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## Review

## A survey on routing techniques in underwater wireless sensor networks

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## ABSTRACT

Underwater Wireless Sensor Networks (UWSNs) are finding different applications for offshore exploration and ocean monitoring. In most of these applications, the network consists of significant number of sensor nodes deployed at different depths throughout the area of interest. The sensor nodes located at the sea bed cannot communicate directly with the nodes near the surface level; they require multi-hop communication assisted by appropriate routing scheme. However, this appropriateness depends not only on network resources and application requirements but also on environmental constraints. All these factors provide a platform where a resource-aware routing strategy plays a vital role to fulfill the different application requirements with dynamic environmental conditions. Realizing the fact, significant attention has been given to construct a reliable scheme, and many routing protocols have been proposed in order to provide an efficient route discovery between the sources and the sink. In this paper, we present a review and comparison of different algorithms, proposed recently in order to fulfill this requirement. The main purpose of this study is to address the issues like data forwarding, deployment and localization in UWSNs under different conditions. Later on, all of these are classified into different groups according to their characteristics and functionalities.

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## 1. Introduction

The ocean is vast as it covers around 140 million square miles; more than 70% of the Earth's surface, and half of the world's population is found within the 100 km of the coastal areas. Not only has it been a major source of nourishment production, but with time it is taking a vital role for transportation, presence of natural resources, defense and adventurous purposes. Even with all its importance to humanity, surprisingly we know very little about the Earth's water bodies. Only less than 10% of the whole ocean volume has been investigated, while a large area still remains unexplored. With the increasing role of ocean in human life, discovering these largely unexplored areas has gained more importance during the last decades. On one side, traditional approaches used for underwater monitoring missions have several drawbacks and on the other side, these inhospitable environments are not feasible for human presence as unpredictable underwater activities, high water pressure and vast areas are major reasons for un-manned exploration. Due to these reasons, Underwater Wireless Sensor Networks (UWSNs) are attracting the interest of many researchers lately, especially those working on terrestrial sensor networks.

Sensor networks used for underwater communications are different in many aspects from traditional wired or even terrestrial sensor networks (Akyildiz et al., 2005; Heidemann et al., 2006). Firstly, energy consumptions are different because some important applications require large amount of data, but very infrequently. Secondly, these networks usually work on a common task instead of representing independent users. The ultimate goal is to maximize the throughput rather than fairness among the nodes. Thirdly, for these networks, there is an important relationship between the link distance, number of hops and reliability. For energy concerns, packets over multiple short hops are preferred instead of long links, as multi-hop data deliveries have been proven more energy efficient for underwater networks than the single hop (Jiang, 2008). At the same time, it is observed that packet routing over more number of hops ultimately degrades the end-to-end reliability function especially for the harsh underwater environment. Finally, most of the time, such networks are deployed by a single organization with economical hardware, so strict interoperability with the existing standards is not required. Due to these reasons, UWSNs provide a platform that supports to review the existing structure of traditional communication protocols. The current research in UWSNs aims to meet the above criterion by introducing new design concepts, developing or improving existing protocols and building new applications (Fig. 1).

When considering underwater sensor networks, due consideration must be given to the possible challenges that may be encountered in the subsurface environment. Continuous node movement and 3d topology are major issues posed by the host

conditions. Further, some of the underwater applications, including detection or rescue missions, tend to be ad hoc in nature, some requiring not only network deployment in short times, but also without any proper planning. In such circumstances, the routing protocols should be able to determine the node locations without any prior knowledge of the network. Not only this, the network also should be capable of reconfiguring itself with dynamic conditions in order to provide an efficient communication environment. Moreover, a significant issue in selecting a system is establishing a relation between the communication range and data rate with the specific conditions. A system designed for deep water may not be suitable for shallow water or even when configured for higher data rates when reverberation is present in the environment (Chitre et al., 2008). Manufacturer's specifications of maximum data rates mostly are only useful for establishing the upper performance bound, but in practice these are not reachable with specific conditions. Users who are well funded have resorted to purchasing multiple systems and testing them in particular environment to determine if they will meet their needs. An international effort for standardizing the tests for acoustic communications is required, but it is not so simple as private organizations or even government institutes performing such comprehensive tests tend not to publish their results.

### 1.1. Related work and contribution

Although many authors have presented quality survey papers in different areas of UWSNs, still the scope of the survey presented in this article is distinguished from the existing works in many aspects. The research in acoustic channel is not new, as three decades earlier, researchers have started to focus their

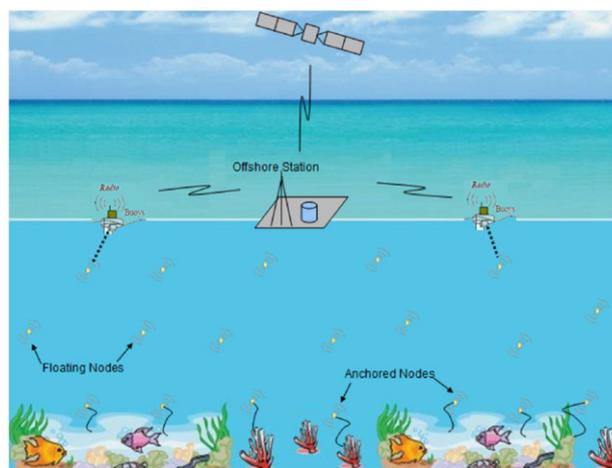


Fig. 1. General scenario of the mobile UWSN architecture.

interest in this area. Numerous review papers including Stojanovic (2003), Proakis et al. (2001), Ethem et al. (2000), and Lanbo Liu and Cui (2008) are available, where the authors have examined the acoustic and underwater communications. Many others like Akyildiz et al. (2005), Jun-Hong et al. (2006), Partan et al. (2007), and Akyildiz et al. (2006) have addressed the challenges and issues posed by underwater environments, and proposed their solutions as well. Further, some authors have discussed energy efficiency and analysis (Ovaliadis and N.S.a.V.K, 2010; Domingo and Prior, 2008), deployment (Pompili et al., 2009), potential applications (Heidemann et al., 2006; Jiejun et al., 2005), network coding schemes (Lucani et al., 2007), and multiple access techniques (Casari et al., 2007) but to the best of our knowledge, no review paper is available where the routing protocols and networking issues of UWSN are classified and discussed thoroughly. Considering the importance of routing in UWSNs when a significant number of routing protocols are available, a comprehensive survey becomes necessary at this stage. The current effort in describing and categorizing the different approaches proposed recently is a step towards network layer and its related factors. The purpose of this study is to provide a detailed view of these routing schemes and to identify some research issues that can be further pursued.

The rest of the paper is organized as follows. Section 2 provides an overview of the basics of acoustic communications, deployment and network architecture, localization and reliability related issues. Section 3 gives the idea about various problems when we implement existing terrestrial routing techniques in underwater environment. In Section 4, we present several important underwater routing schemes proposed recently and highlight related issues with different comparisons and classifications. Section 5 covers the evaluation methods where we discuss different tools developed for this purpose. Section 6 identifies potential research areas (or current issues) for underwater routing and communication. Finally, Section 7 briefly concludes this article.

## 2. Background

Underwater Acoustic Networks (UANs) as a platform for oceanic research have gained much attention during the last decade and a strategy is required for the development of different potential applications. Monitoring the aquatic environment and dynamic changes of the ocean is not an uncomplicated assignment. To preserve marine resources and obtain a sustainable development, changes occurring in the marine environment have to be monitored effectively. The threat of climate changes and increased water-borne activities may have great impacts on oceanic life and ecosystems. A rapid change in the marine environment may have great influence on terrestrial life and environment.

### 2.1. Basics of acoustic communications

Acoustic signal is considered as the only feasible medium that works satisfactorily in underwater environments. Although we have a couple of more options in the form of electromagnetic and optical waves, but underwater characteristics and sensor communication requirements have ruled them out. Considering electromagnetic wave, at high frequencies it has a very limited communication range due to high attenuation and absorption effect, as measured less than 1 m in fresh water (Bin et al., 2004). Propagation is acceptable with low frequencies, but at the cost of high transmission power and long antenna size. Recently, electromagnetic modems for underwater communication have been developed; however available technical details are vague (S1510, 2007). It has been shown that the absorption of electromagnetic

signal in sea water is about  $45\sqrt{f}$  (dB/km), where  $f$  is the frequency in Hertz (Quazi and Konrad, 1982), while the absorption of acoustic signal with the frequencies commonly used for underwater is lesser by three orders of magnitude.

Optical link, even though it is good for point to point communication, especially in very clean water, but it is not good enough for distributed network structure due to its short range (less than 5 m) (Huang and Ma, 2011). Not only this but also a precise positioning is required for narrow beam optical transmitters. In short, it is not considered as a good choice for long distance underwater communications, particularly when the water is not so clean like shallow water.

On the other hand, acoustic signal is the only reliable and the most suitable medium for low cost, ad hoc, and densely deployed underwater sensor network. It provides the facility of omnidirectional transmission and distributed channel access with acceptable signal attenuation. Despite all the attractions (relative to electromagnetic and optical waves), underwater acoustic signal introduces a set of new communication challenge. The erroneous acoustic channel faces the problem of temporary path losses, high bit error rate, small bandwidth and large propagation delays. Path losses are not only due to transmission distance, but also depend on signal frequency. Severely limited bandwidth leads to low data rates, which again depend on both the communication range and the frequency (Sozer et al., 2000; Stojanovic, 2006). Long range systems that operate over kilometers cannot exceed the bandwidth of more than few kHz. On the other hand, a short range system operating over tens of meters can communicate with a bandwidth of more than a hundred kHz. Although, acoustic communications are classified in different categories in terms of range and bandwidth, but it can hardly exceed 40 kb/s at a range of 1 km.

Although the speed of sound is assumed to be constant in most of the situations, but actually it depends on water properties like temperature, salinity, and pressure. Normally, the speed of sound is around 1500 m/s near the ocean surface, which is 4 times faster than the speed of sound in air, but five orders of magnitude slower than the speed of light (Lanbo Liu and Cui, 2008). However, the speed of sound increases with the increase in any of these factors including temperature, depth, and practical salinity unit (PSU). Temperature rise of approximately 1 °C, depth increase of every 1 km and increase of 1 PSU result to increase the speed of sound by 4, 17 and 1.4 m/s, respectively. The routing schemes that consider these variations are expected to provide better results compared to those that assume uniform speed.

### 2.2. Deployment and network architecture

Underwater sensor networks (USNs) consist of a variable number of sensor nodes that are deployed to perform collaborative monitoring over a given volume. Similar to terrestrial sensor networks, for USNs it is essential to provide communication coverage in such a way that the whole monitoring area is covered by the sensor nodes, where every sensor node should be able to establish multi-hop paths in order to reach the surface sink. Many important deployment strategies for terrestrial sensor networks have been proposed such as Targ et al. (2009), Neelofer and Mohamed (2010), and Jain and Qilian (2005), but deployment for USNs requires more attention due to its unique 3d characteristics.

The work done in Akyildiz et al. (2005) is considered as the pioneering effort towards the deployment of sensor nodes for underwater environments. The authors have proposed two communication architectures, i.e., two-dimensional and three-dimensional. In two-dimensional architecture, sensor nodes are anchored at the bottom where these can be organized in different clusters and are interconnected with one or multiple underwater

gateways by means of acoustic links. The underwater gateways are responsible for relaying data from ocean bottom to surface sink. In three-dimensional architecture, sensor nodes float at different depth levels covering the entire volume region being monitored. These nodes are attached with the surface buoys by means of wires and their lengths can be regulated in order to adjust the depth of the sensor nodes. They have used a purely geometric based approach to determine the required number of sensor nodes in order to cover the whole monitoring area. However, the minimum requirement of sensor nodes is shown in the order of hundreds or even thousands, which is not feasible in terms of cost.

