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Comparison of Routing Protocols for Underwater Sensor Networks: A Survey

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Abstract: Sensor networks in underwater environments face unique adverse conditions. In order to be functional, specialized routing protocols are required to route the data from source to destination. This paper surveys routing protocols for underwater sensor networks. The routing protocols are examined and compared with respect to the network conditions and quality measures such as packet delivery ratio, average packet delay, energy consumption among others. Advantages and disadvantages of each routing protocol are pointed out.

Keywords: energy efficiency, routing protocols, underwater sensor networks (UWSNs), wireless networks.

1 Introduction

Sensor networks promise to revolutionize many areas of science, industry, and government. The ability to have small devices distributed near the objects being sensed brings new opportunities to observe and act on the world, for example with micro-habitat monitoring [Cerpa et al., 2001; Mainwaring et al., 2002], structural monitoring [Whang et al., 2004], and industrial applications [Ramanathan et al., 2005]. While sensor network systems are occupying a significant position in land based applications today, underwater operations remain quite limited by comparison. Remotely controlled submersibles are often employed, but due to their size and management their deployment is inherently temporary. Some wide-area data collection efforts have been undertaken, but at quite coarse granularity (hundreds of sensors to cover the globe) [Stephen, 1998.]. Even when regional approaches are considered, they are often wired and very expensive [Delaney and Chave, 2000].

As an emerging technique, Underwater Sensor Network (UWSN) will enable a wide range of aquatic applications [Pompili, Melodia, and Akyildiz, 2006a; Sozer, Stojanovic, and Proakis, 2000; Huang et al., 2009; Pompili, and Akyildiz, 2009]. However, due to the adverse underwater environmental conditions as well as some system constraints, an underwater sensor network is usually viewed as an Intermittently Connected Network (ICN) or Delay/disruption Tolerant Network (DTN) which requires specialized routing protocols [Guo et al., 2008; Partan, Kurose, and Levine, 2006].

UWSNs consist of a certain number of sensors and vehicles that interact to collect data and perform collaborative tasks [Bartoš et al., 2008; Casari, Stojanovic, and Zorzi, 2007]. In order to do so, they employ acoustic channels for communications [Zhang et al., 2009]. Radio signals do not propagate efficiently in water because underwater communications are severely affected by network dynamics [Lanbo, Shengli, and Cui, 2008; Ayaz, and Azween, 2009]. Also, they feature much lower bandwidth and several orders of magnitudes longer propagation delays. Additionally, although optical waves do not suffer from high attenuation, they are affected by scattering [Stojanovic, 2003; Yan, Shi, and Cui, 2008; Filipe et al., 2008; Stojanovic, 2006]. The general architecture for an underwater sensor network is shown in Figure 1, where four different types of nodes in the system can be seen.

[Insert Figure No 1]

a. At the lowest layer, a large number of sensor nodes are deployed on the sea floor (shown as small yellow circles). They collect data through attached sensors (e.g., seismic) and communicate with other nodes through short-range acoustic modems. They operate on batteries. In order to operate for long periods they spend most of their life asleep. They could also be buried for protection. Tethers ensure that nodes are positioned roughly where expected and allow optimization of placement for good sensor and communications coverage.

b. At the top layer, one or more control nodes enable connections to the Internet. The node shown on the platform in Figure 1 is such kind of node. These control nodes may be positioned on an off-shore platform supporting power, or they may be on-shore. These nodes have a large storage capacity to buffer data, and access to ample electrical power. Control nodes may communicate with sensor nodes directly, by connecting to an underwater acoustic modem via wires.
c. In large networks, a third type of nodes, called supernodes, can be deployed. Supernodes have access to high speed networks, and can relay data to the base station very efficiently. Supernodes allow much richer network connectivity, creating multiple data collection points for the underwater acoustic network [Wang et al., 2009].
d. Finally, there are robotic submersibles that interact with other nodes using acoustic communications. In Figure 1, the "fishes" represent robots.

Underwater sensor networks find applications in oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation, tactical surveillance, and mine reconnaissance [Zorzi et al., 2008].

So as for an UWSN to be best designed and fully operable for the afore-mentioned applications, there are certain challenges, due to the peculiarities of the medium that should be taken into account [Huang et al., 2009; Gopi et al., 2008; Hu, and Fei, 2010; Xie et al., 2010]. These are presented as follows:

i) the available bandwidth is severely limited depending on both range and frequency due to absorption as in most acoustic systems operating below 30 kHz, resulting to narrow frequency band,
ii) high bit error rates and temporary losses of connectivity (shadow zones) can be experienced,
iii) sensors are prone to failures because of fouling and corrosion,
iv) battery power is limited and usually batteries cannot be easily recharged,
v) propagation delay is five orders of magnitude higher than in radio frequency terrestrial channels, whereas electromagnetic propagation delay is negligible,
vi) the channel is severely impaired, especially due to multipath and fading,
vii) nodes tend to be inherently mobile either due to their self propelling capability or due to random motion caused by ocean currents [Kilfoyle and Baggeroer, 2000; Kinsler et al., 1999; Kong et al., 2005; Pompili, Melodia, and Akyildiz, 2006b; Urick, 1983; Pompili, and Akyildiz, 2009].

In order to overcome the above challenges it is essential to design energy efficient routing protocols which belong to the category of geographical routing protocols and leverage the location information of sensor nodes to forward packets from a source node to a destination node. Such routing protocols are presented in this paper. The following routing protocols are examined:

1. Depth-Based Routing (DBR)
2. Vector-Based Forwarding (VBF)
3. Hop-by-Hop Vector-Based Forwarding (HH-VBF)
4. Sector Based Routing with Destination Location Prediction (SBR-DLP)
5. Focused Beam Routing (FBR)
6. Distributed Underwater Clustering Scheme (DUCS)
7. Under-Water Diffusion (UWD)
8. Multipath Routing

The paper is organized as follows. Section 2 presents all currently available routing protocols for UWSNs. Section 3 compares the routing protocols based on information regarding the protocol architecture, design and performance. Finally, Section 4 concludes and points out open research problems.

2 Description of routing protocols

In this section the various routing protocols for UWSN are presented. Criteria like packet delivery ratio, average delay, energy consumption, deployment of network and communication cost are used to describe them.

2.1 Depth-Based Routing (DBR)

DBR does not require complete dimensional information of location. It manages a dynamic network with good energy efficiency and utilizes multiple-sink network architecture without introducing extra cost.
Based on the depth information of each sensor, DBR forwards data packets towards the water surface. Furthermore, a data packet has a field that records the depth information of its recent forwarder and is updated at every hop [Yan, Shi, and Cui, 2008; Huang et al., 2009].

2.1.1 Protocol Overview

A multiple sink underwater sensor network architecture can be a benefit to DBR [Cui et al., 2006; Seah, and Tan, 2006] as shown in Figure 2, with the assumption that each underwater node knows its depth information namely the vertical distance from itself to the water surface. In fact, depth information can be obtained easily with a depth sensor. However, obtaining complete dimensional location information is rather difficult [Yan, Shi, and Cui, 2008]. As shown in Figure 2, the sensor nodes transmit acoustic signals (red dotted circle) to the sink nodes located at the surface. In their turn, they transmit radio signals (blue continuous circle) either to land stations or satellites.

[Insert Figure No 2]

The efforts of DBR are focused on the delivery of a packet from a source node to the sinks. The more a packet approaches its destination the smaller the depth of the forwarding nodes become, while trying to deliver a packet. A sensor node makes its decision on packet forwarding in a distributed way, based on its own depth and the depth of the previous sender. When receiving a packet, a node first retrieves the depth d_p of the packet's previous hop, which is embedded into the packet. The receiving node then compares its own depth d_c with d_p. Depending on the distance from the water surface, (dc < dp), it considers itself a qualified candidate to forward the packet. In any other case, it drops the packet considering that it comes from a node closer to the surface. In case that multiple qualified nodes try to broadcast the packet, high collision and high energy consumption will result. Consequently, to reduce collision as well as energy consumption, the number of forwarding nodes needs to be controlled by using a priority queue. Moreover, a node may receive the same packet multiple times. As a result, it may send the packet multiple times. By sending the same packet only once, it improves the energy efficiency [Yan, Shi, and Cui, 2008].

2.1.2 Routing Decision

Here, the procedure for routing packets from one node to the next node is presented. Each node maintains a priority queue Q1 and a packet history buffer Q2. An item in Q2 has a unique packet ID, which is composed of Sender ID and Packet Sequence Number. When a node successfully sends out a packet, it inserts the unique ID of the packet into Q2. When Q2 is full, the new item will replace the Least Recently Accessed (LRA) item. Q2 maintains a recent history of the packets the node has sent. An item in Q1 includes two components: a packet and the scheduled sending time for the packet. The priority of an item in Q1 is represented by the scheduled sending time. An item with earlier sending time has a higher priority. When a node receives a packet, instead of sending the packet immediately, it first holds the packet for a certain amount of time, called holding time. The scheduled sending time of a packet is computed based on the time when the packet is received and the holding time for the packet. At a node, an incoming packet is inserted into Q1 if it has not been sent by the node before (i.e., its unique ID is not in Q2) and it was sent from a lower node (i.e., a node with a larger depth, dp > dc). If a packet currently in Q1 is received again during the holding time, the packet will be removed from Q1 if the new copy is from a node with a smaller or similar depth (dp ≤ dc), or its scheduled sending time will be updated if the new copy is from a lower node (dp > dc). After a node sends out a packet as scheduled, the packet is removed from Q1 and its unique ID is inserted into Q2.

As shown in Figure 2a, node S is the sender, and nodes n_1, n_2, and n_3 are all its one-hop neighbouring nodes. The solid line circle represents the transmission range of node S. When node S broadcasts a packet, all neighbouring nodes will receive this packet. Node n_3 is below S so it discards the packet. Although nodes n_1 and n_2 are both qualified forwarding nodes, node n_1 is preferred to forward the packet. The forwarding of node n_2 is prevented if it receives the packet from n_1 before its own scheduled sending time for the packet [Yan, Shi, and Cui, 2008].

[Insert Figure No 2a]

2.1.3 DBR Performance

In order to evaluate the performance of DBR the following metrics were used [Yan, Shi, and Cui, 2008]:

1. Packet Delivery Ratio which is defined as the ratio of the number of distinct packets received successfully at the sinks to the total number of packets generated at the source node. Although a packet may reach the sinks multiple times, these redundant packets are considered as only one distinct packet.
2. Average End-to-end Delay which represents the average time taken by a packet to travel from the source node to any of the sinks.
3. Total Energy Consumption which represents the total energy consumed in packet delivery, including transmitting, receiving, and idling energy consumption of all nodes in the network.

According to simulations executed in one-sink and multiple-sinks [Yan, Shi, and Cui, 2008] the following conclusions are summarized:

a. When the depth threshold increases, both the packet delivery ratio and the total energy consumption decrease. This happenss because increasing the depth threshold has a similar effect to reducing the number of available nodes in the network. Therefore, the number of forwarding nodes will decrease. Consequently, the packet delivery ratio decreases and less energy is consumed.
b. The packet delivery ratio, the total energy consumption, and the average delay do not change much with respect to the node speed. The reason is that all routing decisions in DBR are made locally based on a node’s depth information. No topology or route information needs to be exchanged among neighbouring nodes. Therefore, DBR can handle dynamic network topologies well.
c. Furthermore, DBR with multiple-sinks achieves a better packet delivery ratio than DBR with one-sink.
d. The best end-to-end delay is achieved in multiple-sink DBR.
e. The total energy consumption for different number of sinks is almost the same; still it is reduced enough due to the redundant packet suppression techniques that are adopted by DBR.

f. DBR works well for dense networks but the delivery ratio in sparse networks is relatively low. However, DBR with the multi-sink settings can achieve a much better delivery ratio especially for sparse networks.

