A comparative view of routing protocols for underwater wireless sensor networks

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Abstract—Design of efficient routing protocols for underwater sensor networks is challenging because of the distinctive characteristics of the water medium. Currently, many routing protocols are available for terrestrial wireless sensor networks. However, specific properties of underwater medium such as limited bandwidth, high propagation delay, high bit error rates, and 3D deployment make the existing routing protocols inappropriate for underwater sensor networks. In this paper, we provide a guideline on use of existing underwater routing protocols, identify their shortcomings, and give an insight on what is needed to design an efficient and reliable underwater routing protocol.

I. INTRODUCTION

The underwater world has always fascinated human beings and almost 75 percent of our planet is covered by seas and oceans. The deep oceans are harsh environments for humans to explore and the existing sensing technologies do not meet the need for easy deployable low-cost equipments. There are great demands in many applications such as oil and gas exploration, safety and security, and environmental monitoring for fine-grained underwater monitoring. Specific characteristics of under water imposes special requirements on algorithms and protocols designed for underwater wireless sensor networks. In this paper we present current routing protocols for underwater sensor networks and their advantages and disadvantages. Our goal is to provide a guideline on use of existing underwater routing protocols, identify their shortcomings, and give an insight on what is needed to design an efficient and reliable underwater routing protocol. In [1] and [2], a number of routing protocols are compared in terms of their delivery ratio, end-to-end delay, and energy consumption. Different from these papers, our paper mainly focuses on conditions and circumstances under which these protocols were evaluated. Using a comparative table, we also compare these protocols in terms of their deployment type, support for mobility, required information, and type of routing.

Currently, many routing protocols are available for terrestrial wireless sensor networks. However, specific properties of underwater medium make existing routing protocols inappropriate for under water. The main challenges in developing efficient routing protocols for underwater environments are:

• High propagation delays - The radio signals do not work efficiently under water and this problem encourages use of acoustic communication instead. The main problems with the acoustic channel, however, are low bandwidths and long propagation delays.

• Node mobility - Due to water currents, nodes can fluctuate or move if they are not anchored at the bottom of the sea. This situation results in a dynamic network topology. Moreover, autonomous underwater vehicles and robots used for exploration and controls can be utilised to route and muling data.

• Error prone acoustic underwater channels - Since the acoustic channels have very low bandwidth capacity, they suffer from high bit error rates.

• Limited energy - Like in terrestrial wireless sensor networks, majority of sensor nodes in UWSNs are battery powered.

• Harsh deployment environment

In addition to these challenges, while developing an underwater routing protocol, it is important to avoid the usage of exchanging overhead messages or flooding-based route discovery mechanisms since energy and bandwidth consumption of these techniques is high.

A. Existing Routing Protocols

1) Vector-Based Forwarding Protocol (VBF) [3]: is a location-based routing protocol designed for underwater sensor networks. In VBF, a “routing pipe” is established between the source and the destination nodes and packet delivery is accruing along this pipe. Each data packet contains position of the sender, the target, and the forwarder and also a RANGE field which is used for mobility concept.

When a node receives a packet, it computes its relative position to the forwarder using the distance to the forwarder and the angle of arrival (AoA) of the signal. It is assumed that each node is equipped with the hardware required to measure the distance and the AoA of the signal. All nodes that receive the packet compute their positions recursively. If a node determines that it is close to the routing vector according to a predefined distance threshold value, it places its own position into the packet and continues forwarding; otherwise it discards the packet. In this way a virtual pipe is established between the source and the target. The nodes which are outside the pipe do not join the forwarding process.
The performance of VBF was evaluated through simulations. Delivery rate, energy consumption, and average delay are used as the performance metrics. VBF works well for dense underwater sensor networks, as the idea of a virtual pipe significantly reduces the network traffic since only the nodes in the pipe join the routing process. However VBF has some disadvantages. For example it assumes that the full dimensional location information of the whole network is available. Besides, node density highly affects the efficiency of creating a pipe from source to destination. In sparse networks, there may be few or sometimes no node in the pipe to forward the packages. Also choice of thresholds can affect the routing performance significantly. This kind of sensitivity is not desirable for real protocol developments.