Further, a different approach for the same idea is proposed in [Pompili et al. \(2006\)](#) where sensor nodes are equipped with the same wire, but anchored at the bottom instead of anchoring to the surface buoys. These nodes are also equipped with a floating buoy that can be inflated by a pump, so it can move towards the surface and then back to its position. Although, this enhanced architecture helps increase the reliability of the network, but it makes the network more costly, especially when we are interested in large monitoring areas.

In [Aitsaadi et al. \(2007\)](#), a deployment strategy is proposed for water quality management in lakes in order to check the level of pollution due to the presence of toxins. The remotely sensed information is used to find the hot spots where relatively more sensors are deployed. In order to find the hot spots and those regions that do not require as many nodes, a mesh of triangle or rectangle is created. The sensing range of the nodes is defined by a probabilistic sensing model, and nodes are deployed in a weighted approach, which depends on the density of the mesh. Although the proposed technique can be a good solution for geographically irregular areas, no information is available on how the sensor nodes can communicate with each other. Ultimately, it is assumed that sensors must be retrieved physically in order to get the sensed information.

Efficient deployment of multiple radio-enabled surface sinks can enhance the performance of network in many aspects. On the basis of this fact, some deployment techniques including [Ibrahim et al. \(2008\)](#) and [Alsalihi et al. \(2008\)](#) are proposed, which tried to maximize the efficiency of the network by choosing proper locations for gateway placement. However, these methods are only for gateway deployment in 2d ocean surface, but no information is available about the deployment of ordinary sensor nodes in 3d areas.

### 2.3. Localization

In some applications, sensed data become meaningless without time and location information. Localization is essential for data labeling while some time critical applications require timely information. In [Erol and Oktug \(2008\)](#), the authors have combined both of these tasks in a localization framework called “*catch up or pass*”, where these tasks mutually help each other. It benefits from the uncontrolled motion of underwater sensor nodes, where these nodes use the position and the velocity information that help decide whether to carry the data packet until they catch up with a sink or pass it to a faster or slower relay node.

During this localization and routing framework, the authors assumed that all the nodes are clock synchronized throughout the network. Such assumptions can be made for short term applications, but for the long-term missions we require some additional mechanism in order to achieve synchronization. Moreover, they used ToA method when determining the distance between two nodes. Although, ToA is considered more promising than other techniques of the same type, but still it is not able to provide accuracy at long distances and is only feasible for short ranges.

Location information can be used to design network architecture and routing protocols. In [Erol et al. \(2007\)](#), the authors proposed an idea of Dive and Rise (DNR) for positioning system. They used mobile DNR beacons to replace static anchor nodes. The major drawback of this DNR scheme is that it requires large number of expensive DNR beacons, which is further improved in [Kai Chen and He \(2009\)](#). In this scheme, they tried to decrease the requirement of mobile beacons by replacing them with four types of nodes, which are surface buoys, Detachable Elevator Transceivers (DETs), anchor nodes, and ordinary sensor nodes.

After such specialized hardware deployments, this localization scheme has some assumptions. First of all, it assumes that all the sensor nodes are equipped with pressure sensor in order to provide depth position or z-coordinate information. Then, after requiring this entire infrastructure they assume that the network is static. Although it can be enhanced for mobile network but still during their simulation study, mobility was not considered. Aside from the unfeasibility of these arrangements for long-term applications, cost will become a major issue particularly for large area of interest.

### 2.4. Reliability

Reliability is a challenging factor for any sort of communication. For underwater environments, reliable delivery of sensed data to the surface sink is a challenging task as compared to forwarding the collected data to the control center. In terrestrial sensor networks, multiple paths and packet redundancy are exploited in order to increase the reliability. For underwater sensor networks, many authors are also proposing schemes based on packet redundancy ([Peng et al., 2007](#); [Seah and Tan, 2006](#)), but for resource constraint underwater environments, techniques like this are not easily affordable. Usually, acknowledgments and retransmissions provide reliability by recovering lost data packets; however these efforts result in additional traffic and large end-to-end delays.

Transmission control protocol (TCP) is an end-to-end based technique and is considered as the most popular solution for reliable data communication. However, it has been shown that TCP and other congestion control mechanisms like this are highly problematic for wireless multi-hop networks ([Holland and Vaidya, 1999](#); [Scheuermann et al., 2008](#)). It requires 3-way handshake between the sender and the sink before starting the actual data packet transmission due to its connection oriented nature. When we talk about UWSN, where most of the time actual data might be a few bytes, the 3-way handshake process followed by TCP can be a burden for such a small volume of data. However, for acoustic channel the propagation time is larger than the transmission time, which can provide a base for well known bandwidth  $\times$  delay product problem ([Peng, 1982](#)). Moreover, TCP assumes that only congestion is responsible for packet losses; so it focuses mainly on those congestion control mechanisms that try to decrease the transmission rate. However, for UWSNs, the threatening conditions like error prone acoustic channel and node failure can also be the reason of packet losses; therefore it is not necessary to decrease the transmission rate in order to maintain throughput efficiency.

On the other hand, user datagram protocol (UDP) uses a simple transmission model without any hand-shaking procedure but it does not offer any flow or congestion control for reliability concerns. During congestion, it simply drops the data packets without providing any mechanism for recovering them. Besides, UDP also does not provide ACKs as it relies on some lower or upper layers when recovery is required for lost data packets. Obviously, approaches like UDP are not considered as a good choice for problematic underwater conditions.

One of the main reasons that help increase the congestion in the network is the convergent nature of the routing protocols, since all the sensor nodes forward their data packets towards a single sink. The degree of congestion increases as the data packets start to progress towards the destination; ultimately the nodes around the destination are seriously affected. For underwater sensor networks, many techniques like Yan et al. (2008) and Ayaz and Abdullah (2009) have been proposed in order to solve this problem as they suggest multiple sinks on surface. With limited resource availability like buffer space, if these congestions are not detected or some appropriate avoidance techniques are not implemented, a significant amount of data packets can be lost. These packet losses lead to retransmissions, which not only cause a significant amount of energy losses, but also lead to large end-to-end delays.

In order to address the challenges of UWSN for reliable data deliveries, a transport layer protocol called Segment Data Reliable Transport (SDRT) is proposed in Xie. SDRT uses Tornado codes in order to recover the errored data packets, which help reduce the retransmission. During the forwarding process, the data packets are transmitted block-by-block while for reliability concern each block is forwarded hop-by-hop. SDRT continues to send data packets inside a block until it receives a successful acknowledgment, which causes energy wastage. In order to reduce this energy consumption, a window control mechanism is introduced where data packets are transmitted quickly within the window and remaining packets at slower rates. However, SDRT follows the hop-by-hop reliability while for unreliable underwater environments, where node failure or loss is common, this one-hop reliability is not considered enough. Moreover, packet redundancy depends on error probability and this overhead will be high due to underwater error prone channel.

In order to handle the dilemma of reliability, a two-hop acknowledgment (2H-ACK) technique is proposed in Ayaz et al. (2009), where two nodes try to maintain the same copy of a data packet. A relay node, which has data packet in order to forward, will not reply the acknowledgment until it cannot find the next hop towards the destination. During this process, if a node is unable to find the next hop due to any failure, or even if it is lost, then packets in the buffer are not considered lost. All the nodes that send the data packets towards this node will wait for a certain amount of time before trying again for the next hop. Simulation results show that even though some duplicate packets are received at the destination, but very few data packets are lost with 2H-ACK as compared to single hop acknowledgment reliability. Further, the proposed scheme seems more suitable for underwater networks where data packets generated at any location of the network normally require a maximum of 5–7 hops in order to reach the destination.

### 3. Problems in existing terrestrial routing protocols

The existing routing protocols proposed for terrestrial mobile and ad hoc networks usually fall into two categories: proactive and reactive. Unfortunately, protocols belonging to both of these extremes are not suitable for underwater sensor networks. Proactive or table driven protocols require large signaling overhead in order to establish end-to-end routes, especially for the first time and every time when any change occur in the topology. For underwater sensor networks, it is already known that continuous node movement produces continuous topology changes. On the other hand, for reactive or on demand routing, the protocols belonging to this category are suitable for dynamic environments, but they face large delays as they require source initiated flooding of control packets for route discovery process.

Not only this, but also the experimental results show that reactive protocols provide better results with symmetrical links in the network. For underwater conditions, the propagation delays are already high with asymmetric links; so the protocols of this type also seem unsuitable for these environments.

Without any proactive neighbor information and with small flooding option, it is a challenging task to construct a multi-hop data delivery routing scheme for a continuous mobile network (Jun-Hong et al., 2006). Geographical routing can be a possible solution for these situations. The protocols that belong to this type forward the data packets using the location information of their neighbors and the location of the destination. This technique has much potential but only for terrestrial networks, where facilities like Global Positioning System (GPS) are available. While for underwater environments, where high frequencies face the problem of quick absorption, GPS waves with 1.5 GHz band cannot propagate in these conditions. Further, a detailed comparison of different characteristics of the terrestrial and underwater sensor networks is provided in Table 1.

## 4. Routing protocols for UWSNs

Routing is a fundamental issue for any network, and routing protocols are considered to be in charge for discovering and maintaining the routes. Most of the research works pertaining to underwater sensor networks have been on the issues related to physical layer, while issues related to network layer such as routing techniques are a relatively new area, thus providing an efficient routing algorithm, which becomes an important task. Although underwater acoustic has been studied for decades, underwater networking and routing protocols are still at the infant stage of research. In this section, we discuss the major routing protocols proposed to date for UWSN, and highlight the advantages and performance issues of each routing scheme.

### 4.1. Vector based forwarding (VBF)

Continuous node movements require frequent maintenance and recovery of routing paths, which can be even more expensive in 3d volume. In order to handle this issue, a position based routing approach called VBF has been proposed in Xie et al. (2006b). For this, state information of the sensor nodes is not required since only a small number of nodes are involved during the packet forwarding. Data packets are forwarded along redundant and interleaved paths from the source to sink, which helps handle the problem of packet losses and node failures. It is assumed that every node already knows its location, and each packet carries the location of all the nodes involved including the source, forwarding nodes, and final destination. Here, the idea of a vector like a virtual routing pipe is proposed and all the packets are forwarded through this pipe from the source to the destination. Only the nodes closer to this pipe or “vector” from source to destination can forward the messages. Using this idea, not only the network traffic can be reduced significantly but also the dynamic topology can be managed easily.

