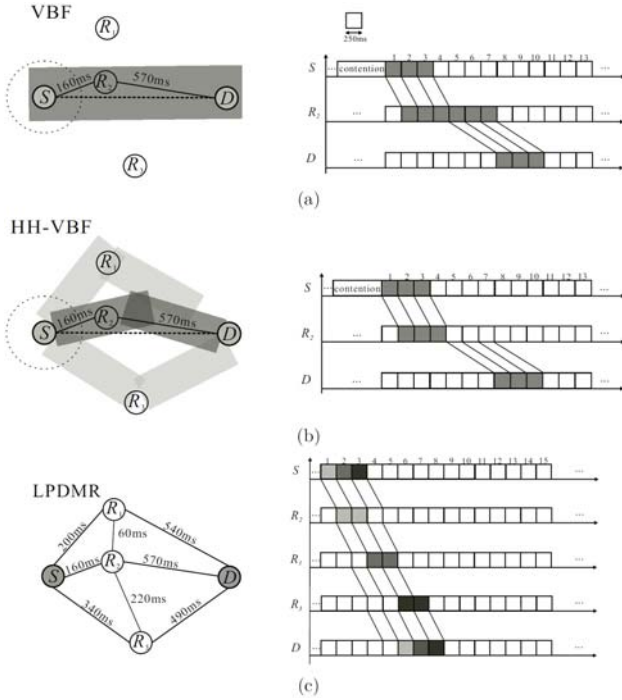


Figure 3: Comparison of time slot (a) VBF, (b) HH-VBF, (c) MPR

Thus it costs large time consumption, as shown in Fig. 3(a). The single-path transmission time slot can be expressed as:

$$\text{Total Time Slot for Single-Path} = \frac{\text{Mount of data}}{\text{Bandwidth of each slot}} \times \text{Number of relay} + \text{Propagation delay} \quad (4)$$

For example, assume that there are three packets, two relay nodes and each path delay costs one time slot, total time slot consumption is $3 \times 2 + 3 = 9$. For the multi-path scheme, the MPR protocol uses more than sensor node to assist transmission. Consequently, data packets distributed into different time slot and thus it reduces the transmission time. The advantage of this way can reduce transmission time. The multi-path transmission time slot can be expressed as:

$$\text{Total Time Slot for Multi-Path} = \frac{\text{Mount of data}}{\text{Bandwidth of each slot}} + \left(\lceil \frac{\text{TSR}}{\text{Number of relay}} \rceil - i \right) + \text{Propagation delay} \quad (5)$$

Where i is a parameter which use for when number of relay large than number of time slot requirement and dependent on the value of time slot requirement divide number of relay. When value i equal to 0, it means that use number of relay equal to number of time slot requirement. In order to compare time efficiency for two scheme for index $I_{efficiency}$. We have to show how multi-path could cost less time consumption than single-path, first we have to know the scale that total time slot of multi-path link on total time slot of single link, then consider the relation

Table 1: Comparison of single-path and multi-path efficiency

Length of Time Slot	31.25ms	62.5ms
Total Time Slot for Single-Path	106	53
Total Time Slot for Multi-Path	56	28
Index of Efficiency $I_{efficiency}$	86%	176.4%

between length of time slot and maximum propagation delay:

$$I_{efficiency} = \frac{\text{Total time slot}_{single link}}{\text{Total time slot}_{multi link}} \times \frac{\text{Length of time slot}}{\frac{\text{Maximum Tx range}}{\text{Velocity of acoustic}}} \quad (6)$$

Here we use an example for different two different time slot length, assume that velocity of acoustic is 1500 m/s. In this example, source node transmit 1Mbytes, use the short transmission range which is 200 m [3], length of time slot is 31.25 m/s and 62.5 m/s [16], bandwidth is 20 kHz propagation delay is 6 time slot and number of relay equal to number of TSR for multi-path scheme. We have to discuss whether time slot is effect transmission delay in the underwater network system, the result shown in Table 1.