2) Robustness Improved Location-Based Routing for Underwater Sensor Networks (HH-VBF) [4]: is similar to [3] as it also uses the idea of “routing pipe”. But instead of constructing one single pipe from source to sink for the entire network, HH-VBF creates a “routing pipe” for each forwarder node. Using this approach, the authors claim to overcome the main problems faced by VBF [3], i.e., low data delivery in sparse networks and being too sensitive to routing pipe radius. The mechanism, which allows each node to make forwarding decisions adaptively based on its current location, causes the maximum pipe radius to become the transmission range. Through inclusion of redundant control in the self-adaptation process, HH-VBF also improves on the problem of inability to find forwarding nodes in sparse networks.

The forwarding process in HH-VBF is as follows: Similarly to VBF, upon receiving a packet, the receiving node keeps the packet for some certain time period. This waiting time is proportional to a factor called “desirableness factor”, which indicates suitability of a node to be a forwarding node and is calculated using distance and angle between the two nodes and the transmission range. When the waiting time period expires, the node with the smallest desirableness factor forwards the packet first. HH-VBF allows overhearing. The node that receives the message, calculates its distances to the vectors of the forwarding nodes. By comparing the pre-defined minimum distance threshold with these distance values, the node decides whether to forward or drop the packet.

Authors use network simulator NS-2 for simulating the 3D underwater sensor networks and set the parameters of the acoustic communication similar to a LinkQuest UWMI1000 acoustic modem. The experiments aim to evaluate the impact of node density and mobility on energy consumption and packet delivery rate. In the first set of experiments, network is supposed to be static and node density is changed between 500 and 3000. Experimental results show improvement of delivery success rate as node density is increased. This is due to the fact that increase of node density obviously results in having more forwarding nodes in the routing pipe, which consequently leads to higher probability of successful packet delivery. Experimental results show that HH-VBF outperforms VBF in terms of both success delivery rate and energy consumption.

3) Depth-Based Routing for Underwater Sensor Networks (DBR) [5]: is a greedy algorithm, in which each sensor node individually, based on its depth and the depth of the previous sender, makes the decision on whether to forward a packet. When a node has data to send, it simply broadcasts it. Neighbouring nodes calculate their depths and make a depth comparison with the sending node upon receipt of the data packets. Nodes which have lesser depths than the sender accept these data packets, while other nodes simply discard them.

For simulations, authors use network simulator NS-2 with an underwater sensor network simulation package extension called Aqua-Sim. To evaluate the performance of the protocol, packet delivery ratio, average end-to-end delay, and total energy consumption are used. One of the disadvantages of DBR is that every node must be equipped with a depth sensor, which on the one hand can increase the cost while on the other hand can increase energy consumption. The second disadvantage is the broadcasting, which increases the complexity of the routing due to making more nodes candidate for forwarding the data packets. Another problem is the dramatic change of performance as node density varies. In sparse networks, if the depth of two nodes are not significantly different, the routing performance can be greatly reduced as finding a suitable forwarder can continuously be repeated.

4) Hop-by-Hop Dynamic Addressing Based (H2-DAB) [6]: assumes there are multiple buoys on the water surface which collect data of nodes anchored at the bottom of the sea and deployed at different depths. Sensor data is sent towards the water surface in a greedy fashion. Each floating node in the network is assigned a dynamic HopID. Anchored nodes, however, have only one static HopID equal to 100, while surface nodes and floating nodes have two types of addresses. The default HopID of every floating node is 99. Sink nodes on the water surface send Hello messages, containing among others, maximum hop count to other nodes in order to allow them to get their HopIDs. The default HopID of the floating nodes does not change until they receive a Hello message. After updating its HopID, the node forwards the Hello message and its new HopID to its neighbour and decreases the value of maximum hop count by one. This process ends when the Hello message reaches an anchored node or the hop count becomes zero. Those neighbouring nodes of the sender, whose HopID is smaller then the sender, compete for being a forwarder. The node which has the smallest backup link wins this competition.