[Insert Table No 1]

2.2 Vector-based forwarding (VBF)

VBF was the first routing protocol designed for mobile underwater sensor networks where each of the sender's neighbouring nodes determines its candidacy to be the next relay node. In sensor networks, energy constraint is a crucial factor since sensor nodes usually run on battery, and it is impossible or difficult to recharge them in most application scenarios. In underwater sensor networks, in addition to energy saving, the routing algorithms should be able to handle node mobility in an efficient way. VBF aims at meeting these requirements successfully and can be more effective for networks with small or medium node mobility (1m/s – 3m/s). However, it makes the assumption that the location information of each sensor node can be obtained through a localization service, which is another difficult issue in UWSNs [Liu, Zhou, and Cui, 2008; Xie, Cui, and Lao, 2006; Yan, Shi, and Cui, 2008; Cheng et al., 2008].

2.2.1 Protocol Overview

In Figure 3, the packet is delivered from the source node S1 to the destination node S0 guided by the vector (a hypothetical line with coordinates beginning from the source to the destination node). Packets are forwarded only by those sensor nodes that are within a range W of the vector, where W is a system parameter that can be tuned. The bigger the W becomes the denser the network is. The forwarding process of VBF is thought to be a routing pipe (virtual pipe) between the source and the destination node. An intermediate node only forwards a packet to one of its neighbouring nodes, which is the closest to the vector. When sensor nodes are densely deployed, VBF may involve too many nodes in data forwarding, which in turn could increase the energy consumption. Still, in VBF only the nodes close to the routing vector are involved in packet forwarding and all other nodes are in idle state, resulting to energy saving [Xie, Cui, and Lao, 2006; Yan, Shi, and Cui, 2008].

[Insert Figure No 3]

In VBF, each packet carries the positions of the sender/transmitter, the target/destination and the forwarder/relay. The routing vector from the sender to the target specifies the forwarding path. Once a packet is received, the node computes its relative position to the relay and if it determines that it is close enough to the routing vector (virtual pipe), it puts its own computed position onto the packet and continues forwarding it. On the other hand, if it is not close enough to the routing vector, it just discards the packet. All the sensor nodes that forward a packet form a routing pipe in the sensor network.
VBF is scalable to the size of the network since it requires no state information at each node. The energy of the network is saved because only the nodes that come across the forwarding path are involved in packet routing [Xie, Cui, and Lao, 2006; Yan, Shi, and Cui, 2008].

2.2.2 Routing Decision

Here, the procedure for routing packets from one node to the next node is presented. A self-adaptation algorithm is created based on the concept of desirableness factor (meaning the criteria to measure the capability of a node to forward packets). This algorithm aims to select the most desirable nodes as forwarders. In this algorithm, when a node receives a packet, it first determines if it is close enough to the routing vector. If so, the node then holds the packet for a time period related to its desirableness factor. Each qualified node delays forwarding the packet by a time interval $T_{adaptation}$, which is calculated by a certain equation [Xie, Cui, and Lao, 2006]. During the delayed time period $T_{adaptation}$, if a node receives duplicate packets from n other nodes, then this node has to compute its desirableness factors relative to these nodes, $a_1,...,a_n$, and the original forwarder, a_0. If $\min(a_0, a_1,..., a_n) < a_c/2^n$, where a_c is a pre-defined initial value of desirableness factor ($0 \leq a_c \leq 3$), then this node forwards the packet; otherwise, it discards the packet [Xie, Cui, and Lao, 2006].

2.2.3 VBF Performance

In order to evaluate the performance of VBF the same metrics to DBR were used [Xie, Cui, and Lao, 2006], i.e. Packet Delivery Ratio, Average End-to-end Delay and Total Energy Consumption. Since the energy consumption on communication is determined by many factors such as the implementation of hardware, sleep control, and MAC protocols, Communication Time is used to evaluate the Energy Consumption [Al Tahan and Watfa, 2010].

According to simulations [Xie, Cui, and Lao, 2006], the following conclusions are summarized:

a. The routing pipe radius affects the above mentioned metrics greatly. The bigger the radius is, the higher success rate VBF can achieve the more energy it consumes and a better path is selected. Thus, in a network with uneven node distribution, it is difficult to choose a proper routing pipe radius threshold.
b. The packet delivery ratio, the total energy consumption, and the average delay do not change much with respect to the node speed. Therefore, VBF can handle node mobility effectively.
c. The packet delivery ratio is decreased for sparse networks whereas it is increased in dense networks.
d. VBF has a small end-to-end delay because it tries to find the shortest path from the source node to the sink along the virtual vector between them. So, the average delay is decreased in dense networks.

Once advanced adaptation algorithms are applied and optimal parameters are chosen (speed of each node, pipe radius, the number of nodes), VBF gets better energy-efficiency by selecting more desirable nodes especially for dense networks.

[Insert Table No 2]

2.3 Hop-by-Hop vector-based forwarding (HH-VBF)

The need to overcome two problems encountered by the VBF, i.e. small data delivery ratio in sparse networks, and sensitivity to the routing pipe's radius, the HH-VBF (hop-by-hop VBF) was proposed [Nicolaou et al., 2007]. HH-VBF forms the routing pipe in a hop-by-hop fashion, enhancing the packet delivery ratio significantly. Although it is based on the same concept of routing vector as VBF, instead of using a single virtual pipe from the source to the sink, it defines a different virtual pipe around the per-hop vector from each forwarder to the sink. In that way, each node can adaptively make packet forwarding decisions based on its current location [Liu, Zhou, and Cui, 2008]. This design can directly bring the following benefits:

i. Since each node has its own routing pipe, the maximum pipe radius is the transmission range. In other words, there is no necessity to increase the pipe radius beyond the transmission range in order to enhance the routing performance.
ii. In sparse networks, though the number of eligible nodes may be small, HH-VBF can find a data delivery path as long as there exists one in the network.

2.3.1 Protocol Overview

In HH-VBF, the routing virtual pipe is redefined to be a per-hop virtual pipe, instead of a unique pipe from the source (A or B) to the sink Z [Nicolaou et al., 2007] (Figure 4). When a node E receives a packet from the source A or a forwarder node D, it computes the vector from the sender to the sink. In this way, the forwarding pipe changes in every hop. After a receiver computes the vector from its sender to the sink, it calculates its distance to that vector. If this distance is smaller than the predefined threshold then it is eligible to forward the packet, and it is referred to as a candidate forwarder for the packet. When some areas of the network are not populated with nodes, for example there exist "voids" in the network, even a self adaptation algorithm may not be able to route the packets. In such case, a forwarder is unable to reach any node other than the previous hop.

[Insert Figure No 4]

In HH-VBF, when a node receives a packet, it first holds the packet for some time period proportional to its desirableness factor (this is similar to VBF). The node with the smallest desirableness factor will send the packet first. However, each node in the neighbourhood may hear the same packet multiple times. HH-VBF allows each node overhearing the duplicate packet transmissions to control the forwarding of this packet. So, the node calculates its distances to the various vectors from the packet forward to the sink. Figure 4 illustrates the basic idea of HH-VBF [Nicolaou et al., 2007].

2.3.2 Routing Decision

Here, the procedure for routing packets from one node to the next node is presented. As in VBF, each candidate forwarder maintains a self-adaptation timer which depends on the desirableness factor. The timer represents the time the node holds the packet before forwarding it. For a candidate forwarder F, the desirableness factor is defined by a new equation [Nicolaou et al., 2007]. The self-adaption algorithm in HH-VBF is different from that in the original VBF. Due to the effective packet suppression strategy adopted in VBF, only a few paths could be selected to forward packets. This may cause problems in sparse networks. Each node that qualifies as a candidate forwarder delays the packet forwarding by an interval $T_{adaptation}$ which is computed the same way as in VBF. Then each node still uses the self-adaptation algorithm to limit the redundant packets [Nicolaou et al., 2007].

2.3.3 HH-VBF Performance

In order to evaluate the performance of HH-VBF the following metrics were used [Nicolaou et al., 2007]:

1. Success rate which is defined as the ratio of the number of packets successfully received by the sink to the number of packets generated by the source.
2. Energy cost which is measured by the total energy consumption of all the nodes in the network.
3. Energy tax which is defined as the average energy consumption for each successfully received packet.

According to simulations [Nicolaou et al., 2007], the following conclusions are summarized:

a. There are more paths for data delivery in sparse networks compared to VBF.
b. The energy cost is high.
c. Increasing the node density, both the success rate and the energy consumption are increased.

[Insert Table No 3]

2.4 Sector Based Routing with Destination Location Prediction (SBR-DLP)

Many existing location-based routing protocols do not work well in underwater environments since the locations of the destination nodes are not assumed to be fixed and accurately known. The self-propelling capability of the destination nodes or the effect from the ocean currents, allow them to be inherently mobile. The SBR-DLP assumes that a node knows its own location and predicts the location of the destination node. The SBR-DLP is shown to enhance the packet delivery ratio significantly when all nodes are mobile [Chirdchoo, Soh, and Chua, 2009].

2.4.1 Protocol Overview

The SBR-DPL is a location-based routing algorithm, in which a sensor node neither carries any information about its neighbouring nodes (including their movements) nor about the network topology. Each node is aware of its own position, and the destination node's pre-planned movements. All other nodes are also aware of the destination's fixed location. Still, the fact that the destination node may deviate from its schedule due to the ocean currents cannot be neglected. More importantly, a node routes a packet to the destination in a hop-by-hop fashion, instead of finding the complete path before sending a packet. This is in contrast to some other applications, where the destination node can be fixed on the water surface acting as a gateway or a sink, and is in turn connected to a high speed backbone [Chirdchoo, Soh, and Chua, 2009]. SBR-DLP is different from both VBF and HH-VBF. Here, it is not the candidate node that decides whether it should relay the packet but the sender who determines its next hop using information received from the candidate nodes. This way the problem of having multiple nodes acting as relay nodes is eliminated. Moreover, it is not assumed that the location of the destination node is fixed and accurately known to the sender node. In addition, instead of using a single transmitting cone that covers only a fraction of the communication area, the SBR-DLP considers the entire communication circle to locate the candidate relay nodes. Furthermore, it does not need to rebroadcast the RTS (request to send) every time it cannot find a candidate node within its transmitting range [Chirdchoo, Soh, and Chua, 2009].

2.4.2 Routing Decision

Here, the procedure for routing packets from one node to the next node is presented. When a node S, wishes to send a packet (either a new or relay packet) to the destination node Z, it finds its next relay node by broadcasting a Chk Ngb packet, which includes the sender's current position and the packet ID. Upon hearing the Chk Ngb, each neighbouring node x, checks whether it is nearer to node Z than the distance between nodes S and Z, using the predicted location of node Z. If the condition is met, node x will have to respond to node S by transmitting a Chk Ngb Reply packet. Supposing that a node has just heard the Chk Ngb packet from a sender at time t_{now}, it first checks if it has previously heard the NTF packet (packet to notify its one-hop neighbours when deviating from the schedule significantly). If so, it will estimate the current location of the destination by looking at the destination's predefined movement, when the movement has changed by $\hat{\Delta}$ from its schedule (where $\hat{\Delta}$ is the estimated time difference from the predefined schedule). The node uses the parameters t_{NTF}, Δ, and t_{now} to compute $\hat{\Delta}$ using a certain equation [Chirdchoo, Soh, and Chua, 2009].

2.4.3 SBR-DLP Performance

In order to evaluate the performance of SBR-DLP the packet delivery ratio (PDR) was used [Chirdchoo, Soh, and Chua, 2009]. It is defined as the ratio of the number of unique DATA packets that are successfully received at the SINK to the total number of DATA packet transmissions.

According to simulations [Chirdchoo, Soh, and Chua, 2009], the following conclusions are summarized:

a. SBR-DLP is rather independent of the number of sectors, as the PDR is quite stable with respect to the number of sectors.
b. When location prediction is introduced, PDR is improved.
c. PDR increases dramatically as the number of nodes increases in this range.
d. PDR improves as the node speed increases.