The ocean current is most reason cause sensor node drift in ocean. Ocean waters move continuously. The speed of these current varies based on the gyres, or currents that are kept in motion by prevailing winds. Each gyre consists of four currents. Whereas speeds of surface currents can reach as high as 250 cm/sec (98 in/sec, or 5.6 mph) a maximum for the Gulf Stream, speeds of deep currents vary from 2 to 10 cm/sec (0.8 to 4 in/sec) or less [15]. VBF and HH-VBF base on vector that construct in initial flooding query to decide next forwarder. In this way, when a node measure the vector to decide whether if proper to forward packet, its affect by the position. In addition, pipe radius range also affects the number of candidate forwarder. In surface area, if pipe radius too small, it difficult to find the forwarder. But in MPR, source node find forwarder did not any restriction. Although it also suffers the ocean current, but after sensor nodes drift at next position, nodes still in transmission range. For example, assume two relay node transmission delay is 500 ms and nodes at surface, we can estimate drift distance is $500\text{ms} \times 2.5\text{m/s} \times 2 = 2.5\text{m}$. Clearly, MPR not affected by the ocean current in short transmission, as shown in Fig. 4.

3.4 Contribution

In this paper, multi-path scheme and multi-sequence transmission of approaching is

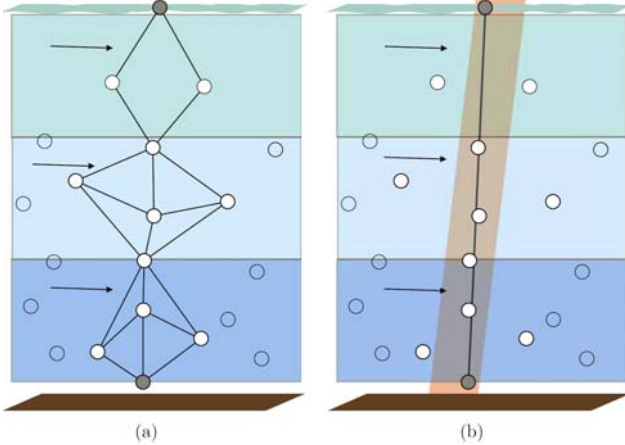


Figure 4: Ocean current affect of (a) MPR and (b) VBF

proposed to efficient in underwater network transmission. It overcome propagation delay seriously in underwater environment. In existing investigations, single-path scheme waste more time to transmission cause ineffective network. The contributions are sum-marized as follows: (1) our MPR protocol achives a new low propagation delay routing protocol to transmission, which use multi-path scheme to transmission packets; (2) every node only need to get two hop information which to adapt rapid change network topology environment; (3) our MPR protocol can reduce end-to-end propagation delay form source node to destination node because every packet distributed sanded by different path.

4 A Multi-Path Routing Protocol

In this section, we describe how MPR work efficiently in underwater environment. The MPR consist of three phases: (1) propagation delay collection phase (2) intermediate node selection phase and (3) relay node selection phase. In first phase, since routing path is determined by propagation delay, so the source node needs to know the two hop delay information from its to neighbor node and form neighbor node to next hop node. In relay node selection phase, node use propagation delay information to decide which node is intermediate node I . The third phase source check all the relay nodes whether if occur the collision each other. The detailed operation is developed as follows.

4.1 Propagation Delay Collection Phase

In order to against long propagation delay and find the routing path is difficulty problem in underwater environment. Thus find the maximum amount path in this phase. The UWSN is not like the existing one for

Ad-Hoc networks, the moving model for UWSN is either meandering jet or captured to eddy keeps the sensor around same place [6]. Assume that sensor nodes drift in same way thus each node only needs two-hop propagation delay information as shown in Figure 4 to illustrate this phase. The procedure of the propagation delay collection phase is described below.