Performance of H2-DAB in terms of delivery Ratio and end-to-end delay was evaluated using was evaluated using NS-2. Authors state that the packet delivery ratio is not affected by the density of the nodes and it can be up to %90. Despite its good delivery ratio, H2-DAB has some disadvantages. While choosing a forwarder node, the sender may not have a response from its neighbours especially in sparse networks. To solve this problem, the protocol waits for a certain time and then forwards the packet to a neighbour who is at the same depth. This will cause high end-to-end delay. However, because H2-DAB does not require any specialised hardware, it does not introduce extra equipment cost. Moreover, it does not...
require availability of full dimensional location information or maintaining complex routing tables. Node movements with water currents can be handled easily and the protocol takes advantage of multiple sink architecture.\cite{6}

5) Focused Beam Routing Protocol for Underwater Acoustic Networks (FBR) \cite{7}: is a scalable routing technique based on location information. FBR is presented as a suitable routing protocol for both mobile and static underwater acoustic networks without the need of clock synchronisation. The idea of FBR is to restrain the flooding by the transmission power so that the energy consumption is reduced. It is assumed that there is a finite number of energy levels ranging from \( P_1 \) to \( P_N \) and each power level is matched with a transmission radius \( d_n \). The candidate forwarders are determined based on the angle of the cone which originates from the source towards the destination.

The source nodes start sending the RTS messages to the area it can reach with the first power level and the nodes in the area reply with a CTS packet. If the source node does not receive any reply, then it increases the power level to the next and send a new RTS message. This procedure continues until sender receives a reply. If the maximin power level is reached and no reply has been received, the source node shifts its cone and searches for new candidates in left and right sides of the main cone.

To evaluate the performance of FBR, a discrete event underwater acoustic network simulator is used considering different node densities and network loads. In the experiments the authors first observed the impact of node density on the performance and the results are compared with Dijkstra’s shortest path algorithm. Authors claim that their technique is able to dynamically discover minimum energy routes with the minimum network knowledge.

6) Path Unaware Layered Routing Protocol (PULRP) \cite{8}: is a routing protocol for dense well-connected underwater 3D sensor networks. PULRP algorithm has two phases. First phase corresponds to a layering process in which concentric spheres are formed around a sink and each sphere corresponds to one of the layers. “The radius of the concentric spheres is chosen based on probability of successful packet forwarding and packet delivery latency” \cite{8}. The selection of the intermediate nodes and the data delivery from source to target, takes place in the second phase. It is assumed that nodes are uniformly distributed and the same packet length used for all nodes.

The area in which the sensors are located is divided into small virtual cubes such that at most one node occupies one virtual cube. To determine a path from a source to the sink, first a node broadcasts a control packet. The collision free communication is ensured if no other node in the neighbourhood sends a control packet at the same time. When a relay node candidate which is located in the lower depth receives the control message responds to it with an ‘ACK’. After the transmission of the control packet, the data packet is forwarded to the relay node by the source. Upon successful receipt of the data packet, the relay node broadcasts the control packet towards the sink. Whenever the packet reaches its destination the process will end.

Advantages of PULRP include no need for fixed routing tables, localisation, or time synchronisation, as well as its high delivery rate and average delay. But PULRP has a disadvantage that, the ring radius value affects the delivery rate to the extent that when it approaches 1, the delivery rate decreases dramatically.

7) Adaptive Routing \cite{9}: is a routing protocol, in which routing is performed adaptively based on the type of the messages and application requirements. The protocol exploits message redundancy and resource allocation to fulfill different performance requirements. The main goal of the protocol is to achieve a good trade-off between delivery ratio, average delay, and energy consumption and to provide different services for data packets having different priority.

Authors assume that underwater sensor nodes are randomly deployed in a target area and periodically report water quality to the sink node placed on the water surface. Data packets are classified into ordinary, intermediate, or emergent, based on the water quality data. If the quality is good or within an accepted threshold, the data packets considered as ordinary and can be delivered to a sink with an acceptable delay and little energy consumption. But in case of pollution sensors generate emergent data packets which has to be delivered to the sink immediately. Other packets, assumed as intermediate, require moderate energy consumption and have average delay.

