A Three-level Propagation Method of Routing Packets Specialized for Underwater Wireless Sensor Networks

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ABSTRACT
Nowadays, underwater sensor networks have many applications, in military and exploration domains, early detection of natural phenomena such as earthquakes and tsunamis, and tracking marine creatures. Early detection of considered events and prompt delivery of necessary data to destination (the sinks) are significant necessities. This paper proposes a simple and efficient packet routing protocol for underwater sensor networks. In the proposed protocol, a three-level propagation mechanism is used for directing packets from source nodes to sink nodes. The proposed protocol is implemented to be assessed, in a series of experiments, in terms of packet delivery rate, average end-to-end delay, and energy consumption and compared with DBR algorithm. Comparison results indicated that the proposed protocol outperforms the base DBR algorithm

Keywords
Underwater Wireless sensor networks (UWSNs), Routing, Three-level propagation Model.

1. INTRODUCTION
In addition to providing high delivery rate and low energy consumption, routing algorithms used in the underwater sensor networks should ensure quick arrival of data to their destination. In the other words, end-to-end packet delay has to be low because data recency is one of the requirements of sensor networks [1-2].

Routing algorithms proposed for terrestrial sensor networks are applicable to underwater sensor networks because topology of underwater sensor networks is very dynamic and on the other hand, they usually have a 3D network environment. Also, due to the characteristics of underwater sensor networks, which are mentioned below, designing a scalable and efficient routing algorithm for these networks is very difficult [3-7]:

- Underwater sensor networks are based on (acoustic) voice communications. But, most of the acoustic channels have low-bandwidth and long propagation delay. Therefore, a routing algorithm that requires high bandwidth or has high end-to-end delay cannot be a suitable option for these networks.
- Connectivity in underwater sensor networks is very dynamic because water flows continuously moves the sensor nodes. So, routing algorithms that are based on the assumption of constant nodes cannot be used.
- Limited battery power of sensor nodes is the final reason since it has made use of routing algorithms with high communication overhead unsuitable for these networks. Because, for charging the nodes' batteries, solar energy can no longer be used underwater.

Geographic routing algorithms are the most common approach used in underwater sensor networks. The main feature of geographic routing protocols is that they consider nodes' location information in routing decision-making. To do this, a GPS is required. But, GPS radio receivers (Bandwidth 1.5 GHz) are not precise in underwater environment [8].

So far, many algorithms have been proposed [9-16] for routing in underwater sensor networks. Most of these algorithms, such as [9] and [10], are based on accurate information of geographic location of all nodes received via GPS that it is expensive. Some other algorithms, such as DBR [11], are based on depth, i.e. nodes' depth in water is the only feature that they require for routing packets. In general, considering packet delivery ratio, end-to-end delay, and energy consumption, DBR algorithm is not efficient.

In this paper, a routing algorithm is proposed for underwater sensor networks that, in addition to increasing the packet delivery ratio, it decreases end-to-end packet delay. The main idea of the proposed algorithm is based upon a three-level propagation mechanism to forward packets from the source nodes to the sink nodes. This mechanism is to direct data toward their destinations (surface water sink nodes) through several separate paths and using intermediate nodes with suitable conditions (closer to the water surface).

The rest of this paper is organized as follows: section 2 reviews the literature. Section 3 explains system hypotheses. Section 4 elaborates on the proposed algorithm and the final section concludes the paper.

2. RELATED WORK
The first routing algorithm, named Vector-Based Forwarding (VBF), for underwater sensor networks is presented in [9]. VBF algorithm assumes that each node is aware of its own location. Also, each packet involves the location information of source, sink, and sender nodes. The main idea of this algorithm is based upon using a virtual routing tube in which "source to sink" vector represents the (tube) axis and W indicates its radius. W is a parameter with pre-defined threshold. A node inside the tube can direct a packet from its source to destination. In this algorithm, a virtual tube is defined for each source node. Figure 1 is an example of how this algorithm works. In [10], another algorithm is proposed, called Hop-by-Hop Vector-Based Forwarding, which uses the same vector routing concept introduced in VBF. But instead of using a single virtual tube from source to sink, several virtual tubes are used elsewhere in the packet (intermediate nodes). Figure 1 shows how the routes are created in this algorithm. DBR algorithm [11] is a greedy algorithm that tries

to deliver the packets from source nodes to sink nodes. This algorithm does not require geographical location of the nodes and only uses their depth for routing the packets. Also, in underwater sensor network with multiple-sink architecture [17], it is much more efficient.