VBF has some serious problems. First, the use of a virtual routing pipe from source to destination as the creation of such pipe can affect the routing efficiency of the network with different node densities. In some areas, if nodes are much sparsely deployed or become sparser due to some movements, then it is possible that very few or even no node will lie within that virtual pipe, which is responsible for the data forwarding; even it is possible that some paths may exist outside the pipe. Ultimately, this will result in small data deliveries in sparse areas. Second, VBF is very sensitive about the routing pipe radius threshold, and

**Table 1**  
Comparison between terrestrial and underwater wireless sensor networks.

Terrestrial WSNs	Underwater WSNs
Most applications require dense deployment	Sparse deployment is preferred not only due to expensive equipment but also in order to cover large monitored areas
Most of the network architectures assume that sensor nodes are stationary so different topologies can be applied	Nodes continue to move 1–3 m/s with water currents, so network cannot be viewed as a fixed topology (Peng et al., 2010)
A network with static nodes considered more stable especially in terms of communication links	Routing messages from or to moving nodes is more challenging not only in terms of route optimization but also link stability becomes an important issue
Generally considered more reliable due to a more matured understanding of the wireless link conditions evolved over years of R&D	Reliability is a major concern due to inhospitable conditions. Communication links face high bit error rate and temporary losses. Fault tolerant approaches are preferred
Nodes are considered moving in 2D space even when they are deployed as ad hoc and as mobile sensor networks	Nodes can move in a 3D volume without following any mobility pattern
Usually the destination is fixed and seldom changes its location. In the event when destination is changes its location, still these movements are predefined	Sinks or destinations are placed on water surface and can move with water current. Due to random water movement, predefined paths are difficult to or cannot be followed.
Deployment affects the performance of the network. Generally, deployment is deterministic as nodes are placed manually so data is routed through pre-determined paths	Non-uniform and random deployment is common. More self-configuring and self-organizing routing protocols are required to handle non-uniform deployment
In most cases, nodes are assumed to be homogenous throughout the network. Networks of this type provide better efficiency in most of the circumstances (Yarvis et al., 2005)	Heterogeneous network is common. Inclusion of heterogeneous set of sensor nodes raises multiple technical issues related to data routing (Shin et al., 2007)
Radio waves are available; nodes can communicate with low propagation delays at speed of light ( $3 \times 10^8$ m/s) (Zhou et al., 2011b)	Acoustic waves replace radio waves (at speed of $1.5 \times 10^3$ m/s). Communication speed is decreased from speed of light to speed of sound, results in high propagation delays (five orders of magnitude) (Heidemann et al., 2006). It can be problematic for real-time applications
High data rate, normally in the order of MHz	Low data rate, normally in the order of KHz. Hardly can exceed 40 kb/s at 1 km distance (Stojanovic, 1999). Moreover the attenuation of acoustic signal increases with frequency and range (Lysanov, 1982; Coates, 1989)
Increased number of hops during the routing process	Number of hops depends on depth of the monitoring area (normally 4–7 hops)
Low energy consumption (Lanbo Liu and Cui, 2008)	High energy consumption due to longer distances (consequence of sparse nodes deployment) and complex signal processing. The power required to transmit may decay with powers greater than two of the distance (Sozer et al., 2000)
Larger batteries can be used and can be replaced or recharged with ease	Battery power is limited and usually cannot be easily replaced or recharged. The routing protocols should adopt a mechanism of power down during the communication and use minimum retransmission
Nodes are less error prone and can continue to work for longer time	Nodes are more error prone and can die (due to fouling or corrosion) or leave the working area. More reliable and self recovering routing algorithms are required
Cooperative localization schemes like Time of Arrival (ToA) and Time-Difference-of Arrival (TDoA) are used for GPS-free localization	Techniques like TDoA are not feasible due to unavailability of accurate synchronization in under water (Jun-Hong et al., 2006)
Schemes like receiver-signal strength- index (RSSI) can be used for cooperative localization	RSSI is highly vulnerable to acoustic interferences such as multipath, Doppler frequency spread and near-shore tide noise, and cannot provide accuracy for more than few meters
Automatic Repeat Request (ARQ) techniques are used for the error recovery and packet loss detections	ARQ techniques are inefficient due to large propagation delays, as retransmissions incur excessive latency as well as signaling overheads (Ayaz and Abdullah, 2009)
Forward Error Correction (FEC) techniques are used to increase the robustness against errors	FEC is not easily affordable due to redundant bits at extremely small bandwidth of acoustic communication
GPS waves use 1.5 GHz band. For terrestrial sensor networks these frequencies are supported and GPS facility can be used for localization purpose	Geographical routing is not supported as such high frequencies bands are impractical for UWSNs (Domingo and Prior, 2008). Ultimately, have to rely on distributed GPS-free localization or time synchronization schemes known as cooperative localization

this threshold can affect the routing performance significantly; such feature may not be desirable in the real protocol developments. Moreover, some nodes along the routing pipe are used again and again in order to forward the data packets from concrete sources to the destination, which can exhaust their battery power. Other than these issues, VBF has much communication overhead due to its 3-way handshake nature, while during this, it does not consider the link quality.

In order to increase the robustness and overcome these problems, an enhanced version of VBF called Hop-by-Hop Vector-Based Forwarding (HH-VBF) has been proposed by Nicolaou et al. (2007). They use the same concept of virtual routing pipe as used by VBF, but instead of using a single pipe from source to destination, HH-VBF defines per hop virtual pipe for each forwarder. In this way, every intermediate node makes decision about the pipe direction based on its current location. By doing so, even when a small number of nodes are available in the neighborhood, HH-VBF can still find a data delivery path, as long as a single node is available in the forwarding path within the communication range. Although simulation results show that

HH-VBF significantly produces better results for packet delivery ratio, especially in sparse areas compared to VBF, but still it has inherent problem of routing pipe radius threshold, which can affect its performance. Additionally, due to its hop-by-hop nature, HH-VBF produces much more signaling overhead compared to VBF.

#### 4.2. Focused beam routing (FBR)

Without any prior location information of nodes, a large number of broadcast queries can burden the network, which may result in reducing the overall expected throughput. In order to reduce such unnecessary flooding, Jornet et al. (2008) presented Focused Bream Routing (FBR) protocol for acoustic networks. Their routing technique assumes that every node in the network has its own location information, and every source node knows about the location of the final destination. Other than this information, the location of intermediate nodes is not required. Routes are established dynamically during the traversing of data packet for its destination, and the decision about the next hop is

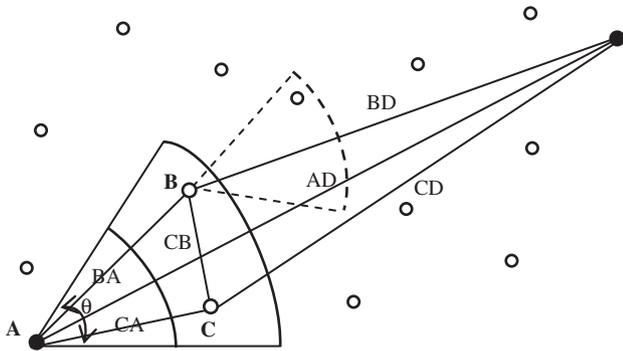


Fig. 2. Illustration of the FBR routing protocol: nodes within the transmitter's cone  $\theta$  are candidate relays.

made at each step on the path after the appropriate nodes have proposed themselves.

Figure 2 explains the data forwarding method used in FBR. Node A has a data packet that needs to be sent to the destination node D. To do so, node A multicasts a request to send (RTS) packet to its neighboring nodes. This RTS packet contains the location of source (A) and the final destination (D). Initially, this multicast action will be performed at the lowest power level, which can be increased if no node is found as the next hop in this communication range. For this, they define a finite number of power levels,  $P_1$  through  $P_N$ , which can be increased only if necessary. Now all the nodes that receive this multicast RTS will calculate their current location relative to the line AD. After calculation, those nodes that lie within a cone of angle  $\pm \theta/2$  emanating from the transmitter towards the final destination are considered as the next hop candidates. After calculating this angle, if a node determines that it is within the transmitting cone, it will reply to the RTS.

However, the approach followed by FBR might have some performance problems. First of all, if nodes become sparse due to water movements, then it is possible that no node will lie within that forwarding cone of angle. Also, it might be possible that some nodes, which are available as candidates for the next hop, exist outside this forwarding area. In such cases, when it is unable to find the next relay node within this transmitting cone, it needs to rebroadcast the RTS every time, which ultimately increases the communication overhead, consequently affecting data deliveries in those sparse areas. Second, it assumes that the sink is fixed and its location is already known, which also reduces the flexibility of the network.

#### 4.3. Reliable and Energy Balanced Routing Algorithm (REBAR)

It is a common analysis that water movements make the underwater environment more dynamic, but Jinming et al. (2008) considered node mobility as a positive factor, which can be helpful to balance energy depletion in the network. The provided reason is that when nodes move then nodes start to alternate around the sink, which brings an effect of balance in energy consumption in the whole network. They tried to solve the problem of network partitioning by altering the node positions as nodes near the sink are prone to die much earlier due to their frequent involvement in the routing process. Their idea looks similar to Xie et al. (2006a) and Jornet et al. (2008) where they assume that every node knows its location and location of the sink, but they designed an adaptive scheme by defining data propagation range in order to balance the energy consumption throughout the network. Since network wide broadcast results in high energy consumption, here nodes broadcast in a specific domain between the source and the sink using geographic information. Particularly, different sensor nodes have different

communication radii depending on the distance between the nodes and the sink. Nodes nearer to the sink are set to smaller values in order to reduce the chance of being involved in the routing process, which helps balance the energy consumption among all the sensor nodes. According to their network model, all the sensor nodes are randomly deployed in an underwater hemisphere as shown in Fig. 3. The sink is stationary and fixed at the center of the surface. All the sensor nodes are assigned a unique ID and have a fixed range. It is assumed that every node knows its location and the location of sink through multi-hop routing. They also assume a data logging application where sensed data  $i$  are sent towards the sink at a certain rate.

However, the idea of altering node positions as in REBAR has a serious problem. At one side they advocate node movements as a positive sign as simulation results show that, with static nodes, delivery ratios are smaller and they start to increase with the increase in node movements. Due to some assumptions like at the start the nodes have the location information of their current position and final destination. For the simulation, they considered the node movements from 0 to 4 m/s, and according to this phenomenon the delivery ratios should continue to increase when movements are more than 4 m/s. In practicality, these node movements are not always helpful, but they can create problem. Besides making the network sparser, large movements could also affect network performance since nodes would be required to update their location more frequently. Furthermore, it is also assumed that these movements are completely dynamic in terms of directions, both vertically and horizontally. In such a movement, a bottom node will move to the surface and then it will move back to the bottom. Again, in a real scenario that might not be possible as only horizontal movements are common in the range of 2–3 m/s, while vertically, only small fluctuations are shown (Jun-Hong et al., 2006). Moreover, the available simulation results have been focused only on delivery ratios and energy consumption with different node speeds, but have not provided any information about the end-to-end delays, which can vary according to different node movements.

#### 4.4. Information-Carrying Routing Protocol (ICRP)

Most of the routing protocols, even for terrestrial or underwater sensor networks, use separate packets for control information and data transmission. Wei et al. (2007) proposed a novel reactive protocol called Information-Carrying Routing Protocol (ICRP) in order to address the routing problem for underwater communications. ICRP is used for energy-efficient, real-time, and scalable routing where control packets used for information sharing are carried by data packets. Most importantly, it does not require state or location information of the nodes, and in addition only a small fraction of the nodes is involved in the routing process.

In ICRP, the route establishment process is initiated by the source node. When a node has a data packet to send, first it will check the existing route for this destination. If no route exists

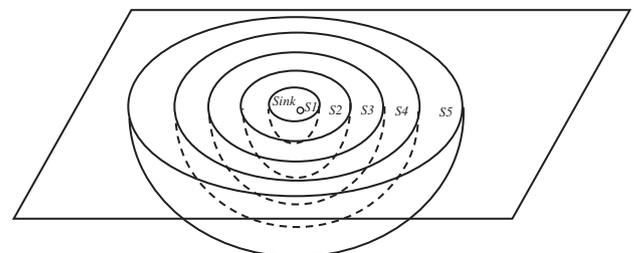


Fig. 3. Sphere energy depletion model in REBAR.

then it will broadcast the data packet, which carries the route discovery message. All the nodes receiving this packet will also broadcast it and maintain the reverse path through which this packet passes. Finally, when the destination node receives this data packet then it gets the complete reverse path from the source to its destination. Now, the destination node can use this path to send the acknowledgment. The path will remain valid for the data packet transmission till the source node receives the acknowledgment packets. Each path has a time priority, which denotes the time that this route is not used for transmission and it is called route lifetime. The larger the lifetime of a route, the longer the route can be valid or even remain unused. When the lifetime exceeds the threshold value TIMEOUT, the route becomes invalid. After this, all the nodes using this route need a route rediscovery when the route is required again.