The target network model considered is a layered 3D sparse underwater sensor network. Underwater sensor nodes are deployed at different depths using buoyancy control and they can move freely in the horizontal 2D plane. In this way the sensors at the same depth form a layer. A data sink is located in the center of the water surface. Furthermore, it is assumed that all sensor nodes know their 3D positions through a certain localisation technique. The sensor nodes are following a basic geographic routing scheme, which uses HELLO and data packets. HELLO packets are used to exchange information and discover neighbours, while data packets are used to determine the packet priorities. The data packets include the ordinary payload and a simple protocol overhead with two fields: emergency level and packet generating time. Basically there are three types of actions which each sensor node have to perform: neighbour discovery, priority calculation, and routing decision.

“In neighbour discovery step, each node periodically broadcasts HELLO packets. Furthermore, in order to suppress the redundant packets existing in the network, ACKs for successfully received packets at the sink are first broadcasted from the sink node using the Epidemic routing approach. Any node which receives the ACKs will delete the corresponding packets and further broadcast the received ACKs to the rest of the network. To simplify the protocol design, each node includes piggy-back ACKs in its periodically broadcasted HELLO packets”\cite{8}.

In priority calculation step, packet priority is calculated based on an information vector, which consists of packet emergency level, packet age, node spatial-temporal density,
and node battery level. A node only calculates the priority of a packet when it encounters a new neighbour. After calculating the priority for a packet, a node needs to make routing decisions accordingly to forward the packet toward the sink.

The whole routing spectrum is divided into four intervals. Each interval corresponds to a routing state. The authors indicated that at most four copies of a data packet are enough for their scenarios. They introduce a new concept called forwarding area, which is a spherical space with predetermined diameter. According to the importance level of the data packet (the routing state), the packet is forwarded to the nodes which are in the corresponding region. As the importance level of a packet increases, the forwarding region becomes larger.

Experimental results show that this approach outperforms Epidemic Routing and Single-copy Routing protocols in terms of achieving a good trade-off between packet delivery and end-to-end delay.

8) GPS-free Routing Protocol for Deep Water (DUCS) [10]: focuses on the applications with random node mobility and without a geographical positioning mechanism support. DUCS is a self-organising routing protocol, in which nodes are organised into clusters and each node is connected to a cluster head through a single hop. The cluster heads receive data from the cluster members and perform aggregation operations on the collected data. Then the cluster heads send the data to the sink using multi-hop routing. In order to prevent the battery draining of a single node, DUCS performs the cluster head rotation in a randomised manner.

In DUCS, the whole operation is divided into rounds. Clusters are formed in the set-up phase, while data transfer occurs in the steady-state phase. A series of data messages form a frame and along the steady-state phase cluster heads receive several frames from the ordinary nodes. These two phases are repeated periodically.

Performance of DUCS in terms of packet delivery, average routing overhead, and the number of required alive nodes for each successful delivery was evaluated using NS-2. The results show that DUCS has a much lower routing overhead and higher packet delivery compared with LEACH. "The reason for that LEACH assumes that all nodes are in the transmission range of each other as well as the sink."[10]. Furthermore, DUCS seem to be able to deliver the data to the sink four times more effective than LEACH.

9) A Low Propagation Delay Multi-Path Routing (MPR) [11]: forms a path from source to the destination consisting of a several multi-subpaths during the routing path construction. Multi-subpaths are defined as sub-paths from the sender to its two-hop neighbours via a relay node in the neighbourhood of both sender and receiver nodes. This approach is used to prevent data collision at receivers since they receive packets from different relay nodes.

When a relay node receives a packet, it immediately checks the transmission schedule in order to decide whether there is collision. The relay node defers appropriate time slots in case of a collision, otherwise it sends the packet to the destination node.

The Multi-path routing protocol completes its operation in three phases. In the first phase, the sender collects the propagation delay from its two hop neighbours since the paths are determined according to these delay values. In the second phase, this information is used to determine the intermediate node. In the last phase, the source node checks all the relay nodes for collision.