REBAR [12] is a routing algorithm based on geographic location which focuses on three important issues: energy consumption, packet delivery ratio, and the empty space issue. In REBAR, the nodes propagates the packets using geographic information of just a specific domain, between the source and sink nodes. In [13], a routing algorithm is presented, called SBR-DLP, which is based on sector division, geographic location, as well as prediction of the target locations. DFR algorithm takes link quality into account in directing packets strategy. The algorithm also assumes that geographic information of all nodes is available. In [15], a clustering algorithm is proposed for underwater sensor networks based on geographic location of sensor nodes with a 3D hierarchical architecture, called LCAD. In this algorithm, the whole network is divided into 3D grids. DUCS algorithm in [16] is a self-adaptive algorithm for clustering. DUCS tries to adapt itself with inherent characteristics of underwater environments, such as long propagation delay, low data delivery rate, and difficulty of synchronization.

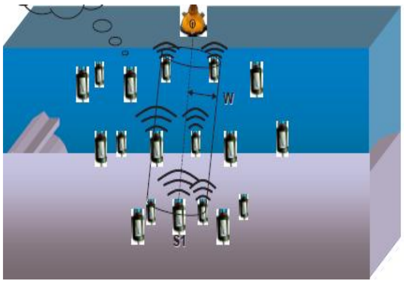

Fig 1: An example of VBF algorithm from [9]

3. SYSTEM ASSUMPTIONS

- The network contains N nodes (including sensor and sink nodes).
- Sink nodes are constantly located at the surface water.
- Sensor nodes distribute and move in the water.
- Each node has a sensor that determines its depth.
- Transmission ranges of all nodes are equal to R.

4. PROPOSED ALGORITHM

The main idea of the proposed protocol is based on using a three-level propagation mechanism in forwarding the packets from the source nodes to the sink nodes. The proposed protocol targets four principles: 1- directing the packets toward their destination (sink nodes) without any delay, 2- using a limited multi-path mechanism, 3- being light weighted, and 4- having low cost. The first one ensures low end-to-end packet delivery delay. The second one ensures high reliability of data delivery and thus increased rate of packet delivery. The third one ensures the proposed protocol imposes very little memory overhead, processing, and communication on resource-constrained sensor nodes to make it applicable. What is more, the proposed protocol uses no additional hardware, such as GPS. So, it does not impose any additional costs to the network.

In implementing the proposed protocol, two simple hypotheses are considered. First, every node is aware the maximum transmission range, i.e. R. Second, every node, at any point in time, can estimate its depth in the water using depth determining sensors. Pseudo-code of the proposed protocol is presented in Figure 2.

In the following, with respect to Figure 2, the proposed protocol is described. In the proposed protocol, the (shallower) area above the sender node is divided to three equal sub-area (L=R/3). It is crystal clear that receiver nodes in propagation level 3 are more suitable and in higher priority for directing the packets toward their destination since they are nearer to the water surface. If no node exists in this area (propagation level 3), propagation level 2 is the next priority, and if no receiver exists in propagation level 2, nodes available in propagation level 1 is the next priority. Nodes located in propagation level 1 are in the third place (unsuitable) for directing the packets toward their destination because they are farther away from the water surface. While, nodes located in propagation level 3 are in the first place (suitable) for directing the packets toward their destination because they are nearer to the water surface.

As a clear example, suppose that node *u* propagates packet *P* in a depth of d_u in the water. Of course, while sending a packet, each node inserts its depth in the packet so that receiver nodes would recognize source depth of the packet. Each receiver node (*v*) calculates the difference between depth of the sender node (the same *u*) and its own depth, i.e. (d_u -d_v), to determine at what propagation levels of the *u* node is located:

- The $0 < d_u - d_v < L$ case means the receiver node *v* is located at propagation level 1 of the *u* node and it is nearer to sender node than water surface. So, node *v* is the 3rd candidate for directing the packet toward its sink node and sends the packet *P* only if no other node exists in propagation level 2 or 3 to send the packet. Hence, the receiver node temporarily holds P in its buffer for 2w. After this time, if no node exists in propagation levels 2 and 3 to send P, it sends the packet P.