Although ICRP has been evaluated through both simulation and real deployment but this physical experiment only consisted of three sensor nodes, which do not reflect the traffic of most real life UWSN scenarios. Basic routing mechanism does have some performance problems. First, when a node does not have route information for a specified destination then it will broadcast the data packet. More broadcasts will result in the wastage of node energy, which decreases the life of the whole network. Second, every route has an expiry time, which can be very sensitive for delivery ratios. On one hand, if it is very long then nodes can move and this route can create complexity, while if too short then it will help increase more and more broadcasts. Moreover, routing decisions are totally based on the cached route information. For UWSN where nodes move continuously at 2–3 m/s with the water currents, in such situations any intermediate node of the route can be unavailable.

#### 4.5. Directional Flooding-Based Routing (DFR)

For UWSNs, the path establishment requires much overhead in the form of control messages. Moreover, dynamic conditions and high packet loss degrade reliability, which results in more retransmissions. Existing routing protocols proposed to improve the reliability did not consider the link quality. That is why there is no guarantee about the data delivery, especially when a link is error prone. In order to increase the reliability, Daeyoun and Dongkyun (2008) proposed the Directional Flooding-Based Routing (DFR) protocol. DFR, basically, is a packet flooding technique, which helps increase the reliability. It is assumed that every node knows about its location, the location of one-hop neighbors, and the final destination. Limited number of sensor nodes takes part in this process for a specific packet in order to prevent flooding over the whole network, and forwarding nodes are decided according to the link quality. In addition, DFR addresses the void problem by allowing at least one node to participate in the data forwarding process.

As shown in Fig. 4, the flooding zone is decided by the angle between FS and FD, where F is the packet receiving node, while S and D present the source and destination nodes, respectively. After receiving a data packet, F determines dynamically the packet forwarding by comparing SFD with a criterion angle for flooding, called BASE\_ANGLE, which is included in the received packet. In order to handle the high and dynamic packet error rate, BASE\_ANGLE is adjusted in a hop-by-hop fashion according to the link quality, which helps find a flooding zone dynamically, that is, the better the link quality, the smaller the flooding zone.

The performance of DFR depends on the number of nodes chosen as the next hop after flooding the data packet. Although the problem of void region is addressed by making sure that at least one node must participate in this process, while in areas where the link quality is not good, multiple nodes can forward the

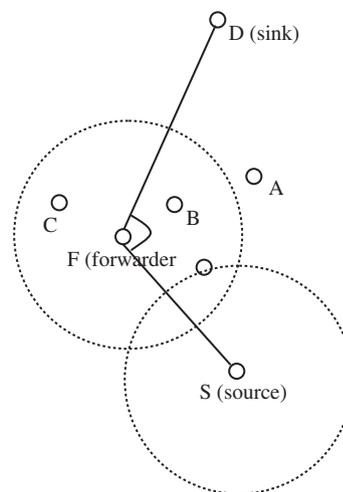


Fig. 4. Example of a packet transmission in DFR.

same data packet; so more and more nodes will join the flooding of the same data packet, which ultimately increases the consumption of critical network resources. Second, they have controlled the void problem by selecting at least one node to forward the data packet towards the sink. However, when the sending node cannot find a next hop closer to the sink, the void problem would still be encountered as no mechanism is available for sending the data packet in the reverse direction.

#### 4.6. Distributed Underwater Clustering Scheme (DUCS)

Energy efficiency is a major concern for UWSNs because sensor nodes have batteries of limited power, which are hard to replace or recharge in such environments. It is a fundamental problem to design a scalable and energy-efficient routing protocol for these networks. Domingo and Prior (2007) presented a distributed energy aware and random node mobility supported routing protocol called Distributed Underwater Clustering Scheme (DUCS) for long-term but non-time critical applications.

DUCS is an adaptive self-organizing protocol where the whole network is divided into clusters using a distributed algorithm. Sensor nodes are organized into local clusters where one node is selected as a cluster head for each. All the remaining nodes (non-cluster heads) transmit the data packets to the respective cluster heads. This transmission must be single hop. After receiving the data packets from all the cluster members, cluster head performs signal processing function like aggregation on the received data, and transmits them towards the sink using multi-hop routing through other cluster heads. Cluster heads are responsible for coordinating their cluster members (intra-cluster coordination) and communication among clusters (inter-cluster communication). The selection of cluster head is completed through a randomized rotation among different nodes within a cluster in order to avoid fast draining of the battery from the specific sensor node. DUCS completes its operation in two rounds. The first round is called setup, where network is divided into clusters, and in the second round, which is called network operation, transfer of data packets is completed. During the second round, several frames are transmitted to each cluster head where every frame is composed of a series of data messages that the ordinary sensor nodes send to the cluster head with a schedule. Simulation results have shown that DUCS not only achieves high packet delivery ratio, but also considerably reduces the network overhead and continues to increase throughput consequently.

Although DUCS is simple and energy efficient, but it has a couple of performance issues. First, node movements due to water currents can affect the structure of clusters, which consequently decreases the cluster life. Frequent division of sectors can be a burden on the network as the setup phase is repeated many times. Second, during the network operation phase, a cluster head can transmit its collected data towards another cluster head only. Again, water currents can move two cluster head nodes away, where they cannot communicate directly even a few non-cluster head nodes are available between them.

#### 4.7. Depth Based Routing (DBR)

For location-based routing schemes, most of the protocols require and manage full-dimensional location information of the sensor nodes in the network, which itself is a challenge left to be solved for UWSNs. Instead of requiring complete localized information, DBR (Yan et al., 2008) needs only the depth information of sensor node. In order to obtain the depth of current node, the authors suggested to equip every sensor node with an inexpensive depth sensor. In their architecture, multiple data sinks placed on the water surface are used to collect the data packets from the sensor nodes. DBR takes decision on the depth information, and forwards the data packets from higher to lower depth sensor nodes. When a node has a data packet to be sent, it will sense its current depth position relative to the surface and place this value in the packet header field "Depth" and then broadcast it. The receiving node will calculate its current depth position and can only forward this packet if its depth is smaller than the value embedded in the packet, otherwise it will simply discard the packet. This process will be repeated until the data packet reaches at any of the data sink. Packets received at any of the data sink are considered as successful delivery at the final destination as these data sinks can communicate efficiently with much higher bandwidth through radio channel.

However, it has some serious problems. First, DBR has only greedy mode, which alone is not able to achieve high delivery ratios in sparse areas. In such areas, it is possible that no node can be eligible as a forwarding node due to greater depth as compared to sending node, and current node will continue to make more and more attempts. Though some nodes can be available here at the higher depths, i.e. those that can forward these packets towards the data sink successfully, but the mechanism that can handle such situations is not available. So in sparse areas, the performance of the protocol can decrease. Second, forwarding the data packets in a broadcast fashion can decrease the performance of the network. The authors have even defined a mechanism when two or more nodes are candidates for further forwarding of the same data packet, then which node will be eligible for the task. Still, as a result of these broadcasts more and more nodes will receive the data packets and calculate their depth every time, which is an inefficient use of limited available energy. In short, both much sparser and high density areas are problems for DBR as increasing densities not only increase the energy consumption but also create complexities, which can lead towards inefficient use of memory and packet losses.

#### 4.8. Sector-based Routing with Destination Location Prediction (SBR-DLP)

Recently, several location-based routing techniques have been proposed and it is said that they could achieve energy efficiency by decreasing the network overhead. Most of them assume that the destination is fixed and its location is already known to all the nodes throughout the network. This assumption may not be suitable for fully mobile networks. Chirdchoo et al. (2009)

proposed a routing algorithm called SBR-DLP, which helps route a data packet in a fully mobile underwater acoustic network, where not only intermediate nodes but also destination can be mobile.

The SBR-DLP is a location-based routing algorithm where sensor nodes need not to carry neighbor information or network topology. However, it is assumed that every node knows its own location information and pre-planned movement of destination nodes. Data packets are forwarded to the destination in a hop-by-hop fashion instead of finding end-to-end path in order to avoid flooding. As shown in Fig. 5, a node S has a data packet that needs to be sent to destination D. In order to do that, it will try to find its next hop by broadcasting a *Chk\_Ngb* packet, which includes its current position and packet ID. The neighbor node that receives *Chk\_Ngb* will check whether it is nearer to the destination node D than the distance between nodes S and D. The nodes that meet this condition will reply to node S by sending a *Chk\_Ngb\_Reply* packet. This method is further depicted in Table 1. SBR-DLP is a location-based routing protocol such as Xie et al. (2006a) and Jinming et al. (2008) but it is different in many aspects from both of them. First, instead of allowing all the candidate nodes to decide about the packet forwarding, in SBR-DLP the sender node decides which node will be the next hop using the information received from the candidate nodes. This solves the problem of having multiple nodes acting as relay nodes.

SBR-DLP handles the issue of destination mobility by assuming that pre-planned movements are completely known to all the sensor nodes before deploying them. However, this assumption has two issues. First, it reduces the flexibility of the network; after launching the network it is not possible to change the position or location of destination nodes. Second, it is important to note that water currents can deviate the destination node from its scheduled movements (Table 2).

#### 4.9. Multipath virtual sink architecture

The network topology is important for determining network reliability, capacity, and energy consumption. Sufficient robustness and redundancy must be available in the network in order to

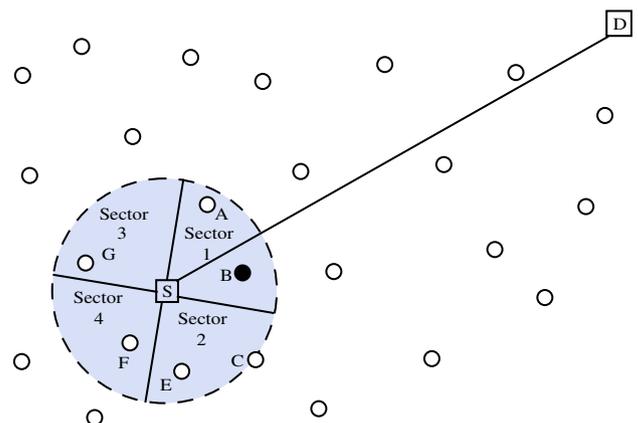


Fig. 5. Forwarder selection at the sender in SBR-DLP.

Table 2  
How node S picks its next relay node.

Sector	Candidates	Distance to D	After filtering
1	A, B	500, 480	A, B
2	C	550	
3	–	–	
4	–	–	
		Next relay node	B

ensure that it will continue to work even when a significant portion of the network is not working properly. Based on these facts, Seah and Tan (2006) proposed a Multipath Virtual Sink architecture in order to make a robust network. In the proposed architecture, the whole network is divided into clusters of sensor nodes where each cluster has either one or multiple local aggregation points. These aggregation points will form a small mesh network that connects to local sinks as shown in Fig. 6. Here it is assumed that local sinks are connected via high speed links, possibly RF communications to a network where resources are more than sufficient in order to fulfill the communication needs of different applications. The ultimate goal of this architecture is to ensure that data packets are received at any one or more of these local sinks, which collectively form a virtual sink.