- S1. The node sets itself as source node S when wants to transmit to data packet. S first sends $RREQ$ packet to one hop neighbor nodes. The reason that S sends $RREQ$ packet is it want to get propagation delay between S and neighbor nodes. There are three fields in $RREQ$ packet to record the time when $RREQ$ packet been sent and received. $PTSR_i$, the propagation delay between S and relay node R_i . $PTRI_i$, the propagation delay between relay node R_i and intermediate candidate node I_c . $PDT_{i,j}$, the total propagation delay form S to I_c , as shown in Fig. 5(a).
- S2. After receiving the $RREQ$ packet from S , relay node R_i for $i = 1 \dots n$ calculates the $PTSR_i$. When each neighbor node receives the $RREQ$ packet, it set $Relay_i$ itself and calculate the $PSRT_i$, the propagation time between S and R_i , as shown in Fig. 5 (a). Second, R_i continues sending the $RREQ$ packet to find the second hop relay node (i.e. intermediate candidate node I_c).
- S3. When the second hop relay nodes (i.e. I_c) receive $RREQ$ packet from R_i , each I_{c_j} calculate the $PTRI_i$. After that, it calculate $PT_{i,j}$ (i.e. $PTSR_i + PTRI_j$). In other hand, each R_i send hello message to neighbor node to get delay time between them and discard each other $RREQ$ packet, as shown in Fig. 5 (b).
- S4. Finally, I_c transmits the $RREP$ packet with $PDT_{i,j}$ back to S , as shown in Fig. 5 (c).

4.2 Intermediate Candidate Node Selection Phase

In this phase, source node S plays an important role due to it has to decide only one I_k in among of intermediate candidate nodes I_{c_j} for form tow hop transmission pattern, for $k = 1 \dots 2026n$. Since S acquire all the propagation information in first phase, S uses two hop count propagation delay information to decide intermediate node. We assume all the node

including surface sink know its position for help to get the distance form relay node to surface sink. The procedure of the intermediate node selection phase is described below.

- S1. S sorts all $PDT_{i,j}$ that collect in the propagation delay collection phase.
- S2. S uses TTL ($TTL = \frac{2hop\ propagation\ delay}{acoustic\ velocity}$) to compare each $PDT_{i,j}$. If there are nodes' $PDT_{i,j}$ equal to TTL or $PDT_{i,j}$ near to TTL , S select these nodes.
- S3. S evaluates which the nodes (i.e. selected by Step 2.) are most closed to destination node by the position in $RREP$.
- S4. The node fit in with above condition be selected as intermediate node candidate, we call it as Ic_j , for $j = 1 \dots n$.

In Fig. 6, S set TTL is 500ms and sort all the $PDT_{i,j}$ been collected. Then S select equal to TTL of $PDK_{i,j}$. In addition, S evaluate these nodes which most close destination node D . In this case $PDT_{i,3}$ for $i = 1 \dots 4$ equal to TTL , and $PDT_{i,1}$ for $i = 1 \dots 2$, $PDT_{i,2}$ for $i = 1 \dots 3$ and $PDT_{i,4}$ for $i = 3 \dots 4$ close to TTL . Then S selects these nodes to be intermediate candidate node Ic_j .

4.3 Intermediate Node and Rely Node Selection Phase

In intermediate node selection phase, S select one intermediate node among these candidate Ic_j . S select the Ic which use the minimum time slot that can reach to candidate Ic_j and every R_i can communicate that Ic_j . In Fig. 7, S select Ic_3 to be intermediate node due to it can communicate with each R_i .

There are two type of collision problem in the MPR protocol : (1) relay node collision and (2) intermediate node collision. Before assign packet to relay node for transmission, S has to void these two problems. In relay node collision, relay node R_i collide with relay node another relay node R_j for $i \neq j$. The intermediate node collision, relay node R_i collide with intermediate node I . In this phase S check the entire relay node whether if occur collision in two hop node pattern. If there is a relay node R_i collide with other node (i.e. relay node or intermediate node), then S drop this R_i and select other to

transmit packet. We describe two collisions as follow.