- The $L \le d_u - d_v < 2L$ case means the receiver node *v* is located at propagation level 2 of the *u* node. So, node *v* is the 2nd candidate for directing the packet toward its sink node and sends the packet *P* only if no other node exists in propagation level 3 to send the packet. Hence, the receiver node temporarily holds *P* in its buffer for *w*. After this time, if no node exists in propagation levels 3 to send *P*, it sends the packet *P*.

- The $2L \le d_u - d_v < 3L$ case means the receiver node *v* is located at propagation level 3 of the *u* node. So, node *v* is the first candidate for directing the packet toward its sink node and sends the packet immediately after it receives *P*.

- Otherwise, $(d_u - d_v) \le 0$ means the receiver node *v* is located at a depth equal to or more than the packet sender node. So, it is not a proper candidate for directing the packet and deletes the received packet.

In this algorithm, *w* is computable proportional to latency and can be calculated according to propagation delay and transfer delay. In general, in the world of telecommunications, given the Propagation Delay P_D, Transmission Delay T_D, and average Queue Delay of a packet Q_D, the latency is equal to $Latency = P_D + T_D + Q_D$. P_D and T_D can be calculated as follows:

$$P_D = Distance/SpeedOfLight$$
$$T_D = PacketSize/Bandwidth$$

Here, *SpeedOfLight* represents the light speed in transmission medium, Distance indicates distance between sender and receiver, *PacketSize* represents size of the sent packet, and Bandwidth represents is the width of a band. In the proposed protocol, only P_D and T_D are used to calculate *w* since latency of a transmission line, not a path, is required.

After propagating the nodes in water environment, having seen the specified events, source nodes generate the required packets in a stepwise manner and direct them toward the sink nodes.

In addition, in the proposed routing algorithm, each node has a history table, as figure 4, which records the history of packets directed by source nodes to avoid sending duplicate packets. Accordingly, each node saves *IDs* of packet generator source nodes in *SID_field* column and *IDs* of last packets directed by the source nodes in *EID-field*. By doing so, when receiving a packet, each node first extracts *ID* of the packet generator source node (*SID*) and *ID* of the packet (*SID*) and explores the history table. If value of the packet ID (*EID*) be larger than value of its corresponding source node in *EID-field*, it directs the packet toward the water surface and updates EID-field with the packet's *EID*. Otherwise, it deletes the packet.

In the proposed method, the packets end-to-end delay is very low since nodes of the propagation level 3 direct the packet immediately. On the other hand, because the proposed method mechanism is such that it directs a packet toward the source nodes via multiple paths (e.g. multiple nodes available at propagation level 3), its packet delivery rate is very high since just few packets fail to arrive the target location due to different reasons (such as accidents, lack of available path, etc.)

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1: Node u at depth d_u send packet P, in broadcast manner
2: for each Node v ∈ NeighborNode(u) that recived the packet P Do
       if (0 < d_u − d_v < L) store P in it's Buffer for 2w time          //Level(1)
       else if (L ≤ d_u − d_v < 2L) store P in it's Buffer for w time     //Level(2)
       else if (2L ≤ d_u − d_v ≤ 3L) forward the P, immediately           //Level(3)
       else Node v drops the P                                            //Level(−i)
3: each NeighborNode v at Level(2), forward the P after w, if its not fowrarded earlier
4: each NeighborNode v at Level(1), forward the P after 2w, if its not fowrarded earlier
5: repeat steps 1 ~ 4 until the P reached to a Sink
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Fig 2: Pseudo-code of the proposed protocol