As the acoustic channel is intermittent in terms of connectivity and available bandwidths are very small, it can be better for the sensor nodes to cache the sensed data and transmit when the channel conditions are favorable instead of making multiple transmission attempts. For delayed sensitive data, instead of caching, the system will try to forward data packets through multiple paths, which increase the probability of successful data delivery. The local aggregation points form a wireless mesh network where multiple paths are available to reach the multiple local sinks. Each sink broadcasts a hopcount message in order to identify itself. All the sensor nodes that receive this message will update their hopcount value, and rebroadcast this message after making an increment of one. When a sensor node has data packet for sending, it can forward this packet towards any connected local sink using the previous hop recursively. They check the performance of the architecture by making multiple transmissions with single path, then forwarding multiple copies at different routes to ensure that the transmissions reach different sinks.

In the proposed scheme, reliability is improved as duplicate packets are delivered towards multiple sinks through multiple paths. However, the problem of redundant transmission exists, which can consume critical underwater resources.

#### 4.10. Hop-by-Hop Dynamic Addressing Based Routing (H2-DAB)

Most of the routing protocols proposed for UWSNs require some special network setups. Many of them make assumptions like full-dimensional location information of whole network is available, which is not simple, as providing the complete dimensional location information for underwater environments is a separate research issue left to be solved, while the remaining ask

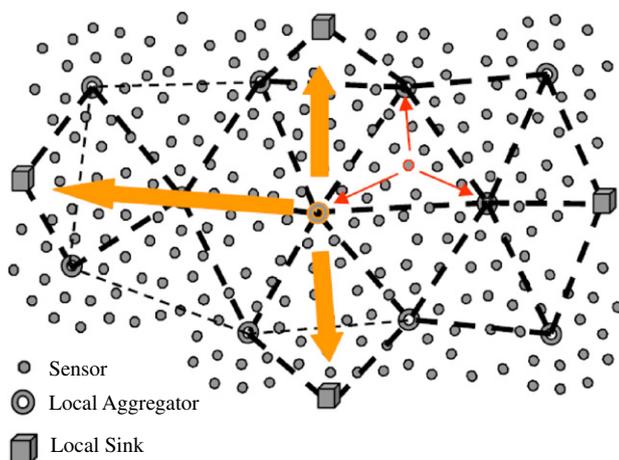


Fig. 6. Proposed underwater network topology for Multipath Virtual Sink architecture.

for special hardware like every node should be equipped with depth or pressure sensor, which not only increase the cost of the network but also become a burden on the critical node energy. By considering these issues, the authors have proposed a dynamic addressing based routing protocol H2-DAB (Ayaz and Abdullah, 2009), which does not make any assumption as most of the schemes.

The purpose of H2-DAB is to solve the problem of continuous node movements. Dynamic addresses are used for sensor nodes in order to solve the problem of water currents, so that sensor nodes will get new addresses according to their new positions at different depth intervals. In their architecture, multiple surface buoys are used to collect the data at the surface and some nodes are anchored at the bottom. Remaining nodes are deployed at different depth levels from the surface to the bottom. Nodes nearer to the surface sinks have smaller addresses, and these addresses become larger as the nodes go down towards the bottom as shown in Fig. 7. H2-DAB completes its task in two phases: first by assigning the dynamic addresses, and, second, by forwarding the data using these addresses. Dynamic addresses will be assigned with the help of Hello packets; these are generated by the surface sinks. Any node that generates or receives data packets will try to deliver it towards the upper layer nodes in a greedy fashion. Packets that reach any one of the sinks will be considered as delivered successfully to the final destination as these buoys have the luxury of radio communications where they can communicate with each other at higher bandwidths and have lower propagation delays.

H2-DAB has many advantages: it does not require any specialized hardware, no dimensional location information required and node movements can be handled easily without maintaining complex routing tables. However, the problem of multi-hop routing still exists as it is based on multi-hop architecture, where nodes near the sinks drain more energy because they are used more frequently.

#### 4.11. Mobile delay-tolerant approach (DDD)

Acoustic channel imposes higher energy consumption than radio signal. Due to higher power usage of acoustic modems, energy saving for underwater sensor networks becomes even

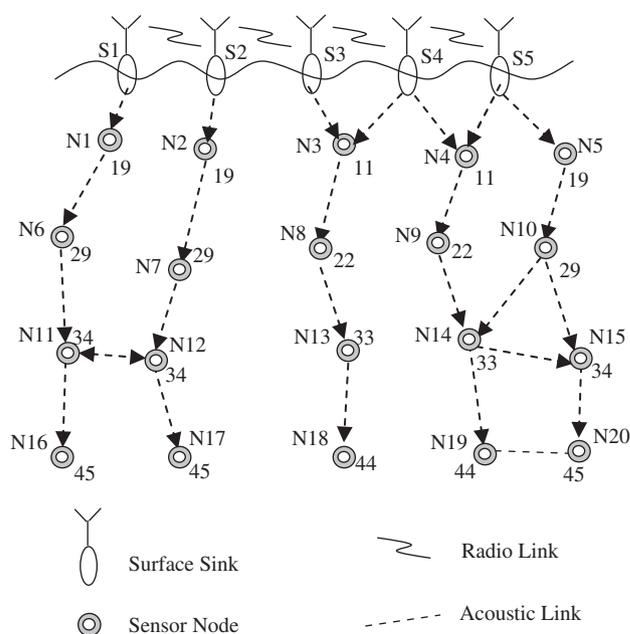


Fig. 7. Assigning HopID's with the help of Hello packets in H2-DAB.

more critical than in traditional sensor networks. In order to increase the energy efficiency in resource constraint underwater environment Magistretti et al. (2007) proposed a Delay-tolerant Data Dolphin (DDD) scheme for delay-tolerant applications. DDD exploits the mobility of collector nodes called dolphins to harvest information sensed by the stationary sensor nodes. The proposed scheme avoids energy expensive multi-hop communication, and each sensor node is only required to transmit its collected data directly to the nearest dolphin when it reaches its communication range.

In their architecture, stationary sensor nodes are deployed on the sea bed in the whole area of interest. These nodes collect the information from the environment and the sensed data are stored locally after processing. These sensors periodically wake up for sensing and event generation. The acoustic modem is based on two components. The first component is used for acoustic communication with the near dolphin, and the other is a low-power transceiver used to determine the presence of dolphin nodes (by a special signal transmitted from the dolphin) and to trigger the first component. Besides the sensor nodes, a number of dolphin nodes are used to collect the data packets when they move within the one-hop range of scattered sensor nodes. The dolphins can move either with random or controlled mobility according to the network condition. A dolphin node broadcasts beacons to advertise their presence. Beacons are transmitted at such acoustic frequencies, those that are compatible with the low-power sensor modem. Advertising period  $t$  is adjusted according to deployment and communication range  $r$  of sensor nodes, and to the speed of dolphin  $v$ . Finally, dolphins deliver gathered data packets as soon as they reach a base station on the surface.

The quantity of dolphin nodes is the most important parameter for the evaluation of DDD performance. If the number of dolphin nodes is not enough, they will not be able to gather all the data packets from the sensor nodes. Since dolphins move randomly, it is possible that they cannot visit some sensors directly, which results in the loss of existing data packets from the limited memory of the sensor node when there is no memory space left. Increasing the number of dolphin nodes, say 7 dolphins for 25 sensor nodes as in the simulation, then cost will become a major issue.

#### 4.12. Efficient data delivery with packet cloning

In mobile sensor networks, possibly multiple paths can exist from a sensor node to the destination and these paths may or may not be disjointed. It has been shown that routing over these multiple paths not only helps increase the data delivery ratios, but also achieves timeliness of delivery. As these paths start to converge at the destination, the possibility of contention starts to increase as well. The contention that arises among nodes in close proximity can be viewed positively. In order to get benefit from the proximity of nodes Peng et al. (2007) proposed a Packet Cloning technique, which helps enhance the data delivery ratios. The proposed scheme utilizes this idea to selectively clone data packets during the forwarding process to the destination. Different from the controlled broadcast or conventional multipath routing, where duplicate packets are indistinguishable because the involved nodes have no idea how many duplicates have been introduced, the current technique has the ability to control the number of packet clones according to the link quality and channel conditions in order to minimize the contention and energy expenditures.

During the packet cloning process, a relay node will not resend an incoming packet if it has already received one copy. This will help prevent excessive network traffic. However, the authors want to exploit the advantage of having two distinct copies of

the same data packet along two disjointed paths. For this, distinct copies of original packet are created while the number of distinct copies is a parameter that can be adjusted according to the conditions. A source node will first determine how many distinct copies it wants, and then it will start to send each copy sequentially with some interval between them. The total number of copies produced and the identification number of the particular copy are mentioned in the packet header. When a clone packet is received by an intermediate relaying node then it can derive some information from the incoming packet. This extracted information is useful for detecting the duplicates and packet losses. Duplicate packet received is simply discarded, and new packet clones are relayed, while missed or lost packet clones are generated and transmitted. When a source node performs the packet cloning then it sends out each clone after selecting a proper value of interval, which depends on the physical channel parameters. By doing so, it will help reduce the chances of clones contending and interfering with each other.

Although multipath routing schemes are able to increase network robustness not only by increasing the delivery ratios, but also by decreasing end-to-end delays, the acoustic channel is power-hungry compared to RF based. Thus, in order to increase the delivery ratio, more paths are suggested and these multiple paths continue to produce duplicates if the channel quality is not good. In short, RF based communications can support these schemes but for high power consuming acoustic environment, techniques like packet cloning are not easily affordable.

#### 4.13. Resilient routing algorithm for long-term applications

For underwater communications, different problems are addressed at different layers, e.g. most of the impairments of acoustic channel belong to physical layer while characteristics like limited bandwidth, temporary losses of connectivity and node failures need to be addressed at higher layers. By considering this phenomenon, Dario Pompili and Ian (2006) proposed a resilient routing algorithm for long-term underwater monitoring applications, which complete its task in two phases. In the first phase, optimal node-disjoint primary and backup multi-hop data paths are discovered in order to minimize energy consumption. This is required because different from the terrestrial sensor networks where nodes are redundantly deployed, the underwater networks require minimum number of nodes. In the second phase, an online distributed scheme observes the network and if required then switches to the backup paths. It is a fact that underwater monitoring missions can be highly expensive; so it is essential that the deployed network must be highly reliable in order to avoid the failure of mission due to failure of single or multiple devices.

The communication architecture used for resilient routing algorithm requires winch-based sensor devices; these are anchored at the ocean bottom. Each sensor device is equipped with a floating buoy that can be adjusted by a pump. The buoy helps the sensor device to move towards the ocean surface. The depth of the device can be regulated by adjusting the length of wire, which anchors that node by means of an electronically controlled engine that resides on the same device.

The proposed architecture has some strengths, including the sensor nodes are not vulnerable to weather and tampering and the nodes are less affected by the water currents. However, this scheme is limited to long-term applications, and with proposed architecture cost will become a major issue if the area of interest is large.

#### 4.14. Pressure routing for underwater sensor networks (HydroCast)

For UWSNs, geographic routing is preferable due to its stateless nature. However, geographic routing requires distributed localization

of mobile sensor nodes, which not only can be expensive in terms of energy, but also can take long time to converge. In order to provide an alternate of geographic routing, Uichin et al. (2010) presented HydroCast, a hydraulic pressure based routing protocol. HydroCast uses any cast routing by exploiting the measured pressure levels in order to forward the data packets towards surface buoys. The proposed hydraulic pressure based protocol is stateless and completes its task without requiring expensive distributed localization.