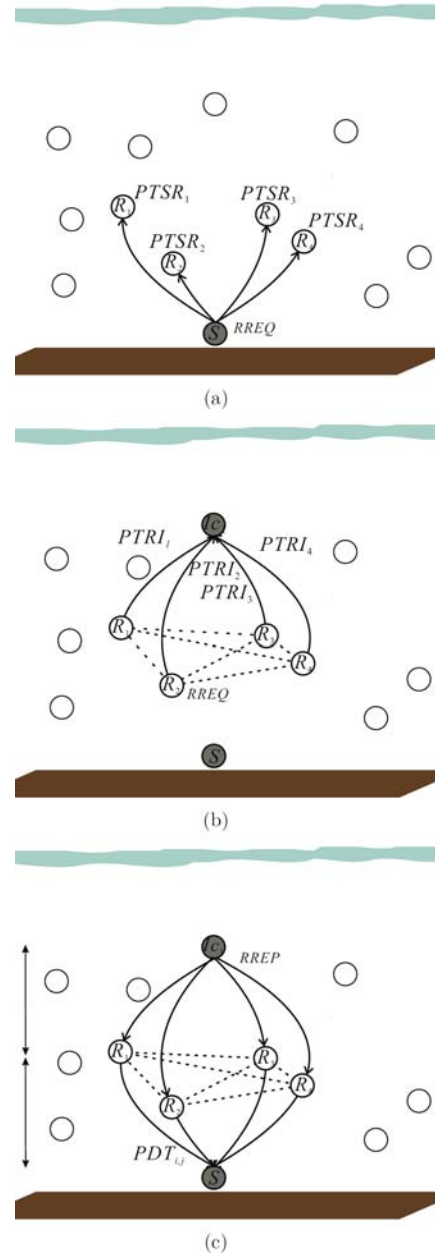


Figure 5: Propagation delay collection

- S1. After S collect all two hop transmission delay information, including between S and R_i propagation delay, between R_i and R_j propagation delay, for $i \neq j$ and between R_i and I propagation delay. Thus S knows information $(R_i, PT_{i,j}, R_i \in N(R_j))$, which represent node ID, propagation delay and belong to which neighbor.

S2. S creates three matrix :

$$SR_i = \begin{bmatrix} TS_{R_1} \\ TS_{R_2} \\ \vdots \\ TS_{R_i} \end{bmatrix} + \begin{bmatrix} PT_{SR_1} \\ PT_{SR_2} \\ \vdots \\ PT_{SR_i} \end{bmatrix} = \begin{bmatrix} P_{SR_1} \\ P_{SR_2} \\ \vdots \\ P_{SR_i} \end{bmatrix},$$

where TS_{R_i} is time stamp for S transmit packet

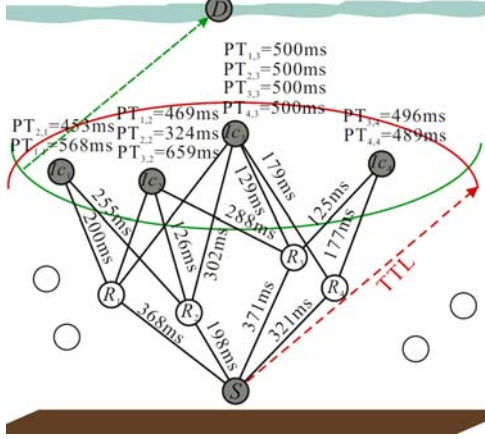


Figure 6: Intermediate candidate node selection

S3. to R_i , PT_{SR_i} is propagation delay form S to R_i .

(2) R_i to R_j propagation matrix

$$R_i R_j = \begin{bmatrix} TS_{R_i R_1} \\ TS_{R_i R_2} \\ \vdots \\ TS_{R_i R_j} \end{bmatrix} + \begin{bmatrix} PT_{R_i R_1} \\ PT_{R_i R_2} \\ \vdots \\ PT_{R_i R_j} \end{bmatrix} = \begin{bmatrix} P_{R_i R_j} \\ P_{R_i R_j} \\ \vdots \\ P_{R_i R_j} \end{bmatrix} \text{ for}$$

$i \neq j$, where $TS_{R_i R_j}$ is time stamp for R_i transmit packet to R_j , $PT_{R_i R_j}$ is propagation delay form R_i to R_j . (3) R_i to I propagation matrix

$$R_i I = \begin{bmatrix} TS_{R_i I} \\ TS_{R_2 I} \\ \vdots \\ TS_{R_i I} \end{bmatrix} + \begin{bmatrix} PT_{R_i I} \\ PT_{R_2 I} \\ \vdots \\ PT_{R_i I} \end{bmatrix} = \begin{bmatrix} P_{R_i I} \\ P_{R_2 I} \\ \vdots \\ P_{R_i I} \end{bmatrix},$$

where $TS_{R_i I}$ is time stamp for R_i transmit packet to I , $PT_{R_i I}$ is propagation delay form R_i to I .

S4. S check SR_i and $R_i R_j$ matrix, if $[P_{SR_i}] - [P_{R_i R_j}] = 0 | i = 1 \dots n$, then the relay node collision detected. S drop that R_i own the longer propagation delay one.