In general, node mobility can be both advantageous and disadvantageous to routing protocols. On the one hand, the change in topology caused by node mobility may harmfully cause the network to be disconnected; on the other hand, it may beneficially allow the network to be reconnected. For those protocols that take node mobility into account adequately, they can make the advantages outweigh the disadvantages. SBR-DLP takes node mobility into account during the process of finding the next relay node. Thus, it benefits more from the change in topology caused by node mobility, which explains why PDR increases with node speed.

[Insert Table No 4]

2.5 Focused Beam Routing (FBR)

FBR protocol is a scalable routing technique for multi-hop ad-hoc networks based on location information [Jornet, Stojanovic, and Zorzi, 2008]. It is suitable for networks containing both static and mobile nodes, which are not necessarily synchronized to a global clock. A source node must be aware of its own location and the location of its final destination, but not those of other nodes. The FBR protocol can be defined as a cross-layer approach, in which the routing protocol, the medium access control and the physical layer functionalities are tightly coupled by power control. It can be described as a distributed algorithm, in which a route is dynamically established as the data packet traverses the network towards its final destination. The selection of the next relay is made at each step of the path after suitable candidates have proposed themselves.

2.5.1 Protocol Overview

The analysis of this routing protocol is done with the presentation of the example illustrated in Figure 5. A network of nodes is distributed in an arbitrary way across an area. Node A wants to transmit to node B. The former issues a RTS to its neighbours. RTS is a short control packet that contains the location of the source node (A) and of the final destination (B). In fact this is a multicast request. The lowest power level is used at the initial transaction and is increased only if required. Power control is performed as an integral part of routing and medium access control.

[Insert Figure No 5]

The transmitting node chooses which power level to use among several discrete levels instead of being instructed by a receiving node. A transmission radius dn, corresponds to a power level Pn. Nodes within this radius (such as node C & D) are able to receive the signal at a level sufficient for detection. Although the signal propagates beyond this radius, it cannot be detected due to attenuation. Additionally it causes interference to other nodes. Until a node is reached or all power levels have been exhausted, the power will be kept increasing by the transmitting node. If no-one can be reached at the maximal level Pn, the transmitter will shift its cone and start looking for candidate relays. Once the transmitter reaches a single neighbour node (like node D), after increasing the power to some level, it passes the data packet on to that neighbour, who becomes a relay. An identical procedure is initiated by the relay, with transmission radius dn1, looking for candidate nodes within its cone towards the final destination (node B). If more than one candidate relays exist, it is up to sender to choose for the one. Node (A) receives all replies when there is no collision and knows which candidate is closest to the final destination since the reply includes the sender's location. Then it chooses the closer one as the relay, and the data packet is passed on to it. The link is secured and there are no risks of data packet collisions. In case a collision is detected (when detecting signal energy without being able to decode a packet), node A will still send the RTS using the same power level [Jornet, Stojanovic, and Zorzi, 2008]. The FBR assumes that the destination node is fixed and its location is accurately known. Furthermore, it needs to rebroadcast the RTS every time it cannot find a candidate node within its transmitting cone. It is worth noticing that even if the FBR extends its transmitting cone to an angle width of 180^0, due to the lack of a collision avoidance mechanism, the CTS (Clear to Send packets) from different neighbours may collide easily, which degrades the performance. This problem is highly pronounced in a dense network [Chirdchoo, Soh, and Chua, 2009]. The above procedure describes the routing decision also.

2.5.2 Routing Decision

Here, the procedure for routing packets from one node to the next node is presented. Supposing that, there is an imaginary line between nodes A and B. All the nodes that receive A's multicast RTS first calculate their location relative to the AB line. The objective in doing so is to determine whether they are candidates for relaying. Candidate nodes are those that lie within a cone of angle $\pm\theta/2$ emanating from the transmitter towards the final destination. If a node determines that it is within the transmitter's cone, it will respond to the RTS. Those nodes that are outside the cone will not respond [Jornet, Stojanovic, and Zorzi, 2008].

2.5.3 FBR Performance

In order to evaluate the performance of FBR the following metrics were used [Jornet, Stojanovic, and Zorzi, 2008]: energy per bit consumption, end-to-end delay, and number of collisions.
The average energy per bit consumption takes into account the energy invested in transmission, listening and active reception of control and data packets, as well as their possible retransmissions.
According to simulations [Jornet, Stojanovic, and Zorzi, 2008], the results are shown for two cone apertures and compared to the ones obtained when following static routes.

a. In very dense networks, paths following minimum power routes (maximum number of hops) are not optimal in terms of energy savings; instead there is a minimum distance that should be traversed in each hop.
b. Both the energy per bit and the average end-to-end delay are very close to the case when static routes are followed.
c. When closing the cone:
    i. Fewer nodes propose themselves as relays.
    ii. Zigzagging is prevented.
    iii. Shorter delay takes place.
    iv. Higher power levels may be used.

[Insert Table No 5]

2.6 Distributed Underwater Clustering Scheme (DUCS)

DUCS is an adaptive self organizing protocol that forms clusters. It is considered that there are always data to be sent to the sink by the underwater sensor nodes and that power control can be used to adjust the transmission power. DUCS tries to be adapted to the intrinsic properties of underwater environments, such as long propagation delays, low data rates and difficulty of synchronization. DUCS compensates the high propagation delays of the underwater medium using a continually adjusted timing advance combined with guard time values to minimize data loss and maintain communication quality [Domingo and Prior, 2007].

2.6.1 Protocol Overview

In DUCS the nodes organize themselves into local clusters (Figure 6) and one node is selected as cluster-head for each cluster. Code 1 is the cluster-head for the cluster consisted of nodes-cluster members N1, N7, N9, and N16. Together, the same stands for the rest of the clusters with cluster-heads Code 2, Code 3, etc.

[Insert Figure No 6]

All data coming from non-cluster head nodes are transmitted to their cluster-head (i.e. Code 3) via a single hop. On the other hand, the cluster-head node receives data transmitted from all cluster members, performs signal processing functions on the data (e.g. data aggregation) and transmits the data to the sink (via the relays of other cluster-heads) using multi-hop routing. The sink is illustrated in the Figure 6 as star shaped. Correlated data are processed very frequently by nodes close to each other since they monitor the same phenomena. With the aid of data aggregation techniques the effective non-redundant data can be extracted by the cluster-head (i.e. Code 2) and sent to the sink (star-shaped), resulting to energy savings. DUCS incorporates randomized rotation of the cluster-head among the sensors to avoid draining the battery of any underwater sensor in the network [Domingo and Prior, 2007].
The operation of DUCS is divided into rounds (Figure 7). Clusters are formed during the set-up or clustering creation process and data transfer occurs during the network operation or the steady-state phase. During the network operation phase several frames are sent to each cluster-head; a frame is formed by a series of data messages that the non-cluster head sensor nodes send to the cluster-head using a schedule (each non-cluster head sensor node sends one data message consuming a time slot). Both phases are repeated periodically.

[Insert Figure No 7]

Due to the different high propagation delay in the underwater medium, there is overlapping at the cluster head of data messages from different cluster members, resulting to communication loss. The problem is solved when each sensor node advances its transmission relatively to its reception by a time compensating the propagation delay. This value is called timing advance, a concept used in other communications systems like GSM (Global System for Mobile Communications). It can only be computed by the cluster-head for each node. When a cluster-head knows which nodes will belong to its cluster, it sends an acoustic signal to them in order to measure the round-trip time, estimating the propagation delay to each non-cluster head node in its cluster [Cui et al., 2006; Mouly and Pautet, 1992].

2.6.2 Routing Decision

Here, the procedure for routing packets from one node to the next node is presented. A node initially sets its probability to become cluster-head. Each non-cluster head decides to which cluster it belongs by choosing the cluster-head that requires the minimum communication energy and consequently its power level required for transmission is minimized. The transmission power is directly proportional to the square of the distance between sensor nodes in deep water scenarios (with sea depth larger than 100 m). Therefore, each non-cluster head should calculate its distance (cost) to each self-elected cluster-head neighbour with the aid of acoustic-only Time-of-Arrival (ToA) approaches (e.g. measuring round-trip time that an acoustic signal suffers) [Cui et al., 2006] and select the nearest one. During the clustering creation process, the nodes compute their remaining energy and calculate their probability to become a cluster-head. During this phase, a node processes the cluster-head announcements it has received to select the lowest cost cluster-head. After each node has decided to which cluster it wants to belong, it must inform the cluster-head sending a join-request message back using CDMA (Code Division Multiple Access). As a result, nodes with higher residual energy become cluster-heads and lower intra-communication cost is spent. After the clustering creation process is over, each cluster-head should coordinate the data transmissions in its own cluster. The cluster-head sets up a TDMA (Time-Division Multiple Access) schedule, and transmits this schedule using CDMA to the cluster members. TDMA has been selected as Medium Access Control (MAC) protocol inside a cluster because it avoids collisions between non-cluster head members of the same cluster and because it enables that non-cluster head nodes are turned off whereas they do not transmit; therefore, they remain in the sleep mode and thus energy consumption is reduced [Domingo and Prior, 2007].

2.6.3 DUCS Performance

In order to evaluate the performance of DUCS the following metrics were used [Domingo and Prior, 2007]: Packet delivery ratio (percentage of data packets successfully delivered), average routing overhead (the number of control packets - for routing - divided by the sum of control packets plus data packets) and number of nodes alive per number of data messages sent that arrive to the sink.
According to simulations [Domingo and Prior, 2007], the following conclusions are summarized:

a. DUCS's routing overhead is maintained well below 30% because the cluster-head advertisement messages are sent directly to the neighbours and not through the entire network.
b. DUCS achieves very high packet delivery ratios even in large network sizes because of the use of timing advance and time guards that enable it to send properly more data packets and avoid acoustic collisions at the cluster head when cluster members using adjacent time slots send their data.
c. DUCS can deliver data to the sink effectively.

[Insert Table No 6]

The simulations demonstrate the DUCS's scalability and good performance. DUCS achieves a very high packet delivery ratio while it considerably reduces the network overhead and increases the throughput; consequently, its basic characteristics can be applied to the design of other routing protocols for UWSNs.

2.7 Under-Water Diffusion (UWD)

Flooding cannot be both reliable and efficient. Since current GPS-free routing and diffusion schemes rely on (network-wise or controlled) floods, a direct application of these schemes fails with high probability. To answer this challenge, UWD is proposed. UWD is a multi-hop ad hoc routing protocol. It minimizes the number of all packet transmissions to avoid possible acoustic collisions. It considers homogeneous GPS-free nodes and random node mobility. UWD is best suited for real-time surveillance applications such as submarine detection [Lee et al., 2006].

2.7.1 Protocol Overview

The UWD protocol follows a non-intrusive design guided by the following principles:

1. No proactive routing message exchange. Once a set of sensor nodes detects an event, multi-hop acoustic paths are created on demand. This way, UWD is able to minimize the number of floods and the number of various other packet transmissions to avoid looming acoustic collisions.
2. Reduce the number of packet transmissions to minimum to avoid acoustic collision. A dynamic unicast-based path management technique is used, called community to community forwarding [Kong et al., 2005] in order to reduce the number of on-demand floods, handle random node mobility and avoid packet floods in general.

There are 6 packet types in UWD (Figure 8): "Interest", "SinkDiscovery", "UnicastReply", "Probe", "TakeOverHappens" and "EventReport". The first two are flooding packets transmitted by MAC broadcast [Lee et al., 2006].