The basic idea of HydroCast is similar to DBR where routing decisions are made after comparing the local pressure or depth information, such that data packets are greedily forwarded towards a node with the lowest pressure level among the neighbor nodes. DBR faces a serious problem of local maximum when a data forwarding node cannot find the next hop with lower depth among its neighbor nodes. In such void regions, it does not provide any solution to handle such situation. While in HydroCast scheme, each local maximum node maintains a recovery route towards a neighboring node with higher depth than itself. After one or several forwardings through local maxima, a data packet can be routed out of the void region and can be switched back to the greedy mode.

The problem of void regions that existed in DBR has been successfully solved by the HydroCast. The authors have considered the quality of wireless channel for simultaneous packet reception among the neighbor nodes. These simultaneous receptions enable the opportunistic forwarding by a subset of the neighbors that have received the data packet correctly, which ultimately increase the delivery ratios. At the same time, due to this opportunistic routing, multiple copies of the same data packet can be delivered to a sink, which will be a burden on the network resources. Although the simulation results have shown that HydroCast is able to provide high delivery ratios with small end-to-end delays, still no information is available about the energy usage, consumed by the pressure sensor in order to find its depth.

#### 4.15. Energy-Efficient Routing Protocol (EUROP)

Underwater sensor nodes are battery powered and these batteries cannot be replaced easily; so power efficiency is a critical issue for these environments. Additionally, extremely long delays for acoustic communications could lead to the collapse of traditional terrestrial routing protocols due to limited response waiting time. In order to handle these issues, Chun-Hao and Kuo-Feng (2008) designed an energy-efficient routing protocol called EUROP, where they tried to reduce large amount of energy consumption by reducing broadcast hello messages.

In the proposed architecture, they suggest the use of pressure sensor as a significant indicator for every sensor node to get its depth position. This depth sensor will eliminate the requirement of hello messages for control purpose, which can be helpful for increasing the energy efficiency. These sensor nodes are deployed at different depths in order to observe the events occurring at different locations in the network. Further, every node is anchored at the bottom of the ocean, and is equipped with a floating module that can be inflated by a pump. This electronic module that resides on the node helps push the node towards the surface and then back again to its initial position. The depth of the sensor node can be regulated by adjusting the length of wire that connects the sensor to the anchor. All the sensor nodes at different depths will form layers, while the amount of layers depends on the depth. The sink on the surface can communicate only with the sensors that belong to shallow water. Each sensor node on all the layers communicate through acoustic channel after deciding to which layer it belongs by detecting the value

of pressure. The sensor nodes use RREQ and RREP packets to communicate with each other, and the next hop can be determined by the rule of from deep to shallow and so on.

EUROP seems simple in terms of communication as many control packets are eliminated by introducing depth sensor inside the sensor node. Besides depth sensor, an electronic module is also required by every node in order to push it towards the upper layer and back to its original position again. Installing the depth sensor and electronic module is not a simple decision because cost per node will increase and the additional devices will burden the critical node energy, hence decreasing the life of the sensor node.

#### 4.16. Distributed Minimum-Cost Clustering Protocol (MCCP)

In LEACH (Heinzelman et al., 2002), a protocol proposed for terrestrial sensor networks, clusters are formed with optimal number of cluster heads using the prior knowledge of uniform node distribution. However, due to continuous movement of ocean current, usually node deployment becomes non-uniform, which makes LEACH unsuitable for these environments. HEED (Younis and Fahmy, 2004) solves this problem where clusters are formed without assuming a uniform distribution of the sensor nodes. Although a cluster head rotation scheme is also implemented, still the traffic loads in different areas remain unbalanced. Moreover, both of these are based on cluster-head-centric scheme, in which the cluster head is selected first followed by each of the non-cluster head node joining its nearest cluster. In order to handle these problems, a distributed minimum-cost clustering protocol (MCCP) is proposed in Pu et al. (2007) with an objective to improve energy efficiency and prolong the network life.

The proposed scheme uses a cluster based approach where clusters are formed by computing the following three parameters: total energy required by the cluster members for sending data to the cluster head, the residual energy of the cluster head and its entire members, and relative location of the cluster head and underwater-sink (uw-sink). To solve the problem, a centralized algorithm minimum-cost clustering algorithm (MCCA) is proposed where clusters are selected using a centralized approach. The MCCA is further extended to a distributed approach called MCCP. In this approach, initially all the sensor nodes are candidates for cluster head as well as the cluster member. Every candidate constructs its neighbor set and uncovers neighbor set in order to form a cluster. The average cost of that particular cluster is calculated and broadcasted to all the candidates within its 2-hop range with its cluster-head ID. After receiving this cost, every candidate node will compare with its own calculated cost. If it has minimum average cost, then it becomes a cluster-head and advertises an INVITE message to other cluster nodes to become its cluster member, otherwise it sends a JOIN message to the specific cluster head. Finally, all the nominated clusters define a TDMA schedule and forwarded it to the respective cluster members.

MCCP has many advantages as it avoids the formation of hot spots around the uw-sink by generating more cluster heads, which helps balance the traffic load. The number of cluster members depends on the cluster-head and uw-sink locations, which mean clusters closer to uw-sink will have less cluster members. Further, it has the ability to balance the traffic load by re-clustering the sensor nodes periodically. However, it does not support multi-hop routing and for this it depends on some other scheme. Second, the period for re-clustering the network is defined in the range of days or months. For underwater environments, nodes are in continuous movements from 2 to 3 m/sec (3–5 km/h) (Lanbo Liu and Cui, 2008). Due to this nodes can leave and enter different clusters during such long periods, which ultimately affect the cluster efficiency.

#### 4.17. Underwater Wireless Hybrid Sensor Networks (UW-HSN)

In underwater wireless sensor networks, acoustic channel is considered as the only feasible means of communication. In practicality, acoustic channel presents many key challenges specifically in shallow water such as large propagation delays, high signal attenuation and transmission energy consumption, and low bandwidth. In order to handle this situation where we only have the choice of acoustic channel, [Ali and Hassanein \(2008\)](#) introduced a hybrid architecture called Underwater Wireless Hybrid Sensor Networks (UW-HSN).

UW-HSN is a hybrid of both acoustic and radio communications. The basic idea here is to use the radio communication for large and continuous traffic, and acoustic for small amount of data. Every node supports both types of communication; so they will use acoustic for underwater communication with the neighboring nodes, and radio is used when nodes are on the surface in order to communicate directly with the base station. By doing so, the over-water network is a high speed, short range multi-hop with the help of radio channel. For this purpose, any existing link layer, routing, networking, and localization protocol can be used from the WSN literature with minor changes for surface communication. Every node should be equipped with both radio and acoustic modem in order to support both types of communication. In addition to acoustic and radio interface, every node is also equipped with a mechanical module, which allows the node to swim to the surface and then dive back to different levels in the water. The philosophy is to incorporate the mobility of underwater sensor nodes in order to increase overall throughput of the network. They introduce TurtleNet, based on the hybrid concept, where nodes use piston based negative and positive buoyancy for the vertical movements in order to reach water surface, and then back to the ocean bottom or at pre-configured depth. For this architecture, they provide an algorithm called Turtle Distance Vector (TDV), based on distance vector approach. According to the current state of node, TDV will determine the communication channel in order to minimize average event delay. The event delay is defined as the time duration between its creation at the source and successful reception at the base station.

Performance evaluation of the UW-HSN by simulation shows that UW-HSN provides high goodput and smaller delays as compared to all previous acoustic approaches. However, no information is available about the energy consumption, which is an important metric in order to check the performance of TurtleNet due to its special network setup requirements. These extra hardware requirements drain the crucial energy, which not only can decrease the network life, but also can increase the cost of the network.

#### 4.18. Temporary Cluster Based Routing (TCBR)

Many multi-hop routing protocols have been proposed for underwater sensor networks, but most of them face the problem of multi-hop routing where nodes around the sink drain more energy and are suspected to die early. In order to solve this problem and make equal energy consumption throughout the network, [Ayaz et al. \(2010\)](#) proposed a Temporary Cluster Based Routing (TCBR) algorithm.

In TCBR architecture, multiple sinks are deployed on the water surface and data packets received at any sink are considered as delivered successfully because they can communicate at higher bandwidth and small propagation delay with the help of radio communication. Two types of nodes are used: ordinary nodes and some special nodes called courier nodes. Ordinary sensor nodes are used to sense the event happening, collect information and try to forward these data packets to a nearer courier node. A small number of courier nodes (2–4% of total sensor nodes) are used,

and these can sense as well as receive the data packets from the other ordinary sensor nodes and deliver them to a surface sink. These courier nodes are equipped with a mechanical module, which helps push the node inside the water at different predefined depths and then pull back the node to the ocean surface. Any node equipped with a piston can do this by creating the positive and negative buoyancy. These courier nodes will reach different depth levels and stop for a specified amount of time. After reaching the specified position, these will broadcast hello packets so that ordinary nodes around them will be aware of their presence. These hello packets can be forwarded only within 4 hops, and if an ordinary node receives them from more than one courier node then it will forward the data packet to a nearer one within a specified amount of time, which is defined in the Hello packet.

TCBR completes its task of equal energy consumption throughout the network with requiring a small number of courier nodes, instead of equipping the mechanical module with every sensor node. However, data can be collected when a courier node reaches the communication range of every sensor node. Due to this, all the sensor nodes will hold their generated data packets in a limited buffer until a courier node visits them. Despite this feature, the TCBR is not suitable for time critical applications.

#### 4.19. Multi-sink opportunistic routing protocol

[Tonghong \(2008\)](#) proposed multi-sink opportunistic routing protocol for underwater mesh networks. They defined a tiered architecture for deploying the underwater sensor nodes, where an acoustic mesh network is located between underwater network and central monitoring system, which acts like a backbone network for sensor nodes. A quasi-stationary 2D UWSN architecture is considered for shallow-water coastal area. This architecture is composed of five types of elements including ordinary sensor node, mesh node, UW-sink, surface buoy, and monitoring center. Among these, three of them, including sensor node, mesh node, and UW-sink, are anchored to the sea bed and surface buoy is placed at the ocean surface. Further, both the UW-sink and the surface buoy are connected through a wire. An onshore central monitoring system is used, which is connected to the Internet. Compared with ordinary sensor node, a mesh node is more sophisticated as it has more memory, longer transmission range, and better processing power. In order to help the network survive for longer period, an underwater man controlled vehicle is used for recharging these mesh nodes.

After observing the occurred phenomena, each sensor node transmits its sensed data to the nearer mesh node. Mesh nodes first aggregate the received data and then send it to the UW-sinks via multi-hop acoustic channel. Finally, the aggregated packets are delivered to the surface buoy and from here these packets are sent to the onshore monitoring system. The proposed scheme is the best protocol where data packets are forwarded along redundant and interleaved paths. The source node transmits the data packets simultaneously, but not sequentially, over multiple UW-sinks located at different locations. Different from the opportunistic routing, this protocol exploits the packet duplications to increase packet delivery ratio.

However, the proposed routing protocol has some serious performance issues. First of all, it is assumed that each mesh node has information not only about its adjacencies but also about all the UW-sinks like node IDs and their geographic positions. Second, the authors considered a quasi-stationary network but not completely mobile, which is the reason for assuming that the mesh nodes and their neighbors are relatively static, which can be different in practicality. Moreover, packets are forwarded along redundant and interleaved paths; so multiple copies of the same packet can be generated and these duplications will continue to increase as the number of hops along the path starts to increase.