S5. S check $R_i R_j$ and $R_i I$ matrix, if $[P_{R_i I}] - [P_{R_i R_j}] = 0 | i = 1 \dots n$, then the intermediate node collision detected. S drop that R_i own the longer propagation delay one.

In Fig4.3, we give an example to check two collision problems. After S get all the propagation delay information and decide the intermediate node, S transforms the propagation delay into time slot. In

addition, S calculates SR_i , $R_i R_j$ and $R_i I$ tables and use $[P_{SR_i}] - [P_{R_i R_j}] = 0 | i = 1 \dots n$ to check the relay node to relay node collision. Now, S get

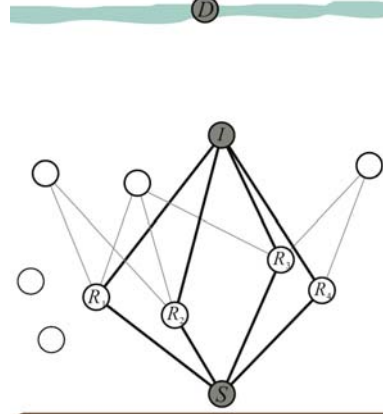


Figure 7: Intermediate node selection

$$R_1 R_j - SR = \begin{bmatrix} NULL \\ 0 \\ 3 \\ 3 \\ 3 \end{bmatrix}, \quad R_2 R_j - SR - i = \begin{bmatrix} 4 \\ NULL \\ 2 \\ 2 \\ 4 \end{bmatrix},$$

$$R_3 R_j - SR_i = \begin{bmatrix} 8 \\ 5 \\ NULL \\ 1 \\ 2 \end{bmatrix}, \quad R_4 R_j - SR_i = \begin{bmatrix} 8 \\ 5 \\ NULL \\ 1 \\ 2 \end{bmatrix},$$

$$R_5 R_j - SR_i = \begin{bmatrix} 14 \\ 11 \\ 7 \\ 5 \\ NULL \end{bmatrix} \quad \text{and} \quad [P_{R_1 R_2}] - [P_{SR_1}] = 0$$

Then S know R_1 and R_2 could collide at time slot 5. S drop the R_2 because R_2 use more time slot than R_1 , as shown in Fig. 8 (a) and (b). After checking relay and relay node procedure, S use $[P_{R_i I}] - [P_{R_i R_j}] = 0 | i = 1 \dots n$ to check relay and intermediate node collision. Now, S get

$$R_4 R_j - R_i I = \begin{bmatrix} 7 \\ NULL \\ -1 \\ NULL \\ 0 \end{bmatrix} \quad \text{and} \quad [P_{R_4 R_5}] - [P_{R_i I}] = 0.$$

Then S knows R_4 and R_5 could collide at time slot 11. S drops the R_5 because R_5 use more time slot than R_4 . S drop two relay node in collision problem checking, as shown in Fig. 8 (c) and (d) After checking all collision problem, S reassign the packet to R_1 , R_3 and R_4 . R_1 get the first packet at time slot 3, R_3 get the second packet at time slot 6 and R_4 get the third packet at time slot 7. Finally, I get first packet at the time slot 6, second packet at the time slot 10 and third packet at the time slot 11.