[Insert Figure No 8]

Initial floods are expensive and required at the beginning phase of UWD. In the beginning, the sink floods a message to the network called "Interest", containing monitoring information such as a monitored area, types of events, a report interval and expiration time. Depending on whether the sensor node is able to detect an event within a time threshold, two cases are distinguished. Firstly, if the detection of the event happens within T, then the source node can send data to the sink via the shortest latency path. It is named the Immediate Report Protocol (IRP). Secondly, if the event happened after time > T, routing entries are no longer current. A new procedure commences where the node must once again issue a "SinkDiscovery" message to find the optimal route towards the sink. Afterwards, there will be a "UnicastReply" response towards the source by the sink node, in a delayed fashion, giving the characterization of Delayed Report Protocol (DRP). In UWD, there are two types of flooding messages: "Interest" and "SinkDiscovery". In either IRP or DRP, an "Interest" is only sent once. In DRP, a source proactively sends a "SinkDiscovery" message when it detects an event. Then a "UnicastReply" is reactively sent back by the sink. The UWD limits the use of flooding unless it is necessary. This is achieved by virtue of the community to community forwarding approach as described in the following paragraph regarding the routing decision [Lee et al., 2006].

2.7.2 Routing Decision

Here, the procedure for routing packets from one node to the next node is presented. The community-to-community forwarding approach exploits two innate characteristics of wireless sensor networks: (1) redundancy of deployment and (2) omni-directional signal propagation in wireless channels. Figure 8a shows the simplest example of a forwarding community between a source A and its sink C that is two-hop away. In a 3-D UWSN, the community area is defined by the intersection of three transmission balls of A, B and C. The nodes in the community area are community members that can forward a packet between A and C. As depicted in Figure 8b, this approach can be extended to a chain of forwarding communities along a multi-hop path.

[Insert Figure No 8a]

[Insert Figure No 8b]

2.7.3 UWD Performance

In order to evaluate the performance of UWD the following metrics were used [Lee et al., 2006]: average event delivery delay, distinct-event delivery ratio, and average overhead. Average delay measures the average event latency that is the time between sending an event from a source and receiving the event at a sink. Distinct-event delivery ratio is the ratio of the total number of events received by the sink to the number of events sent by the source(s). This

metric shows how the proposed protocol reacts to the node mobility. Average overhead measures the average number of packets sent per node. Since a major source of overhead is flooding, this metric is used to show how UWD limits the use of flooding compared to Directed Diffusion.
According to simulations [Lee et al., 2006], the following conclusions are summarized: Reducing the number of floods is a key design choice in designing underwater sensor network protocols. In underwater, Directed Diffusion which manages mobility using periodical flooding is less efficient because of its heavy use of flooding. UWD, on the other hand, by limiting flooding, can increase overall delivery ratio and reduce per node overhead.

[Insert Table No 7]

2.8 Multipath Routing

A way to achieve robustness in underwater environment is the use of multipath data delivery. Typical multipath routing protocols setup multiple routes between a pair of communicating nodes [Guo et al., 2008]. Depending on how the routes are selected, there is a strong likelihood of contention occurring among nodes that are on different routes but close to one another (Figure 9).

2.8.1 Protocol Overview

In this network the local sink (cube-shaped) connections are assumed to be via high speed links. This can be accomplished with the local sinks being wired to a buoy on the surface equipped with RF communications link or an undersea high-speed optical fibre. It is assumed that the resources of the network are more than sufficient to support the communication needs of the various applications. Therefore, the ultimate goal of the underwater network is to ensure that data are delivered to one or more of these local sinks which collectively form a virtual sink [Seah, and Tan, 2006; Zhou, and Cui, 2008].

[Insert Figure No 9]

An end-to-end connectivity to the local aggregation points is provided by a robust multi-path data delivery scheme. Due to the properties of the underwater medium it is preferable for the nodes to cache data and transmit when the channel conditions are favourable rather than attempt multiple retransmissions. On the contrary, for time-critical data, a successful delivery is considered by delivering data over more routes rather than caching. Similarly, the local aggregation points form a wireless mesh network that provides multiple paths to multiple local sinks which collectively form the virtual sink. Simultaneous arrival of high traffic from sensor nodes may cause congestion at aggregation points (mesh nodes). The strategy of deploying redundant nodes is used in order to increase the availability of multiple disjoint paths such that backup routes are readily available. This is crucial for sending time-critical delay intolerant data that cannot be cached until the channel conditions improve. The multipath routing protocol will select the appropriate routes from those available to achieve the required service levels. As shown in Figure 9, the local aggregators (tube-shaped) collect the data from the sensors (dots) of the network and transmit them to the local sinks through acoustic signals. Finally, the local sinks are connected with surface sinks-buoys either with wires or high-speed optical fibers.
Between a pair of communicating nodes, multiple routes are setup by typical multipath routing protocols [Mueller, Tsang, and Ghosal, 2004]. It is possible that contention occurs among nodes that are on different routes but close to one another depending on how the routes are selected. That contention is even higher as the routes converge at the destination node. Hence, the redundancy that multipath provides in the attempt to improve packet delivery is nullified by the contention among nodes, which can be made worse by

retransmissions. Considering that a node (e.g. A in Figure 10) sends a packet simultaneously over spatially diverse routes to multiple sinks (S1, S2 and S3), which form the virtual sink, and as long as a copy of the packet reaches one of these sinks, delivery is successful. This can be considered as "retransmitting" a packet simultaneously instead of sequentially, achieving lower latency and less packet transmissions, thus saving energy. The use of spatially diverse paths also reduces the possibility of contention [Seah and Tan, 2006].

[Insert Figure No 10]

In Figure 10, two procedures are compared to each other with respect to the number of transmissions, in order to save energy. When simultaneously transmitting from source A to the 3 sinks, the number of transmissions is calculated considering the number of sources (equals to 1) and the number of the nodes in between (equals to 2). So, by following the equation 1+3x2, the result is 7. On the other hand, when sequentially transmitting from source A to a sink there has to be a retransmission back to the source in order for the source to know whether it should transmit to the next node or not. In that case the total transmissions reach the total number of 9. In conclusion, the sequential procedure is most preferable.

2.8.2 Routing Decision

Here, the procedure for routing packets from one node to the next node is presented. The basic procedure of multi-path routing is illustrated in Figure 10a. When the source node has some packets to send, it will flood a "Route Request" message to the destination. Any intermediate nodes that receive this "Route Request" for the first time will forward it. When the destination receives "Route Request" messages, it will reply with "Route Reply" messages reversely along the paths of the corresponding "Route Request" messages. The destination can also make path selection. It can select node-disjoint paths and send "Route Reply" back to them. After the source node receives the "Route Reply" messages, the routes between the source and the destination are established. From the received "Route Reply" messages, the source node gets to know some path characteristics, such as the number of available paths, m, and the hop lengths of the paths. Based on this information, the source node will determine the optimal number of paths, m*, and select m* paths from the m available paths. It also needs to calculate the optimal power level that every intermediate node on these paths should use for packet transmission [Seah and Tan, 2006].

[Insert Figure No 10a]

2.8.3 Multipath Routing Protocol Performance

In order to evaluate the performance of Multipath Routing Protocol the following metrics were used [Seah, and Tan, 2006]:

1. Total number of packets forwarded – As the static nodes in the network may not be within the transmission range of the sink(s), data that are generated may have to travel through multiple hops before they can reach the sink(s). Hence, this metric counts the total number of packets that are forwarded by intermediate nodes before they reach the sink.
2. Total number of transmissions – It is the total number of packet transmissions that take place throughout the network, during the simulated network lifetime. It includes any retransmissions as well as data forwarding by the intermediate nodes.
3. Total number of packets received by all the sinks – In the multipath schemes, different sinks may receive the same packet. This metric counts all packets received by all sinks.
4. Packet Delivery Ratio (PDR) – It is given by the total number of unique packets received by all the sinks as a fraction of the total number of packets that are generated by the sinks.

5. Redundancy factor R_f – It is given by the total number of duplicate packets received as a fraction of the total number of unique packets received by all the sinks in the network. It gives a measure of the overall efficiency and redundancy of the schemes. A redundancy factor of 0 means that there are no duplicate packets being received by the sinks. The higher the value of R_f, the higher the number of duplicated packets and the higher the amount of wasted resources in the network
6. Average end-to-end delay – It is the average shortest time taken for a packet to travel, from its origin to any one of the sinks.
7. Total number of ACKs sent – This is the total number of one-hop ACKs that are being sent by the nodes in the network, upon the receipt of a data packet.
8. Total number of retransmissions – Retransmissions may be performed by the source node or the intermediate forwarding node when it does not receive an ACK from the next forwarding node or expected destination.

According to simulations [Seah and Tan, 2006], the following conclusions are summarized:

a. The total number of forwarded packets in the single path scheme is less than that of the multiple path scheme which sends multiple copies of the same data packet to multiple sinks at the same time.
b. Under the multipath scheme, the total number of transmissions decreases with increasing PLR (Packet Loss Ratio) because the probability of dropped packets increases. In the single-path scheme, the number of transmissions decreases less gradually than that of the multipath scheme because retransmission attempts are allowed for lost data packets.
c. The single-path scheme achieves lower PDR than that of the multi-path scheme due to the unnecessary retransmission of data packets resulting from lost ACK packets. When the number of permissible retransmissions is higher, there is a higher possibility of more redundant data duplicates in the network, resulting in more packet collisions and data loss.
d. Under the multi-path scheme, the delay appears to be quite constant and independent of the PLR, because the source node sends multiple copies of a packet to different sinks, and only the shortest end-to-end delay (of the first copy to reach a sink) is being considered during the delivery.

[Insert Table No 8]

3 Comparisons among routing protocols

In this paper several types of underwater routing protocols have been presented. Each one is based on different protocol designs. The most important features of each protocol are the following:

1. DBR with multi-sink settings can achieve very high packet delivery ratios for dense networks with only small communication cost. DBR can work in one-sink networks but it achieves better performance in multiple-sink settings.
2. VBF gets better energy efficiency by selecting more desirable nodes especially for dense networks. Furthermore, it is scalable to the size of the network since it requires no state information at each node.
3. HH-VBF facilitates the avoidance of any “void” areas in the network.
4. SBR-DLP eliminates the problem of having multiple nodes acting as relay nodes.
5. FBR is suitable for networks containing both static and mobile nodes.
6. DUCS is a new GPS-free clustering scheme.
7. UWD is a multi-hop ad hoc routing protocol which minimizes the number of all packet transmissions to avoid possible acoustic collisions.
8. Multi-path routing reduces the forward delay by the use of multipath data delivery.

The presented protocols make different assumptions regarding the network conditions, their operations, their objectives, etc. So, it is not feasible to compare all of them simultaneously.

However, there exist simulation comparisons between pairs: i) DBR vs. VBF, ii) VBF vs. HH-VBF, and iii) SBR-DLP vs. FBR.

3.1 DBR vs. VBF

When comparing DBR with VBF [Xie, Cui, and Lao, 2006], two DBR settings were considered: One-sink and multiple-sinks. For one-sink DBR, the depth threshold was set to 0. In multiple-sink DBR, 5 sinks were randomly deployed at the water surface and the depth threshold was set to 20 meters. For VBF, the routing pipe radius was set to 100 meters, which is the maximal transmission range. In Figure 11 (a, b, c) DBR and VBF are compared with respect to the packet delivery ratio, the energy consumption and the end-to-end delay.

[Insert Figure No 11a]

In the one-sink setting, DBR achieved a similar packet delivery ratio to VBF (Figure 11a). In the multi-sink setting, DBR achieved a much better delivery ratio, especially for sparse networks.

[Insert Figure No 11b]

DBR achieved better energy efficiency compared to VBF (Figure 11b). The total energy consumption of DBR was about half that of VBF because of the redundant packet suppression techniques adopted by DBR.

[Insert Figure No 11c]

In one-sink setting, VBF achieved a better end-to-end delay (Figure 11c). VBF tries to find the shortest path from the source node to the sink along the virtual vector between them. In multi-sink setting, DBR achieved better end-to-end delay. Packets can be delivered to any sink, instead of a fixed sink.