#### 4.20. Location-based Clustering Algorithm for Data Gathering (LCAD)

Data transmission phase is the main source of energy consumption for a sensor node. Dissipation of energy during the data transmission is proportional to the distance between the sender and the receiver. As we have discussed earlier, another problem with the multi-hop approach is that sensor nodes around the sink process a large number of data packets, which rapidly drain their energy. In order to solve both of these problems, Anupama et al. (2008) suggested a cluster based architecture for three-dimensional underwater sensor networks. Here, sensor nodes are deployed in the whole area of interest at fixed relative depths from each other. These sensor nodes at each tier are organized in clusters with multiple cluster heads. They suggest an algorithm for the cluster head selection at each cluster according to the node position in the network. Horizontal acoustic links are used for intra-cluster communication. For energy concern, the length of this horizontal acoustic link is restricted to a maximum of 500 m as it has been shown that the performance of acoustic link can be optimal at this communication distance (Stojanovic et al., 1994).

In the proposed architecture, the entire network is divided into three-dimensional grids where each grid is set approximately to  $30\text{ m} \times 40\text{ m} \times 500\text{ m}$ . The entire communication process is completed in three phases: (i) setting up phase, where the cluster head is selected; (ii) data gathering phase, where data are sent to the cluster head by the nodes in the same cluster; and (iii) transmission phase, where data gathered by the cluster heads are delivered to the base station with the help of Autonomous Underwater Vehicles (AUVs). About cluster head (ch-node), some of the sensor nodes in every cluster have additional resources like memory and energy, and such nodes can qualify as ch-head. Having multiple ch-nodes increases not only the reliability, but also the load balancing in the network. These ch-nodes are located approximately at the center of the grid, which helps communicate with maximum number of ordinary sensor nodes. These grids are organized just like the cells in a cellular network.

AUVs are used as data mules for collecting data packets from these cluster heads instead of every sensor node in the network. As it has been proven that acoustic link is not suggested for distances more than 500 m, the required number of tiers depends on the average depths of oceans. For the best results, they advocate a dense deployment of sensor nodes at the lower tiers and sparser distribution at the higher tiers.

Nonetheless, the proposed protocol seems to have some serious performance issues. The performance of LCAD depends on grid structure, especially the position of ch-node inside it. For terrestrial sensor networks, such type of structure is easily possible. However, for underwater environments where node movements are frequent, the assumption of such grid structure is not so simple as nodes can come and leave different grids frequently. For performance analysis, they evaluated the performance of LCAD in terms of network lifetime but have not provided any information about the node movements.

#### 4.21. Location-Aware Source Routing (LASR)

Dynamic Source Routing (Johnson et al., 2001) is a well known routing protocol originally proposed for the MANET, but suffers from high latency in the underwater acoustic environment. In these conditions, the topology rate of change is very high compared to acoustic latency. Hence, topology continues to change more quickly such that DSR can adapt. In order to solve this problem without losing the experience of DSR, Carlson et al. (2006) proposed LASR, a modification of DSR. LASR uses two techniques in order to handle the high latency of acoustic channel: first, link quality metric, and,

second, location awareness. DSR depends only on the shortest path metric, which leads to poor performance in highly mobile networks. LASR replaces this shortest path metric with expected transmission count (ETX) where link quality metric provides more-informed decisions, thus giving better routes through the network. Location awareness can be achieved from the incoming transmissions as an aid for estimating local network topology. Topology prediction uses a tracking system to predict the current location of other vehicles in the network based on one way and range only measurements, while all the explicit informations of the network including the routes and topology information are passed on in the protocol header.

After all these modifications, still LASR depends on source routing technique inherited from DSR. Therefore, as the hop count between source and destination increases, the packet header continues to increase as well. The increasing header size leads to overhead for acoustic communication with a narrow bandwidth. Second, it uses Expected Transmission Count (ETX) as a link quality metric, for which it assumes that links are symmetrical and are with the same link quality in both directions, which is not easily possible for underwater acoustic communication

#### 4.22. Adaptive routing

An underwater sensor network can be easily partitioned due to continuous node mobility and sparse deployment. This results in unavailability of persistent route from the source to the destination. Therefore, an underwater sensor network can be viewed as Intermittently Connected Network (ICN) or Delay/Disruption Tolerant Network (DTN). Traditional routing techniques are not usually suitable for ICN or DTN, since data packets will be dropped when routes are not available. Further, an USN is frequently required to provide distinguished packet deliveries according to different application requirements. Therefore, it is desirable to design a smart routing technique that could manage different application requirements adaptively (Figs. 8 and 9; Table 3).

For this purpose, Zheng et al. (2008) proposed a novel routing technique called adaptive routing for underwater Delay/Disruption Tolerant Sensor Networks where it assumed that all nodes know about their 3d position. Here routing decisions are made according to the characteristics of data packets and the network conditions. The purpose of this protocol is not only to satisfy different application requirements, but also to achieve a good trade-off among delivery ratios, end-to-end delays, and energy consumption for all data packets. The packet priorities are calculated from the packet emergency level, packet age, density of the neighbors around a node, and battery level of the node. The novelty of their work is that here different number of message copies are created according to the characteristics of data packets and network. In order to make the protocol flexible according to the conditions, all the elements in the information are variable except the emergency level. They divide the whole routing spectrum into four states, and routing is conducted according to calculated results. Simulation results show that such a strategy can satisfy different application requirements like delivery ratio, average end-to-end delay, and energy consumption. However, the proposed scheme calculates these priorities separately for each data packet after receiving them. Such calculations require high frequent communication with the neighbor nodes, which not only can be a burden on node energy but also can help increase end-to-end delays (Table 4).

## 5. Evaluation methods

Analytical modeling, real deployment, and numerical simulation are the most commonly used techniques in order to analyze the performance of terrestrial and underwater acoustic sensor

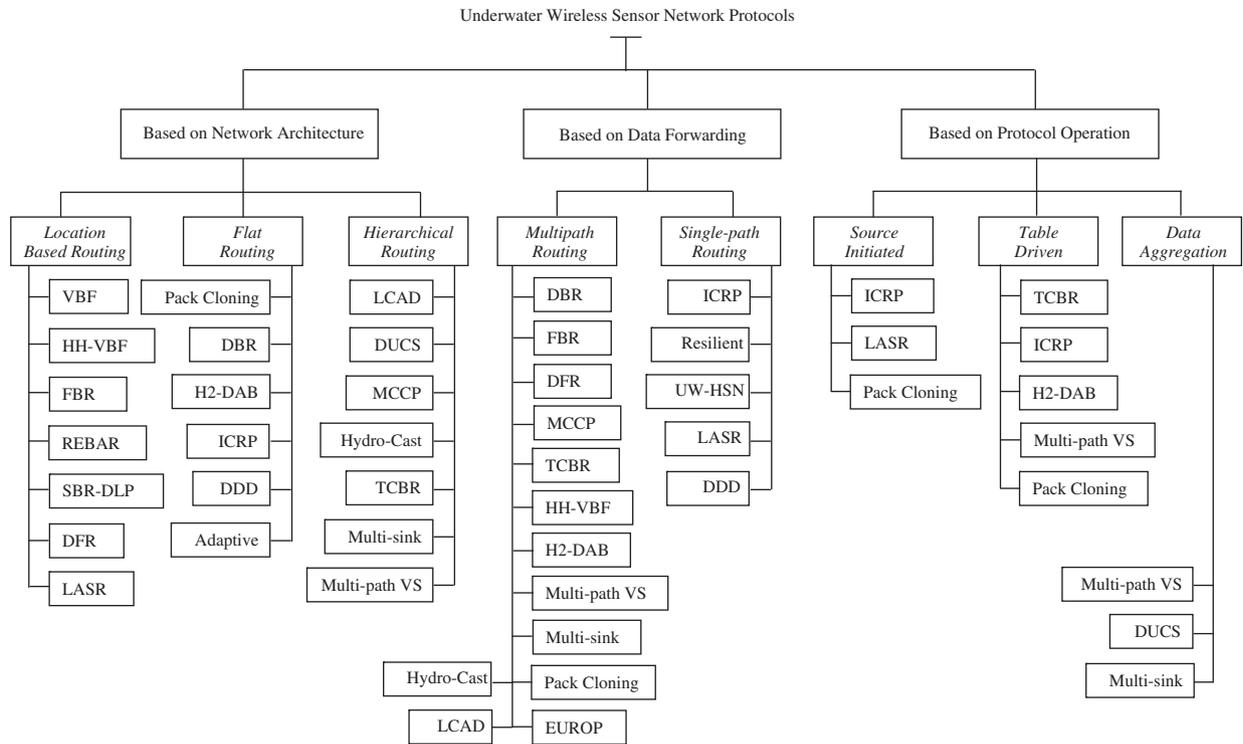


Fig. 8. General classification of UWSN routing protocols discussed in this article.

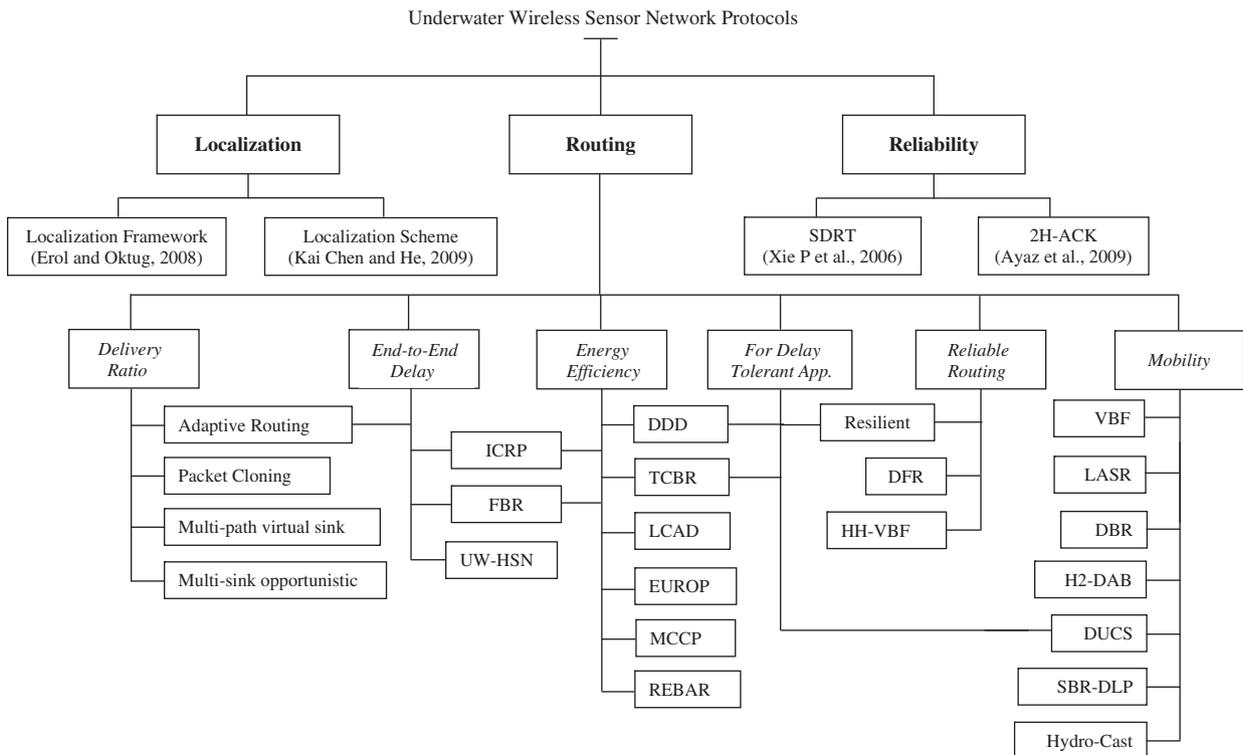


Fig. 9. Classification of UWSN protocols according to their proficiency.