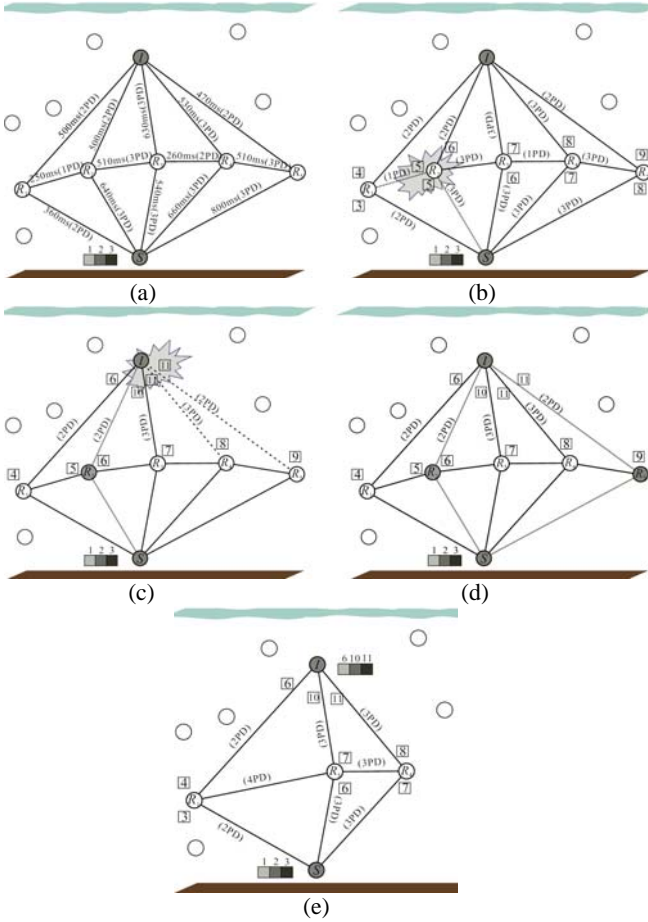


Figure 8: Relay node selection

In Fig. 9 gives an example to illustrate MPR, there are three packets sent form source node. S sends $RREQ$ message to neighbor nodes to get the propagation delay information, then qualified neighbor nodes set relay node R_i (R_1, R_2 and R_3) itself and send another $RREQ$ packets to their neighbor nodes. Each node receives $RREQ$ packet form relay node and sends $RREP$ back to S to complete propagation delay collection phase. When S collects all the delay information and selects the I_1 , then checks the collection problem. After checked collision problem, S sends first data packet to R_1 , second packet to R_2 and third data packet to R_3 . Each data packet occupies 250ms time slot, first data packet sent at time slot 1 and received at time slot 2, second data packet sent at time slot 2 and received at time slot 3, third data packet sent at time slot 3 and received at time slot 5. Similarly, intermediate node I_1 does the same selection process and checks collision process as well as source node S . Finally, destination node D received packet orderly, the data packet received at time slot 6, 7, 8 respectively.

5 Performance Analysis

MPR protocol is performed an analysis in terms of end-to-end delay, successful rate, throughput and overhead. Based on NS-2, we implement and modify our simulation using underwater module [19]. To consider the effect of the network density and node velocity do a UWSN, our simulator consider a 3-Dimensional space of 2000m x 2000m x 500m; The source is fixed at location (1850, 1850, 550) near corner at the floor. Sink is located at location (500, 500, 250) near the opposite corner at the surface. All the nodes are mobile which affect by the water current, only the source and the surface sink are static. Mobile nodes move in X-plane and Y-plane in common mobility pattern. We set the parameters similar to a commercial acoustic modem, Link Quest UWM 1000: the bit rate is 10kbps; the transmission range is 100m and the energy consumptions in sending mode, receiving mode and idle mode are $2w$, $0.75w$ and $8mw$ respectively. The result is obtained from 100 runs, with a randomly generated topology in each run. The simulation time for each round is 1000 seconds. The performance metrics to be observed are:

- *End-to-End Delay with ocean current* (ETEDOC) is given by the time taken for a packet to reach the node with ocean current.
- *Packet deliver ratio* (PDR) is the percentage of node successfully receive the packet at vary node speed and node density.
- *Throughput* is the total number of data packets which node by the source.
- *Overhead ratio* is the total number control of packets used.

An efficient multi-path protocol in a UWSN is achieved with a low ETED, high DSR, low TP and

Table 2: Network parameters

Variable	Description
Transmission range	100m
Bit rates	40kbps
Data packet size	35bytes
Control packet size	4bytes
Time slot length	200ms
Pipe radius	50m