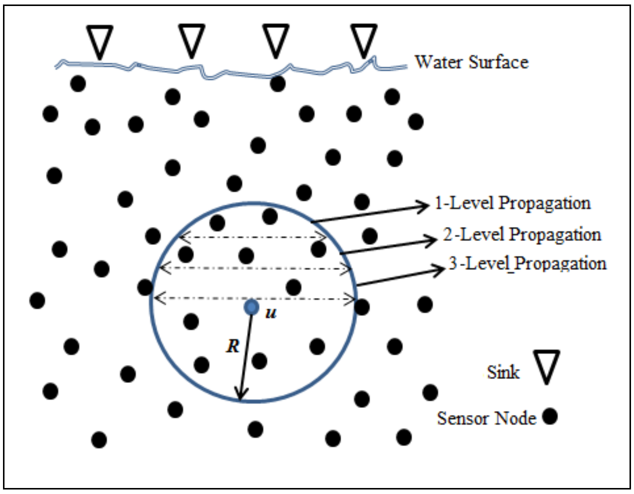

Fig 3: A model implemented by the proposed algorithm

SID_field	EID_field

Fig 4: Structure of the nodes' history of proposed algorithm

5. PERFORMANCE EVALUATYION AND SIMULATION RESULTS

5.1 Overheads

Memory overhead: in the proposed algorithm, each node requires a temporary storage space to save the packets for maximum duration of 2*w*, as well as a storage space to save the history table. Therefore, assuming that the buffer size is *b* and at most there are *s* source nodes in the network, memory overhead of the proposed algorithm follows O (*b*+*s*) function.

Processing overhead: processing overhead of the proposed algorithm in decision making phase is of O(*s*) type. This is because, upon receiving a packet, each node has to explore its history and see if it has directed the packet before, or not.

5.2 Simulation Model

The proposed algorithm is implemented by JSIM simulator [18] and its performance is compared, through a series of test, with the base DBR algorithm [11]. In all experiments it is assumed that the sensor nodes are randomly distributed in a 3D area ($500m \times 500m \times 500m$). Total number of sensor nodes in the network is N. The network includes 10 sink nodes that are distributed in fixed locations on water surface. The network has one source node. During the network lifetime, the source node generates and propagates a 50 bytes packet, at every 5 seconds. Also, in order to consider the most difficult condition, source nodes are randomly set at the lowest layer of the environment, i.e. the bottom of the water, so their distance to the water surface and sink nodes would be the maximum. The rest of the nodes in the network are intermediate nodes that are randomly distributed in water and randomly move in the environment during the network lifetime. Intermediate nodes are responsible for delivering the packets generated by source nodes to sink nodes. Maximum transmission range of all nodes is 50 meters. Considered bandwidth of transmission lines is 1 Mbps. Energy consumed for sending packets, receiving packets, and idle status are 0.016, 0.008, 0.0002 joules, respectively (default setting of JSIM simulation software). Initial energy of all sensor nodes is considered as 5 Joules. CSMA protocol is used in MAC layer. Each simulation takes 1000 seconds and final results are obtained from an average of 20 different operations. Evaluation criteria of the proposed protocol include:

- **Packet delivery rate**: equals to ratio of number of unique packets received by all sink nodes to total number of packets sent by all source nodes in the network.
- **Average end-to-end delay**: average packet delivery delay since it is sent by source nodes until it arrives to sink nodes.
- **Average energy consumption**: average energy consumed by each sensor nodes (except sink and source nodes) during the network lifetime.

5.3 Experiment Results

After simulating the proposed, its performance is tested with the base DBR algorithm. In the test, DBR algorithm parameters are set as $d_{th} = 0$ and $\delta = R, R/2$. Other network parameters, including environment dimensions, number of sink nodes, number of source nodes, transmission range of the nodes, and total number of the nodes are equally assumed for both algorithms. In simulations, number of the nodes in network varies between *N*=200 and *N*=500 and the obtained results are depicted in figures 5, 6, and 7, in terms of packet delivery rate, average end-to-end delay, and average energy consumed, respectively.

As indicated in figure 5, packet delivery rate of the proposed algorithm is always higher than DBR. As an example, when *N*=200 nodes exist in the network, packet delivery rate of the proposed and DBR algorithms are about 50% and 30%, respectively. Also, when *N*=300 nodes exist in the network, packet delivery rate of the proposed and DBR algorithms are about 97% and 86%, respectively. Of course, the difference between these two algorithms decreases as the number of nodes increases and the rate is about 100%. For example, when *N*=500, packet delivery rate of the proposed and DBR algorithms are about 100% and 99%, respectively. It's clear that, number of probable paths from source nodes to sink nodes increases by increasing the network density which results in higher packet delivery rate. Since all the nodes of the proposed algorithm direct the packets from the 3rd propagation level to water surface, a given packet may be directed from different paths. Then, it is more probable for the packet to reach its target location. But, DBR algorithm severely avoids multi-path function and directs the packets usually via a single path. So in the latter algorithm, it is less probable than the proposed algorithm that the packets reach sink nodes at the water surface.