Concluding, DBR achieved better performance in multiple-sink settings and performed well for dense networks. However, the delivery ratio in sparse networks was relatively low. The reason is that DBR has only a greedy mode. The greedy method alone is not able to achieve high delivery ratios in sparse networks, without investigating recovery algorithms for DBR. It requires more memory in sensor nodes to maintain two buffers. Since the underwater sensor nodes normally are equipped with more resources than land-based sensor nodes, the memory overhead is not significant in most systems. Moreover, the applications for underwater sensor networks have relatively low data rate so only small buffers need to be maintained [Yan, Shi, and Cui, 2008].

3.2 VBF vs. HH-VBF

The VBF achieves small delivery ratio in sparse networks. It is sensitive to the routing radius of the pipe. The candidate node decides for the relay of a packet. The location of the destination node is fixed and accurately known to the sender.
The HH-VBF enhances the packet delivery ratio significantly, by forming the routing pipe in a hop-by-hop fashion. The candidate node decides for the relay of a packet. It can find more paths for data delivery in sparse networks and it is less sensitive to the routing pipe radius. The location of the destination node is fixed and accurately known to the sender. In Figures 12(a, b) VBF and HH-VBF are compared with respect to the success rate and energy cost.

[Insert Figure No 12a]

The success rate of HH-VBF was significantly improved compared to VBF, especially when the network was sparse (Figure 12a).

[Insert Figure No 12b]

The energy cost of HH-VBF was higher than that of VBF, and the gap became more significant as the network got denser (Figure 12b). This is reasonable as the higher the node density, the more paths HH-VBF can find. When the network was sparse, the normalized energy cost of HH-VBF was much lower than that of VBF.

This further confirms that VBF is not efficient for sparse networks. On the other hand, when the network gets denser, VBF shows its advantage over HH-VBF: HH-VBF still tends to find more paths, while the delivery ratio has reached the maximum. In this case, more paths do not help to increase the success rate, but more energy cost will be introduced. All the above conclusions are briefly summarized in Table 9. DBR and VBF can easily be compared due to the fact that they have the same metrics.

[Insert Table No 9]

3.3 SBR-DLP vs. FBR

SBR-DLP: The sender decides which will be its next hop using information from the candidate nodes trying to eliminate the problem of having multiple nodes acting as relay nodes. It makes no assumption about the location of the destination node being fixed and accurately known to the sender node. It takes into consideration the entire communication circle to locate the candidate relay node. It does not need to rebroadcast RTS every time it cannot find a candidate node within its transmitting cone. Each node is only aware of its own position and the destination of node's pre-planned movements. It avoids the need for flooding by routing a packet in a hop by hop fashion.
Focused Based Routing (FBR): The sender decides which will be its next node using information from the candidate nodes. The destination node is fixed and accurately known to the sender. It needs to rebroadcast RTS every time it cannot find a candidate node within its transmitting cone. It lacks of a collision avoidance mechanism regarding dense networks, so the CTS from different neighbours may collide easily, resulting to performance degradation.

In conclusion, the advantages and weaknesses of each routing protocol are summarized in Table 10.

[Insert Table No 10]

To summarize, a complete presentation of all routing protocols for UWSNs is presented in Table 11, by using criteria such as performance, robustness, sparse and dense network, mobility, static-dynamic, full dimensional location, information needed, multi-hop and scalability.

[Insert Table No 11]

4. Conclusions

In this paper, routing protocols for underwater sensor networks are presented and compared. After presenting the overview of each routing protocol, available comparisons among them are presented. The comparison is necessary in order to point out which routing protocol is best according to the desirable use.

As a general conclusion we could notice that all of them are energy efficient and scalable, they can handle dynamic networks and most of them require full dimensional localization of the source, the destination and the intermediate nodes.

Taking into consideration that the major goal of building an UWSN is achieving the best possible performance, there are certain factors worth noticing which are depended on one another. Factors such as the number of deployed nodes in the network regulate metrics dealing with matters of economical and energy consumption value. As a result the network layer is affected accordingly. It has been pointed out that in a sparse network the PDR and the total energy consumption are usually low. The routing protocols that prove the above remark include the DBR, VBF, HH-VBF, and SBR-DLP. There is no general conclusion but it is mostly noticed that the end-to-end delay is higher as the number of nodes is decreasing. The FBR is opposed to the above remark since not only the energy consumption is higher but the end-to-end delay becomes significantly low in a sparse network. Regarding the DBR, VBF, and HH-VBF protocols, the node speed has minor or no affect at all on the PDR, on the total energy consumption and on the end-to-end delay. Only the SBR-DLP makes the difference since by increasing the node speed, the PDR also increases.

Finally, DUCS performs very well since it meets at a satisfactory level all the desirable criteria [Domingo and Prior, 2007]. On the other hand, DBR seems to be not adequate enough having as a major drawback the low performance especially in dense networks [Yan, Shi, and Cui, 2008].

Concluding, the major advantages and disadvantages of the routing protocols for the UWSNs in headlines are presented in Table 12

[Insert Table No 12]

Based on the work discussed in the previous sections, it is clear that some issues need further investigation. The following include open challenging issues:

- The extensive evaluation of the performance and reliability of every routing protocol and the comparison among various routing protocols with respect to multiple measures.
- The implementation of these routing protocols in real world conditions taking into consideration all the underwater challenges such as high propagation delay, impaired channel due to fading, limited bandwidth, high bit error rate and failures because of fouling and corrosion among others.
- The development of routing protocols that:
  - achieve increased PDR in sparse networks,
  - reduce the communication time in dense networks,
  - reduce the disconnections due to the nodes' mobility.
  - minimize the total energy consumption regardless of the network's density,
  - avoid the void areas in the network and handle the loss of connectivity.
- The investigation of innovative methods for battery recharge (e.g. by sea currents).

REFERENCES

Al Tahan, A. M., and Watfa, M. K. (2010). "A position-based routing algorithm in 3D sensor networks", *Wireless Communications and Mobile Computing*, Published online in Wiley InterScience (www.interscience.wiley.com) DOI: 10.1002/wcm.888.

Ayaz, M., and Azween, A. (2009). "Underwater wireless sensor networks: Routing issues and future challenges", in *Proceedings of the 7th International Conference on Advances in Mobile Computing and Multimedia*, Kuala Lumpur, Malaysia, 2009, pp. 370-375.

Bartoš, R., Chappell, G. S., Komerska, J. R., Haag, M. M., Mupparapu, S. S., Agu, E., and Katz, I. (2008). "Development of routing protocols for the solar-powered autonomous underwater vehicle (SAUV) platform". *Wireless Communications and Mobile Computing*, Vol. 8, Issue 8, October 2008, pp. 1075-1088.

Casari, P., Stojanovic, M., and Zorzi, M. (2007). "Exploiting the bandwidth–distance relationship in underwater acoustic networks", in *IEEE/MTS Oceans 2007*, Vancouver, BC, Canada, October 2007, pp. 1–6.

Cerpa, A., Elson, J., Estrin, D., Girod, L., Hamilton, M., and Zhao, J. (2001). "Habitat monitoring: Application driver for wireless communications technology", in *Proceedings of the ACM SIGCOMM Workshop on Data Communications in Latin America and the Caribbean*, Apr. 2001, pp. 20-41.

Cheng, X., Shu, H., Liang, Q., and Du, D. H.-C. (2008). "Silent positioning in underwater acoustic sensor networks". *IEEE Transactions on Vehicular Technology,* Vol. 5, No. 3, pp. 1756-1766.

Chirdchoo, N., Soh, S. W., and Chua, C. K. (2009). 'Sector-based routing with destination location prediction for underwater mobile networks', in *Waina, 2009, International Conference on Advanced Information Networking and Applications Workshops*, pp. 1148-1153.

Cui, H. J., Kong, J., Gerla, M., and Zhou, S. (2006). 'Challenges: Building scalable mobile underwater wireless sensor networks for aquatic applications', *Special Issue of IEEE Network on Wireless Sensor Networking*, Vol. 20, No. 3, pp. 12–18.

Delaney, R. J., and Chave, D. A. (2000). 'Neptune: A fiber-optic 'telescope' to inner space', *Oceanus*, Vol. 42, No. 1, pp. 10–11.

Domingo, C. M., and Prior, R. (2007). 'Design and analysis of a GPS-free routing protocol for underwater wireless sensor networks in deep water', in *International Conference on Sensor Technologies and Applications (SENSORCOMM 2007)*, pp. 215-220.

Filipe, L., Vieira, M., Lee, U., and Gerla, M. (2008). "Phero-trail: A bio-inspired location service for mobile underwater sensor networks", in *Proceedings of the third ACM international workshop on Underwater Networks, International Conference on Mobile Computing and Networking,* San Francisco, California, USA, 2008, pp. 43-50.

Gopi, S., Kannan, G., Desai, U. B., and Merchant, S. N. (2008). "Energy optimized path unaware layered routing protocol for underwater sensor networks", in *Proceedings of Global Telecommunications Conference, IEEE GLOBECOM 2008*, New Orleans, LO, December 2008, pp. 1-6.

Guo, Z., Colombi, Wang, B. G., Cui, H. J., Maggiorini, D., and Rossi, G.P. (2008). 'Adaptive routing in underwater delay/disruption tolerant sensor networks', in *Wireless on Demand Network Systems and Services, WONS 2008*, pp. 31–39.

Heidemann, J., Wills, W. Y. J., Syed, A., and Yuan, L. (2006). 'Research challenges and applications for underwater networking', in *Wireless Communications and Networking Conference 2006*, Las Vegas, NV, Vol. 1, April 2006, pp. 228–235.

Hu, T., and Fei, Y. (2010). "QELAR: A machine-learning-based adaptive routing protocol for energy-efficient and lifetime-extended underwater sensor networks", I*EEE Transactions on Mobile Computing*, Vol. 9, Issue 6, pp. 796-809.

Huang, C. J., Wang, W. Y., Shen, Y. H., Hu, W. K., Hsu, A. P., and Chang, Y. T. (2009). "A direction-sensitive routing protocol for underwater wireless sensor networks", in *Proceedings of the 22nd International Conference on Industrial, Engineering and Other Applications of Applied Intelligent Systems,* Taiwan, pp. 419-428.

Jornet, M. J., Stojanovic, M., and Zorzi, M. (2008). 'Focused beam routing protocol for underwater acoustic networks', in *Proceedings of the third ACM International workshop on Underwater Networks, International Conference on Mobile Computing and Networking,* pp. 75-82.

Kilfoyle, B. D., and Baggeroer, B. A. (2000). 'The state of the art in underwater acoustic telemetry', *IEEE Journal of Oceanic Engineering*, Vol. 25, No. 1, pp. 4–27.

Kinsler, E. L., Frey, R. A., Coppens, A. B., and Sanders, V. J. (1999). '*Fundamentals of Acoustics*', John Wiley and Sons.

Kong, J., Cui, H.J., Wu, D., and Gerla, M. (2005). 'Building underwater ad-hoc networks and sensor networks for large scale real-time aquatic applications', in *Proceedings of IEEE Military Communications Conference (MILCOM'05)*, Atlantic City, pp. 1535–1541.

Kong, J., Hong, X., Yi, Y., Park, S. J., Liu, J., and Gerla, M. (2005). 'A secure ad-hoc routing approach using localized self-healing communities', in *ACM MOBIHOC'05*, pp. 254–265.

Lanbo, L., Shengli, Z., and Cui, H.J. (2008). "Prospects and problems of wireless communication for underwater sensor networks", *Wireless Communications & Mobile Computing*, Vol. 8, Issue 8, October 2008, pp. 977-994.