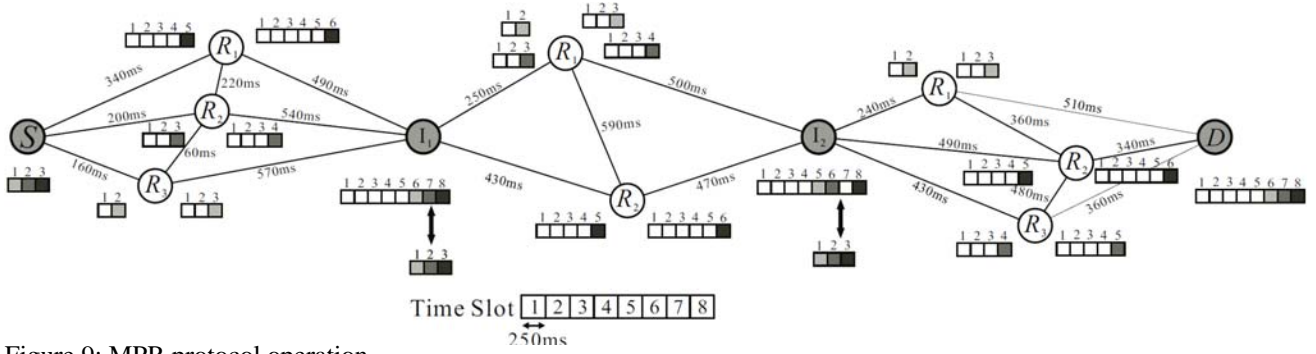


Figure 9: MPR protocol operation

low POR. The parameters of these three protocols are presented in Table 2.

5.1 End-to-End Delay with ocean current

The simulation results of the ETED under various node velocities in different depth of ocean are shown in Fig. 10. We set the deepest of ocean is 500m with node velocity is 1.0m/s, and top of ocean is near 50m with node velocity is 2.5m/s. In addition, in every 100m is the junction ocean current, there are four junctions in this simulation, as shown in Fig. 10(a). We can observe that ETEDOC (End-to-End Delay with ocean current) of the MPR, VBF and HH-VBF is decreasing with ocean of depth. VBF protocol uses single pipe to forward packet, cost large delay in this scene, especially at ocean surface. VBF and HH-VBF affected seriously delay time. These two protocols according to vector to decide next forwarder, the node position is very important, once node leave the position it could not be find any forwarder or it not be forwarder. For VBF and HH-VBF, when the pipe radius is big, the ETEDOC reduce for node mobility. In the ocean of bottom, the ocean current affects nodes mobility. MPR use multi-path scheme, two-hop transmission and did not perform the self-adaption algorithm, it can reduce the transmission time delay. In addition, MPR did not use any pipe or vector, although it also affected by ocean current, but the ETEDOC is better than VBF and HH-VBF.

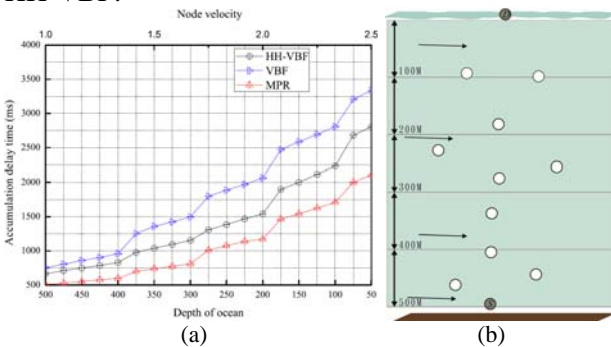


Figure 10: Performance of end-to-end delay with ocean current

5.2 Packet Delivery Ratio

The simulation results of the PDR under various node speed and node density are shown in Fig. 11. In Fig. 11 (a) MPR, VBF and HH-VBF scheme increases PDR with higher network density. We can observe that for VBF and HH-VBF when the nodes closer to the routing vector can forward packets and own low adaption delay. At high node densities, there are too many nodes want forward packet cause large number of collision and decrease the PDR. For MPR, PDR is low in the spare node density, because it hard to find the path in the underwater environment. In high node density, node can find more forwarding path; besides the different packet distributed into different path, thus the collision can be decreased. In Fig. 11 (b), even though drift velocity is slow, it still impact on VBF, HH-VBF and MPR. For VBF, mobility can help increasing successful rate because unconnected path become connected path, HH-VBF has more pipe in the network, it whole performance is better than VBF. On the other hand, MPR only need two hop nodes transmission which can alleviate node mobility problem than above two protocol and we can observe that the more velocity increasing success rate can more static.