Performance of MPR is evaluated in terms of end-to-end delay, delivery rate, throughput, and overhead. In terms of end-to-end delay MPR outperforms VBF and HH-VBF since these two protocols use the virtual pipe mechanism. In dense networks, VBF and HH-VBF have higher collision rates, which decrease the packet delivery ratio. MPR has higher throughput compared with VBF and HH-VBF in dense networks, while in sparse networks all three protocols suffer from low throughput. MPR and HH-VBF both have higher overhead than VBF since VBF just uses a single path to transmit the packets. At low velocity, HH-VBF has higher overhead value than the other two protocols because it uses flooding for neighbour discovery. In order to avoid collision, MPR uses many matrix operations that lead to high energy consumption.

10) Pressure Routing for Underwater Sensor Networks (HydroCast) [12]: is a hydraulic pressure based anycast routing protocol that uses the pressure levels in other words the depth information to find the routes for forwarding packets from source to the surface buoys. It is presented as a novel opportunistic routing approach that limits the co-channel interference and offers an efficient underwater dead end recovery mechanism along with the clustering of the nodes.

Authors claim that HydroCast does not require expensive distributed localisation schemes and the localisation process can be performed on the data after it reaches the surface. As a contribution they consider the channel features to be used to select the forwarding nodes without causing the hidden terminal problem. The process of selecting a forwarding set (which corresponds to one cluster), is based on maximum progress of the nodes that is calculated using the parameters packet delivery probability and distance to destination. The forwarding process is performed along the maximum progress node and accordingly a cluster towards the destination is chosen. In forwarding, vertical transmissions are preferred but if there is no suitable forwarder node at a lower depth, the recovery mechanism is used.

For the evaluation of the proposed approach, the simulator QualNet is used and the performance of HydroCast is compared with DBR protocol under different settings. The results show that when the node density is low DBR has higher delivery ratio without recovery since DBR does not use redundant packet suppressing mechanism and delivers the data on multiple paths. But with recovery support the reliability of the proposed routing approach is improved and HydroCast outperforms DBR in terms of delivery ratio. Also HydroCast has lower end to end delay than DBR because HydroCast is using an adaptive timer setting at each hop.
B. Discussion

To compare the aforementioned protocols, we use tables illustrated in Figure 1. We first start with comparing the protocols in terms of type of deployment, support for mobility, required information, and type of routing mechanism. We then continue with presenting the overall performance of these protocols including simulation parameters, mobility patterns, transmission, and data rates.

One can observe that all these routing protocols consider underwater sensor networks being deployed in 3 dimensional space. Within 3D deployment, layered structure, dense, or sparse networks have been considered. What is missing in this regard is considering two dimensional linear and star shape topologies. Almost all routing protocols consider mobile nodes which are slightly moving in 2D or 3D space. The bottom nodes are usually anchored to the sea bottom and fluctuating with the water currents. Sink is always static and located on the sea surface. Some of the protocols use the advantage of multi sink architecture. Except for VBR, HH-VBF and MPR, source nodes are not fixed and any node can start the data transmission.

Many routing protocols are based on epidemic (flooding) or geographical routing. The usage of geographic routing mechanism demands location information, while DBR and HydroCast protocols only need depth information. 2-hop neighbouring information is needed for the protocols using multihopping. Only two protocols, i.e., DUCS and HydroCast, use clustering mechanism among all. Being able to suppress redundant packets and having recovery route mechanisms, HydroCast offers a good solution, which meets the requirements of underwater communication but the clustering mechanisms cause processing overhead and also with mobile nodes re-clustering is needed and this process has to be performed carefully in terms of time and frequency.

In terms of performance evaluation, all of these routing protocols have been evaluated in simulation environment. This motivates the need for performing real experiments. DUCS and Adaptive Routing protocols do not have significant disadvantages. The idea of Adaptive Routing to assign an importance level to each packet in the network and to perform the route operation accordingly is efficient. But authors supposed a spare network in order to run the simulations. In dense networks the performance of Adaptive Routing is not presented clearly.

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REFERENCES


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Fig. 1. Comparison of underwater routing protocols