Lee, U., Kong, J., Park, S. J., Magistretti, E., and Gerla, M. (2006). 'Time-critical underwater sensor diffusion with no proactive exchanges and negligible reactive floods', in *Proceedings 11th IEEE Symposium on Computers and Communications (ISCC'06)*, pp. 609-615.

Liu, L., Zhou, S., and Cui, J. H. (2008). 'Prospects and problems of wireless communication for underwater sensor networks', *Wireless Communications & Mobile Computing*, Vol. 8, October 2008, pp. 977-994.

Mainwaring, A., Polastre, J., Szewczyk, R., and Culler, D. (2002). 'Wireless sensor networks for habitat monitoring', in *Proceedings of the ACM Workshop on Sensor Networks and Applications*, Atlanta, Georgia, USA, Sept. 2002, pp. 88-97.

Mouly, M., and Pautet, B.M. (1992). "*The GSM System for Mobile Communications*", Telecom Publ.

Mueller, S., Tsang, P. R., and Ghosal, D. (2004). 'Multipath routing in mobile ad hoc networks: Issues and challenges', in M.C. Calzarossa and E. Gelenbe (Eds.): *MASCOTS 2003*, LNCS 2965, Springer-Verlag Berlin Heidelberg, pp. 209–234.

Nicolaou, N., See, A., Xie, P., Cui, H. J., and Maggiorini, D. (2007). ‘Improving the robustness of location-based routing for underwater sensor networks’, in *Proc. OCEANS’07*, June 2007, pp. 1–6.

Partan, J., Kurose, J., and Levine, N. B. (2006). “A survey of practical issues in underwater networks”, in *ACM WUWNet’06,* also *ACM SIGMOBILE Mobile Computing and Communications Review*, Vol. 11, No. 4, pp. 23-33.

Pompili, D., and Akyildiz, F. I. (2009). “Overview of networking protocols for underwater wireless communications”, *IEEE Communications Magazine*, Vol. 47, Issue 1, January 2009, pp. 97-102.

Pompili, D., Melodia, T., and Akyildiz, F. I. (2006). ‘Routing algorithms for delay-insensitive and delay-sensitive applications in underwater sensor networks’, in *Proceedings of the 12th Annual International Conference on Mobile Computing and Networking (MobiCom’06)*, pp. 298-309.

Pompili, D., Melodia, T., and Akyildiz, F. I. (2006). ‘A resilient routing algorithm for long-term applications in underwater sensor networks’, in *Proc. of Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net)*, Lipari, Italy, Jun. 2006.

Ramanathan, N., Yarvis, M., Chhabra, J., Kushalnagar, N., Krishnamurthy, L., and Estrin, D. (2005). ‘A stream-oriented power management protocol for low duty cycle sensor network applications’, in *Proceedings of the IEEE Workshop on Embedded Networked Sensors*, Sydney, Australia, May 2005, pp.53–62.

Seah, K. W., and Tan, X. H. (2006). ‘Multipath virtual sink architecture for underwater sensor networks’, in *Proceedings of the first international conference on Integrated Internet ad hoc and sensor networks*, Nice, France, InterSense; Vol. 138, 2006.

Sozer, E., Stojanovic, M., and Proakis, J. (2000). ‘Underwater acoustic networks’, *IEEE Journal of Oceanic Engineering*, Vol. 25, No. 1, pp. 72–83.

Stephen, A. R. (1998). ‘Ocean seismic network seafloor observatories’, *Oceanus*, Vol. 41, No. 1, pp. 33–37.

Stojanovic, M. (2003). ‘Acoustic (underwater) communications’, in J. G. Proakis (editor), *Encyclopedia of Telecommunications*, John Wiley and Sons.

Stojanovic, M. (2006). “On the relationship between capacity and distance in an underwater acoustic communication channel”. In *WUWNet’06*, Los Angeles, CA, Sep. 2006.

Urick, J. R. (1983). ‘*Principles of Underwater Sound’*, McGraw-Hill.

Wang, W., Donghyun, K., Willson, J., Thuraisingham, B., and Wu, W. (2009). “A better approximation for minimum average routing path clustering problem in 2d-underwater sensor networks”, *Discrete Mathematics, Algorithms and Applications (DMAA)*, Vol. 1, Issue 2, June 2009, pp. 175-191.

Whang, D., Xu, N., Rangwala, S., Chintalapudi, K., Govindan, R., and Wallace, J. (2004). ‘Development of an embedded networked sensing system for structural health monitoring’, in *Proceedings of the International Workshop on Smart Materials and Structures Technology*, Jan. 2004, pp. 1-8.

Xie, P., Cui, H. J., and Lao, L. (2006). ‘Vbf: Vector-based forwarding protocol for underwater sensor networks’, in *Proceedings of IFIP Networking*, May 2006, pp. 228–235.

Xie, P., Zhou, Z., Nicolaou, N., See, A., Cui, J.-H. and Shi, Z. (2010). “Efficient vector-based forwarding for underwater sensor networks”, *EURASIP Journal on Wireless Communications and Networking,* Vol. 2010, Article ID 195910, pp. 1-13 DOI:10.1155/2010/195910.

Yan, H., Shi, J. Z., and Cui, H. J. (2008). ‘DBR: Depth-based routing for underwater sensor networks’, in *NETWORKING 2008 Ad Hoc and Sensor Networks, Wireless Networks, Next Generation Internet,* Lecture Notes in Computer Science. Springer Berlin / Heidelberg, 2008, pp. 72-86.

Zhang, Y., Xiao, Y., Chen, M., Bahri, P., and Kamboj, M. (2009). "Medium access control layer for underwater sensor networks"*, Underwater Acoustic Sensor Networks*, Publisher: Auerbach; 1 edition, April 2009.

Zhou, Z., and Cui, H. J. (2008). “Energy efficient multi-path communication for time-critical applications in underwater sensor networks”, in *Proceedings of the 9th ACM international symposium on Mobile ad hoc Networking and Computing*, Hong Kong, 2008, pp. 221-230.

Zhou, Z., Cui, H. J., and Bagtzoglou, A. (2007). “Scalable localization with mobility prediction for underwater sensor networks,” UCONN CSE Report UbiNet-TR07-01, July 2007.

Zorzi, M., Casari, P., Baldo, N., and Harris, A. (2008). “Energy-efficient routing schemes for underwater acoustic networks”, *Journal on Selected Areas in Communications*, IEEE, Vol. 26, No. 9, pp. 1754-1766.

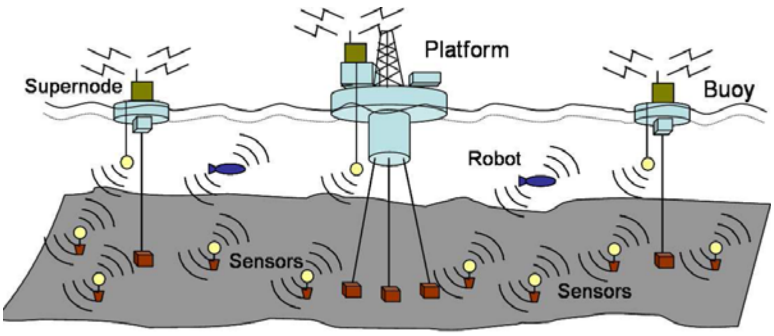


Figure 1. One possible approach regarding network deployment [Heidemann et al., 2006]

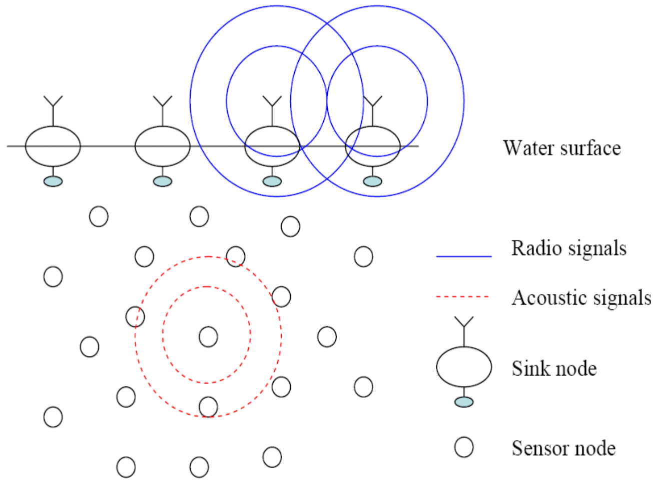


Figure 2. Multiple-sink underwater sensor network architecture [Yan, Shi, and Cui, 2008]

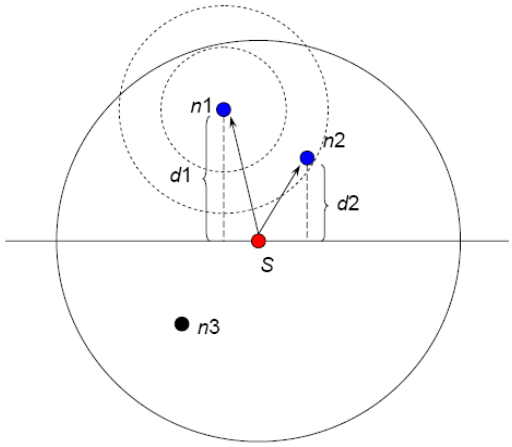


Figure 2a. Forwarding node selection [Yan, Shi, and Cui, 2008]

Table 1: DBR Results

↗	Depth threshold	➡	↘	Packet delivery ratio Total energy consumption End-to-end delay
↗	Number of nodes	➡	↗	Packet delivery ratio Total energy consumption
			↘	End-to-end delay
↗↙	Node speed	➡	stable	Packet delivery ratio Total energy consumption End-to-end delay

(Explanation of symbols: ↗ increase, ↙ decrease, ↗↙ fluctuation)

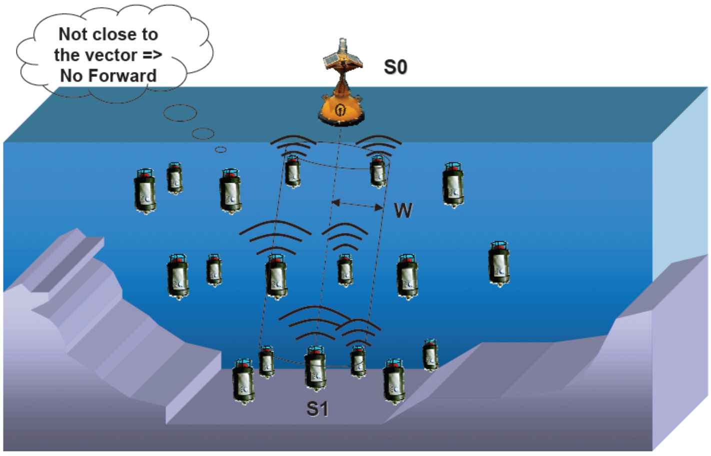


Figure 3. A high-level view of VBF [Xie, Cui, and Lao, 2006]

Table 2: VBF Results

↗	Pipe radius	➡	↗	Packet delivery ratio Total energy consumption
			↘	End-to-end delay
↗	Number of nodes	➡	↗	Packet delivery ratio Total energy consumption
			↘	End-to-end delay
↗↙	Node speed	➡	stable	Packet delivery ratio Total energy consumption End-to-end delay

(Explanation of symbols: ↗ increase, ↙ decrease, ↗↙ fluctuation, ➡ leads to)

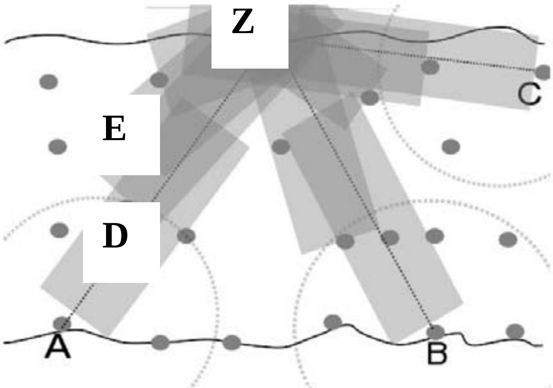


Figure 4. Per-hop vectors in HH-VBF [Nicolaou et al., 2007]