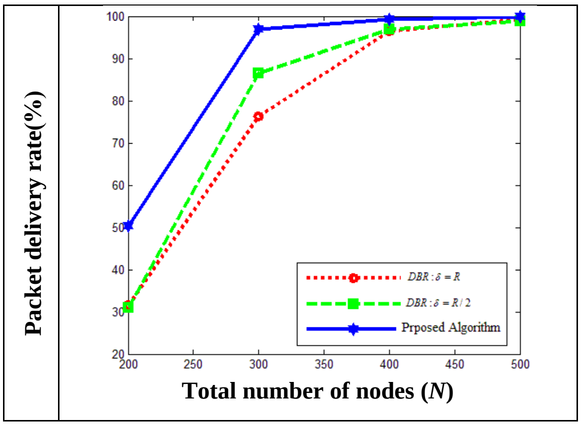

Fig 5: Comparison between packet delivery rate of the proposed algorithm and DBR algorithm

Also, as indicated in figure 6, average end-to-end delay of the proposed algorithm is much less than DBR. Because, after receiving a packet, all the nodes of DBR algorithm wait for a while, called "hold on time", and then send the packet if it is necessary. But, in the proposed algorithm, upon receiving the packets sent by nodes in the 3rd propagation level, intermediate nodes immediately direct them toward the sink nodes. Thus, the packets arrive at water surface with less latency.

Also, figure 7 shows that average energy consumption of sensor nodes in the proposed algorithm is less than DBR algorithm. Because, in the proposed algorithm, most of the time, only the nodes at the 3rd propagation level direct the received packets. However, in DBR algorithm, more than one node may have almost equal waiting time for the received packets. As such, after hold on time, these nodes direct the received packets simultaneously. This lead to increased collisions and higher energy consumption.

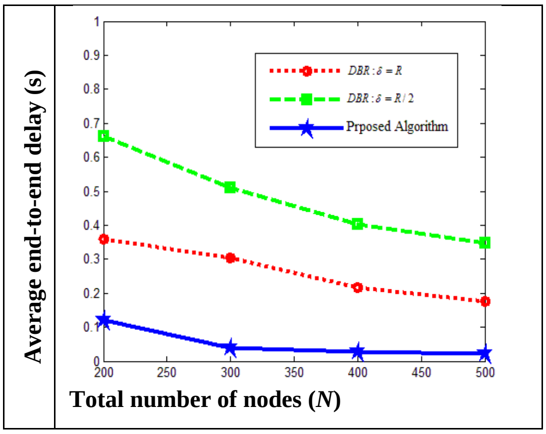

Fig 6: Comparison between average end-to-end delay of the proposed algorithm and DBR algorithm

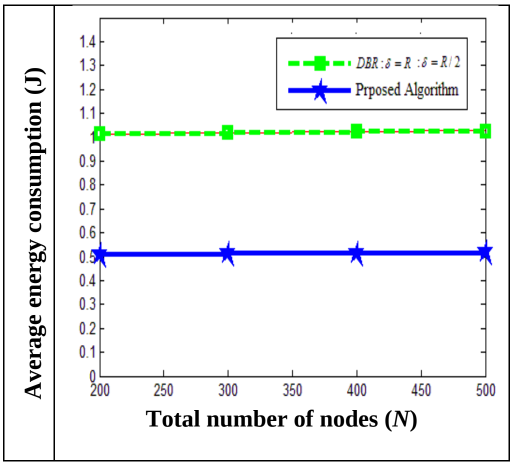

Fig 7: Comparison between average energy consumption of the proposed algorithm and DBR algorithm

6. CONCLUSION

In this paper, a simple and efficient packet routing protocol is proposed for underwater sensor networks. In the proposed protocol, a three-level propagation mechanism is used for directing packets from source nodes to sink nodes. The proposed protocol is implemented to be assessed, in a series of tests, in terms of packet delivery rate, average end-to-end delay, and energy consumption and compared with DBR algorithm. Comparison results indicated that the proposed protocol outperforms the base DBR algorithm. In future, the performance of proposed algorithm will improve by using a dynamic mechanism of selecting the number propagation levels.

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