5.3 Throughput

Fig. 12 show the simulation result of the throughput for three routing protocol. In Fig. 12 (a), MPR throughput is higher than VBF and HH-VBF, because nodes in HH-VBF have to according to β to transmit packet and VBF use single-path to transmit

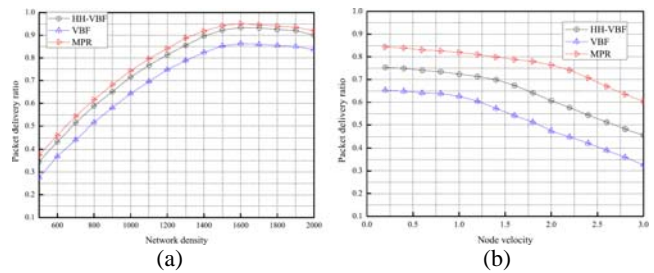


Figure 11: Performance of packet delivery ratio vs. (a) network density and (b) node velocity

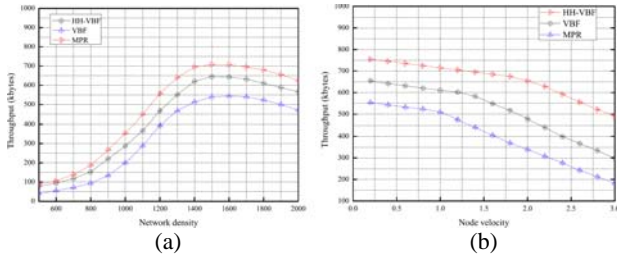


Figure 12: Performance of packet throughput vs. (a) network density and (b) node velocity

packet thus these condition affect the throughput performance. Although MPR use multi path to transmission but not use the entire node for relay and no transmit restrict for MPR. In high node density, HH-VBF every node occur too many same packet and drop the throughput. These three protocols suffer low throughput in spare network and increasing node density, throughput is enhanced. We can easy observe that in high density network, more nodes enter in pipe, which means more nodes are qualified for packet forwarding. In Fig. 12 (b), MPR and HH-VBF get close value in low density network because they affect lightly for node velocity. But for VBF, low velocity node still cause source hard to find the forwarder. In high velocity node network, VBF get the more throughput decrease but throughput for MPR affect less by node velocity.

5.4 Overhead

In Fig. 13 shows the simulation results of the packet overhead ratio for three routing protocol. Because MPR and HH-VBF use multi-path transmission, thus the overhead in Fig. 13 (a) overhead is more than VBF. In the other hand, VBF use single path transmission and thus use single flooding in network. That can be reducing the overhead. In Fig. 13 (b) VBF and HH-VBF affect by the node velocity thus they get high overhead ratio. At the low node velocity, because HH-VBF uses flooding to find the neighbor, cause it higher overhead than MPR and VBF. When node velocity increase, VBF affected by the node speed because it fix pipe. MPR less affected by node velocity cause the slope is moderate than VBF. We can observe that HH-VBF is less affected by node velocity because use multi-pipe and increase the reliability.

6 Conclusion

In this paper, we present a time efficient transmission protocol for underwater sensor network. To consider the long propagation delay and mobility for underwater sensor node, in this thesis, we develop a

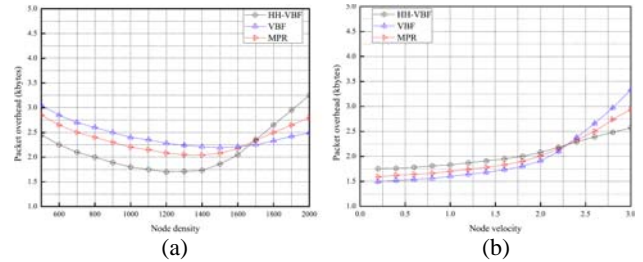


Figure 13: Performance of overhead ratio vs. (a) network density and (b) node velocity

routing protocol by utilizing multi-path to achieve low-propagation delay and use two-hop transmission to handle sensor node mobility. The main results of our multi-path protocol are summarized as follows: (1) our routing protocol is a multi-path scheme and use multi-sequence transmission which effectively reduce the delay propagation delay time and effectively increase packet delivery. (2) our routing protocol builds a two hop transmission, which form a “segment” in one transmission; source node only need two hop nodes information. (3) Our routing protocol offer high successful rate than single-path scheme. Finally, the simulation result illustrated the performance achievements in terms of low propagation delay time and load-balance.

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