Table 3: HH-VBF Results

↗	Number of nodes	⇒	↗	Success rate Energy cost
			↘	Energy tax
↗↙	Node speed	⇒	Stable	Success rate Energy cost Energy tax

(Explanation of symbols: ↗ increase, ↙ decrease, ↙↙ fluctuation, ⇒ leads to)

Table 4: SBR-DLP Results

↗↙	Sector size	➡	Stable	Packet delivery ratio
↗	Number of nodes	➡	↗	Packet delivery ratio
↗	Node speed	➡	↗	Packet delivery ratio

(Explanation of symbols: ↗ increase, ↙ decrease, ↗↙ fluctuation, ➡ leads to)

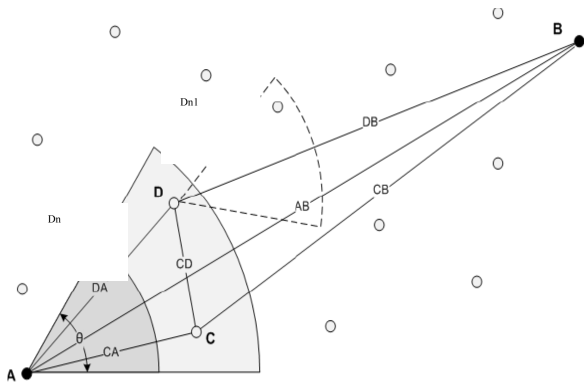


Figure.5. Illustration of the FBR protocol: nodes within the transmitter's cone θ are candidate relays [Jornet, Stojanovic, and Zorzi, 2008]

Table 5: FBR Results

↗	Number of nodes	➡	↗	End-to-end delay Number of collisions
			↘	Energy per bit consumption
↗	Angle of cone in sparse networks	➡	↘	Energy per bit consumption
↗	Angle of cone in dense networks	➡	↗	End-to-end delay Number of collisions

(Explanation of symbols: ↗ increase, ↙ decrease, ↗↙ fluctuation, ➡ leads to)

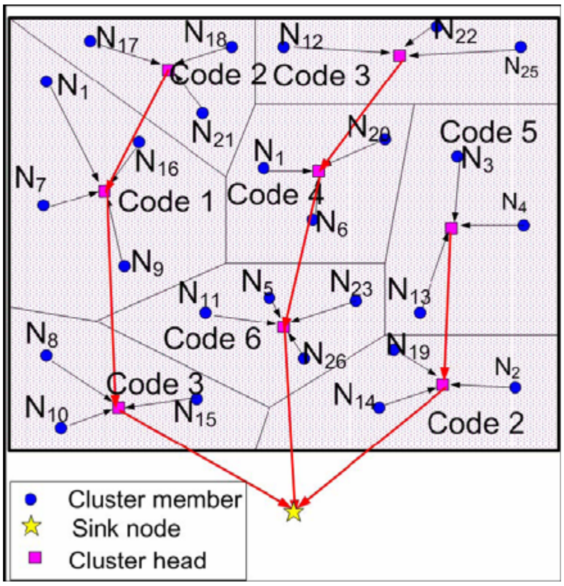


Figure 6. A network case using DUCS [Domingo and Prior, 2007]

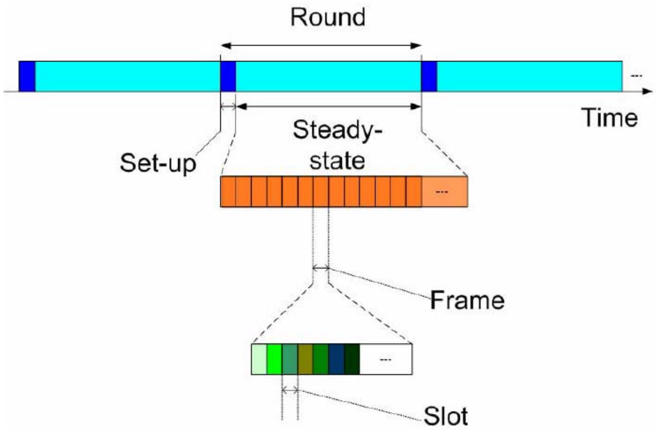
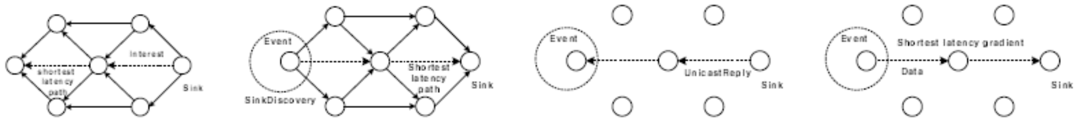


Figure 7. Time line of DUCS [Domingo and Prior, 2007]

Table 6: DUCS Results

↗	Number of nodes	➡	↗	Packet delivery ratio
			↗	Average routing overhead Number of data messages

(Explanation of symbols: ↗ increase, ↙ decrease, ↗↙ fluctuation, ➡ leads to)



(a) Initial *Interest Dissemination*

(b) Upon detecting an event, a SINKDISCOVERY message is flooded to find route towards the sink

(c) A sink replies back an UNICASTREPLY message and using this each node sets up a path

(d) Event report

Figure 8. Under-Water Diffusion: Delayed Report Protocol (DRP) [Lee et al., 2006]

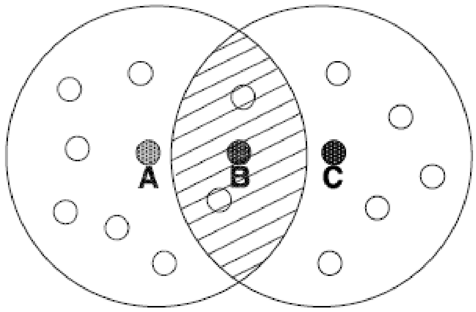


Figure 8a. A single forwarding community: any node in the shaded region can forward a packet between A and C [Lee et al., 2006]

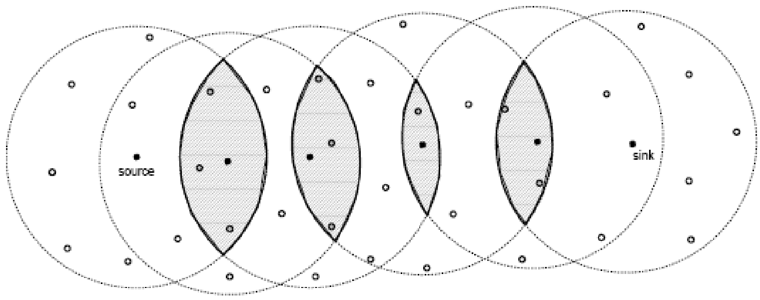


Figure 8b. Chain of forwarding communities [Lee et al., 2006]

Table 7: UWD Results

↗	Network size (density stable)	➡	↗	Average event delivery delay Distinct-event delivery ratio Average overhead

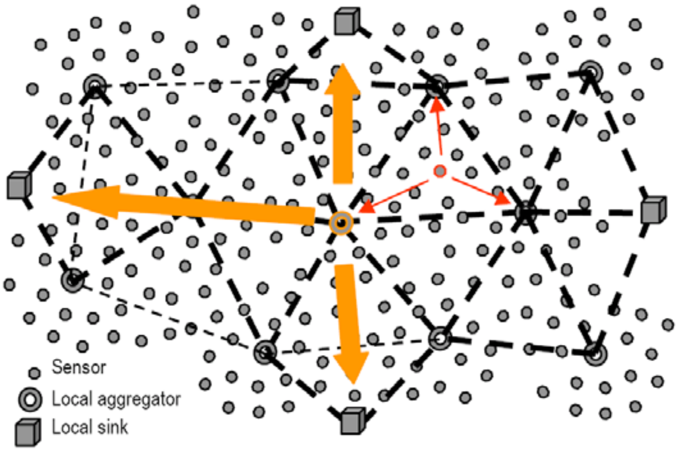


Figure 9. Underwater network topology [Seah and Tan, 2006]

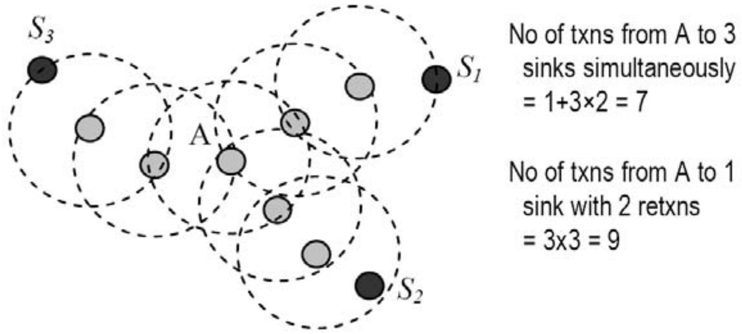


Figure 10. Multi-path Multi-sink/Virtual Sink [Seah and Tan, 2006]

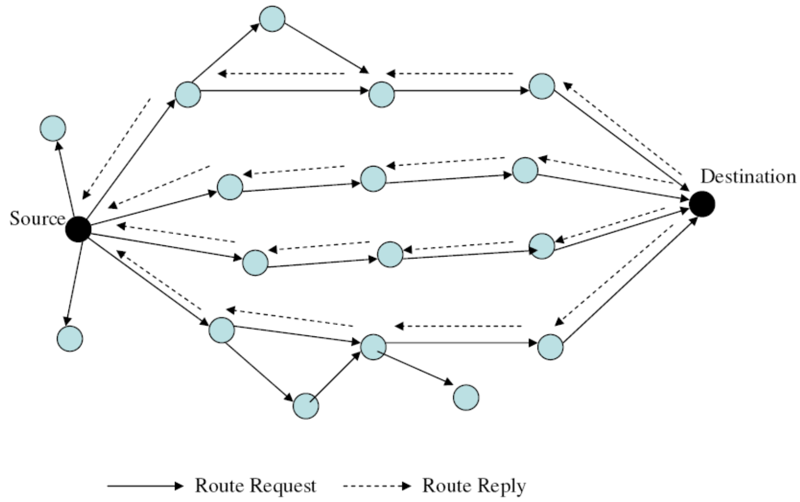


Figure 10a. Basic procedure of multi-path routing [Seah and Tan, 2006]

Table 8: Multipath Results

↗	PLR (Packet Loss Ratio)	➡	↙	Total No of packets forwarded Total No of transmissions Total No of packets received PDR No of ACKs
			↗	Redundancy factor
			stable	End-to-End delay No of retransmissions

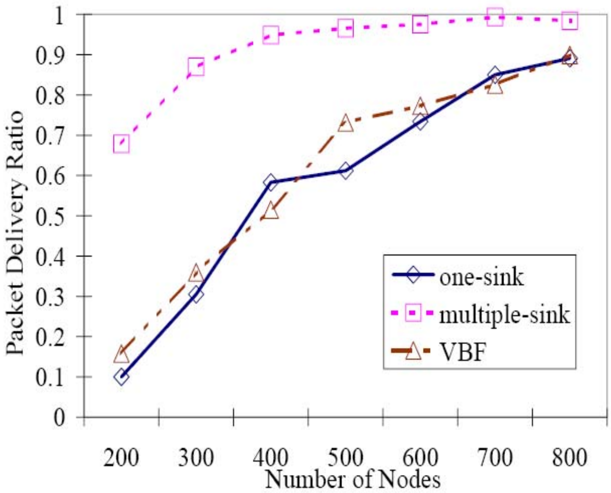


Figure 11(a). DBR vs. VBF according to packet delivery ratio [Xie, Cui, and Lao, 2006]

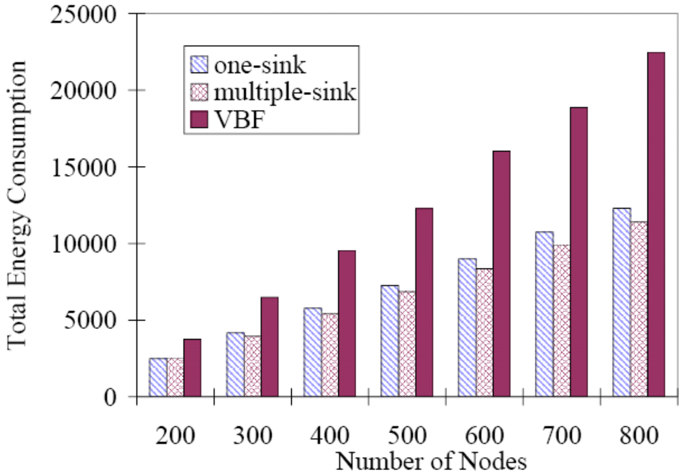


Figure 11(b). DBR vs. VBF according to total energy consumption [Xie, Cui, and Lao, 2006]

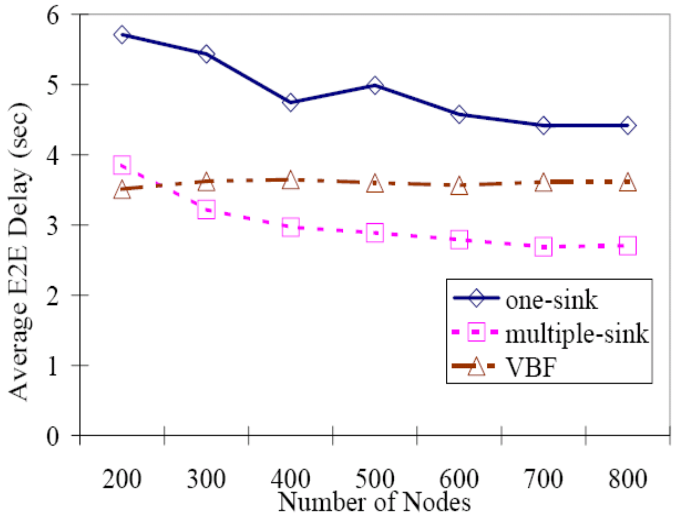


Figure 11(c). DBR vs. VBF according to average end to end delay [Xie, Cui, and Lao, 2006]

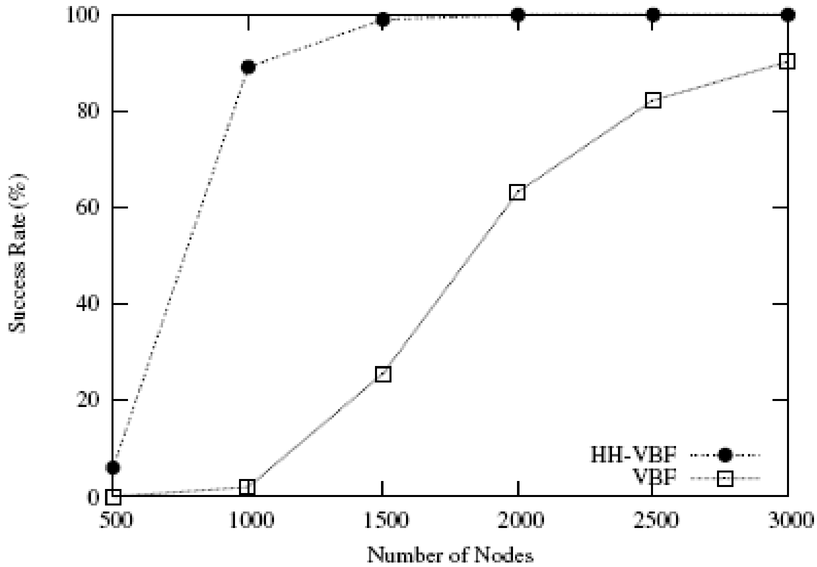


Figure 12a. VBF vs. HH-VBF according to success rate [Xie, Cui, and Lao, 2006]

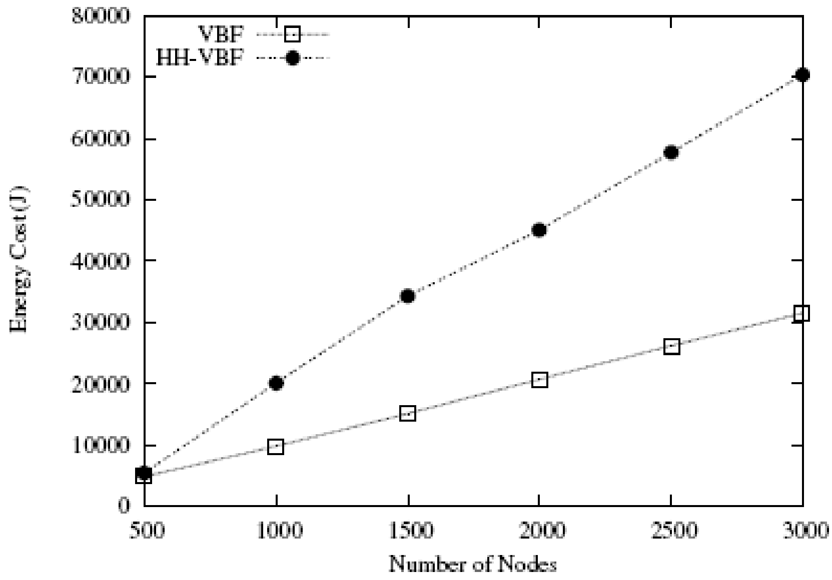


Figure 12b. VBF vs. HH-VBF according to energy cost [Xie, Cui, and Lao, 2006]

Table 9: Comparison among DBR & VBF

	Packet delivery ratio	End to end delay	Energy efficiency	Energy consumption	Sparse networks	Dense networks
One sink setting DBR vs. VBF	similar	DBR is worse	DBR is better	DBR=½ of VBF	VBF is better	DBR is better
Multiple sink setting DBR vs. VBF	DBR is better	DBR is better	DBR is better	DBR=½ of VBF		
HH-VBF vs. VBF	HH-VBF is better	HH-VBF is better	HH-VBF is better	HH-VBF Higher in dense Lower in sparse	HH-VBF is better	VBF is better

Table 10: Advantages and weaknesses of routing protocols for UWSNs

Routing protocols	Description
DBR Depth based Routing	+ Very high packet delivery ratios for sparse networks, low energy consumption in multiple sink settings. + Small communication cost. + No need for full dimensional location information; only local depth information of each node is needed. + Node speed does not affect packet delivery ratio, total energy consumption and average delay. Routing decisions are based on depth information of node. – The delivery ratio decreases by increasing the depth threshold. – Significant end to end delay in sparse networks. – High total energy consumption in sparse networks.
VBF vector-based forwarding	Candidate node decides which will be its next relay node. + Low end-to-end delay in dense networks. + It handles node mobility efficiently. + Robust against packet loss and node failure. + Node speed has minor impact on delivery ratio, energy consumption and average delay. + Energy efficient, scalable and use of path redundancy. – Small data delivery ratio in sparse networks. – Delivery ratio slightly decreases when nodes are mobile. – Sensitivity to the routing pipe's radius. – Multiple nodes acting as relay nodes. – High communication time in dense networks. Many nodes involved in packet forwarding.
HH-VBF Hop-by-hop VBF	+ High packet delivery ratio in sparse networks. + Less sensitive to the routing pipe radius. − Large propagation delay. − High energy cost in dense network. − Not efficient enough with node mobility.
SBR-DLP Sector Based Routing with Destination Location Prediction	Sender decides about its next relay node. Destination node is not fixed and its location is not accurately known by the sender node. + It uses a communication circle to locate the candidate relay nodes, so it does not need to rebroadcast. + No multiple nodes acting as relay nodes. + Flooding is avoided by routing a packet in a hop-by-hop fashion. − Node speed causes disconnections. − Relatively low PDR in sparse networks. − Relatively high energy consumption in dense networks.

FBR Focused Beam Routing	Sender decides about its next relay node. Destination node is fixed and its location is accurately known. + It is used for both static and mobile nodes. + Low power request. Power is increased only if requested. + Secure links. No risks of data packet collisions. – It uses a single transmitting cone that covers only a fraction of the communication area. – It needs to rebroadcast RTS every time it cannot find a candidate node within its transmitting cone. – It lacks of a collision avoidance mechanism. CTS may collide easily in dense networks.
UWD Under-Water Diffusion	+ It minimizes the number of all packet transmissions to avoid possible acoustic collisions. – Not so good performance in dense networks. – It is not considered to be robust.
DUCS Distributed Underwater Clustering Scheme	+ The nodes organize themselves into clusters. + Power control can be used to adjust the transmission power. + Data aggregation techniques result to energy saving. + It avoids drainage of the batteries. – It is considered that there are always data to be sent to the sink by the nodes. – As the number of nodes decreases a slight decrease occurs in the number of data messages and the packet delivery ratio.
Multipath Routing	+ Data are cached and transmitted when ready. Multiple transmissions are avoided. + For time critical data, delivery is made over more routes rather than caching. + It uses spatial reverse paths achieving lower latency. Less packet transmission and energy saving, as well possibly reduced contention. – Connection is established through wire or optical fibre. – Backup routes created by deploying redundant nodes. – Contention occurrence among nodes due to redundancy.

Table 11: Comparison among routing protocols

	Performance	Robustness	Sparse networks	Dense networks	Mobility support	Static –dynamic	Requires full localization (Co-ordinates of source and destination nodes)	Information needed	multi-hop	scalability
DBR	Dense net.: Low end-to-end delay, high PDR & total energy consumption		Not so good	Good	Static sink and mobile nodes	Dynamic	No	Local depth of each node		Yes
VBF	Small and medium node mobility: Good PDR, end-to-end delay, energy	Yes	Good	Not so good	Efficient & effective	Dynamic	Yes	Requires full dimensional info		Yes
HH-VBF	Sparse net: Low energy cost		Good	Good	Not so efficient as VBF	Dynamic	Yes	Requires full dimensional info		Yes
SBR-DLP	High PDR in dense net with high node speed		Good	Good	Yes	Dynamic	Yes	Uses information received from the candidate nodes. Each node is aware of its own position, and the destination node's pre-planned movements		Yes
FBR	Sparse net: Low energy consumption for bigger cone aperture	Yes	Good	Not so good	Static and mobile nodes	Both	No	A source node must be aware of its own location and the location of its final destination, but not those of other nodes		Yes
UWD	High net size – High average event delivery delay	No	Good	Not so good	Static sink and mobile nodes	Dynamic	Yes	Time threshold within which the sensor node detects an event	Yes	No
DUCS	Dense net: Good PDR	Yes	Good	Very	Yes	Dynamic	Yes	Frames are sent to each cluster-	Yes	Yes

				good				head		
Multipath Routing	Dense net: Good PDR	Yes			Yes	Static	Yes	Spatially diverse paths	Yes	

Table 12: Major advantages and disadvantages of routing protocols

Routing Protocol	Advantage	Disadvantage
DBR	Adopts techniques to reduce energy consumption	Decreases the delivery ratio by increasing the depth threshold
VBF	Small end to end delay	The higher the success rate it achieves the higher the energy it consumes
HH-VBF	Many paths to choose from in order to forward the packet	High energy cost
SBR-DLP	Node speed eliminates the disconnections	Node speed causes disconnections
FBR	Best power management	It lacks a collision avoidance mechanism
DUCS	Data aggregation techniques are applied, resulting to energy savings	A slight PDR decrease occurs as the network gets sparser
UWD	Increases overall delivery ratio	Not so good performance in dense networks
Multipath	Multiple copies of the same data packet are sent to multiple sinks at the same time	The more retransmissions the more the packet collisions and data loss