networks. Each of the available techniques has its own advantages and limitations depending on the considered network characteristics. First of all let us talk about analytical modeling. These methods are very complex, especially for underwater scenarios and usually certain simplifications are assumed to predict the

performance of the proposed scheme. Such assumptions and simplifications may lead to imprecise results with limited confidence. Further, it may not be feasible to evaluate the performance of these schemes through real experiments due to the unavailability of appropriate hardware in terms of technical and

**Table 3**  
Comparison of routing protocols based on their characteristics.

Protocol/ architecture	Single/ Multiple copies	Hop-by-hop/ end-to-end	Clustered/ single entity	Single/multi- sink	Hello or control packets	Requirements and assumptions	Knowledge required/ maintained	Remarks	Year of pub.
VBF (Xie et al., 2006b)	Multiple	End-to-end	Single-entity	Single-sink	No	Geo. location is available	Whole network	Considered as first geographic routing approach for UWSN	2006
HH-VBF (Nicolaou et al., 2007)	Multiple	Hop-by-hop	Single-entity	Single-sink	No	Geo. location is available	Whole network	Enhanced version of (Xie et al., 2006a), robustness improved by introducing hop-by-hop approach instead of end-to-end	2007
FBR (Jornet et al., 2008)	Single-copy	Hop-by-hop	Single-entity	Multi-sink	Yes	Geo. location is available	Own and sink location	A cross layer location-based approach, coupling the routing, MAC and phy. layers.	2008
DFR (Daeyoung and Dongkyun, 2008)	Multiple	Hop-by-hop	Single-entity	Single-sink	No	Geo. Location is available	Own, 1-hop neighbors and sink info.	A controlled packet flooding technique, which depends on the link quality, while it assumed that, all nodes can measure it.	2008
REBAR (Jinming et al., 2008)	Single-copy	Hop-by-hop	Single-entity	Single-sink	No	Geo. location is available	Own and sink location info.	Similar with (Jornet et al., 2008) but use adaptive scheme by defining propagation range. Water movements are viewed positively	2008
ICRP (Wei et al., 2007)	Multiple	End-to-End	Single-entity	Single-sink	No	n/a	Source to sink information	Control packets of route establishment are carried out by the data packets	2007
DUCS (Domingo and Prior, 2007)	Single-copy	Hop-by-hop	Clustered	Single-sink	Yes	n/a	Own cluster info. (1-hop)	A self-organizing algorithm for delay-tolerant applications, which assumes that sensor nodes always have data to send	2007
Packet Cloning (Peng et al., 2007)	Multiple	Hop-by-hop	Single-entity	Multi-sink	No	n/a	amount and sequence of clones	Unlike controlled broadcast, discernible clones of a data packet are forwarded according to network conditions	2007
SBR-DLP (Chirdchoo et al., 2009)	Single-copy	Hop-by-hop	Single-entity	Single-sink	Yes	Geo. location is available	Own location and sink movement	Similar with (Jinming et al., 2008), but does not assume that destination is fixed plus it consider entire communication circle instead of single transmitting cone	2009
Multipath Virtual Sink (Seah and Tan 2006)	Multiple	Hop-by-hop	Clustered	Multi-sink	Yes	Network with special setup	Own cluster information	Advantage of multipath routing without creating any contention near the sink	2006
DDD (Magistretti et al., 2007)	Single-copy	Single hop	n/a	n/a	Yes	Network with special setup	About dolphin node presence	A sleep and wake-up scheme, which requires only one-hop transmission	2007
DBR (Yan et al., 2008)	Multiple	Hop-by-hop	Single-entity	Multi-sink	No	Nodes with Special H/W	No network information maintained	Considered 1st depth based routing. After receiving data packet, nodes with lower depth will accept and remaining discards	2008
H2-DAB (Ayaz and Abdullah, 2009)	Single-copy	Hop-by-hop	Single-entity	Multi-sink	Yes	n/a	1-hop neighbor's	Short dynamic addresses called Hop-IDs are used for routing, assigned to every node according to their depth positions	2009
HydroCast (Uichin et al., 2010)	Multiple	Hop-by-hop	Clustered	Multi-sink	No	Nodes with special H/W	2-hop neighbor's	Similar with (Yan et al., 2008). Any cast pressure based routing, a subset of forwarder nodes are selected to maximize greedy progress	2010
EUROP (Chun-Hao and Kuo-Feng, 2008)	Single-copy	Hop-by-hop	Single-entity	Single-sink	Yes	Network with special setup	1 hop neighbor's	Nodes are deployed in layers. Water pressure is used for deep to shallow depth based routing	2008
UW-HSN (Ali and Hassanein, 2008)	Single-copy	Hop-by-hop	Single-entity	Single-sink	Yes	Network with special setup	1 hop neighbor's	A hybrid approach, RF is used for large and acoustic for small data volumes	2008
	Single-copy	Hop-by-hop	Clustered	Multi-sink	Yes				2010

TCBR (Ayaz et al., 2010)	Single-copy	Hop-by-hop	Clustered	Multi-sink	Yes	Network with special setup n/a	3-hop neighbors 2-hop neighbors	Temporary clusters are formed to balance energy consumption in whole network 2-hop cluster formation algorithm, but does not support multi-hop communication	2007
MCCP (Pu et al., 2007)	Single-copy	End-to-end	Single-entity	Single-sink	No	Nodes with special H/W	Discovered paths to destination	A 2-phase resilient routing. First, primary and backup paths are configured, and then these are repaired if node failure occurs	2006
Resilient Routing (Dario Pompili and Ian 2006)	Multiple	Hop-by-hop	n/a	Multi-sink	No	Network with special setup	Location of nearer mesh node	A best effort protocol. Data packets are forwarded along redundant and interleaved paths, towards multi-sinks	2008
Multi-Sink Opportunistic (Tonghong, 2008)	Single-copy	Hop-by-hop	Clustered	Single-sink	Yes	Nodes with special H/W	Own cluster information	Clusters are formed, in order to avoid multi-hop communication	2008
LCAD (Anupama et al., 2008)	Single-copy	End-to-end	Single-entity	Single-sink	Yes	Network with special setup	Source to sink information	A DSR modification. Location and link quality awareness is included. Preferred only for small networks	2006
LASR (Carlson et al., 2006)	Multiple	Hop-by-hop	Single-entity	Single-sink	Yes	n/a	Own and 1 hop neighbors info	Both, the packet and network characteristics are considered before deciding about the packet forwarding	2008

design limitations (Akyildiz et al., 2002; Xu, 2002). Even we are able to arrange some suitable hardware, it may still be not practical to experiment in an appropriate environment like deep water. Usually, such experiments require hundreds of sensor nodes; so cost becomes another important issue. In a nutshell, evaluating any scheme proposed for UWSNs through real deployment is not only complex and costly but also time consuming. Among all the techniques discussed in this article, only Wei et al. (2007) evaluated through physical deployment. However this experiment was based on only three sensor nodes, which may not practically reflect the traffic of most of the real life UWSN scenarios.

To solve this problem, some underwater acoustic research laboratories like Underwater Sensor Network Lab prefer to analyze protocol performance through physical testbed as presented in Peng et al. (2007) and Shang et al. (2010). Testbed in Shang et al. (2010) provides a set of acoustic communication hardware and software including an emulator with realistic network settings. Such tools are very helpful to provide an environment that is similar to the real deployment. Testbed is not only considered an effective option when real deployment is not feasible, but also provides more trusted results than software based tools. However, it may be limited in scope and may fail to offer realistic environment.

Most of the routing protocols proposed for UWSNs consider different design philosophies and application requirements. None of them can work efficiently for all the performance parameters like network size, communication overhead, node mobility, etc. The large variations in the performance metrics make it a difficult task to present a comprehensive evaluation for a large number of routing strategies (Kaiser, 2005).

Simulation is the most popular and effective approach to design and test any routing scheme in terms of cost and time; it also provides higher level of detail as compared to real implementation. When we talk about underwater environments, evaluation through simulation becomes an ideal choice as because highly sophisticated hardware is required and at the same time difficulty factor is presented in setting up real deployment scenario. However, the appropriate selection of a simulation framework according to problem and network characteristics is a critical task (Stojanovic, 2003). Excluding a few, the performance of all the schemes discussed in this article has been evaluated with the help of different simulation tools. Most commonly used in terrestrial sensor network simulations, open source ns-2 (NS-2) is used in underwater sensor networks as well like Chun-Hao and Kuo-Feng (2008) and Harris and Zorzi (2007). Generally, it does not support acoustic communication characteristics; so it can be used with two options. First, many authors used ns-2 by inserting larger propagation delays and other channel problems in order to produce more realistically accurate results, i.e. nearly or equal to real conditions. Multi InterFace Cross Layer Extension (MIRACLE) (Baldo et al., 2007) is another important example of NS-2 extension, which supports multiple wireless interfaces and cross layering features. Further a module for ns-miracle is developed (Underwater Channel) and used in Jan Bauer and Ernst (2010) and Zorzi et al. (2008) for detailed simulation of underwater channel according to the propagation speed in underwater environment including the impact of depth, salinity, and temperature. Some other has developed ns-2 extensions for the aquatic environment. AquaSim (Peng et al., 2009) used in Yan et al. (2008) and Tiansi Yungsi is an important example, which supports not only acoustic links but also 3D topology. Some commercial network simulators like Opnet (The Opnet Simulator) was used in Sözer and Proakis (2000) and Xianhui et al. (2009) and Qualnet (The Qualnet Simulator) was used in Uichin et al. (2010). Tools, especially developed for

**Table 4**  
Performance comparison of UWSN protocols.

Protocol / architecture	Delivery ratio	Delay efficiency	Energy efficiency	Bandwidth efficiency	Reliability	Cost (\$ efficiency)	Performance
VBF (Xie et al., 2006b)	Low	Low	Fair	Fair	Low	n/a	Low
HH-VBF (Nicolau et al., 2007)	Fair	Fair	Low	Fair	High	n/a	Fair
FBR (Jornet et al., 2008)	Fair	High	High	Fair	Fair	n/a	High
DFR (Daeyoung and Dongkyun, 2008)	Fair	Fair	Low	Fair	High	n/a	Fair
REBAR (Jinming et al., 2008)	Fair	Low	High	Fair	Fair	n/a	Fair
ICRP (Wei et al., 2007)	Low	Low	Fair	Fair	Low	High	Low
DUCS (Domingo and Prior, 2007)	Fair	Low	Fair	Fair	Low	High	Low
Pack cloning (Peng et al., 2007)	High	Fair	Low	Low	Fair	High	Fair
Multipath VS (Seah and Tan, 2006)	Fair	Fair	Low	Fair	High	Low	Fair
DDD (Magistretti et al., 2007)	Low	Low	High	Fair	Fair	Low	Low
DBR (Yan et al., 2008)	High	High	Low	Fair	High	Fair	High
H2-DAB (Ayaz and Abdullah, 2009)	High	Fair	Fair	Fair	Fair	High	Fair
HydroCast (Uichin et al., 2010)	High	High	Fair	Fair	Fair	Fair	High
EUROP (Chun-Hao and Kuo-Feng, 2008)	Fair	Low	Fair	High	High	Low	Fair
UW-HSN (Ali and Hassanein, 2008)	Fair	High	Low	Fair	Fair	Low	Low
TCBR (Ayaz et al., 2010)	Fair	Low	Fair	Fair	Fair	Low	Low
MCCP (Pu et al., 2007)	Low	Low	High	Fair	Fair	High	Fair
Resilient (Dario Pompili and Ian, 2006)	High	Low	Fair	Fair	High	Low	Fair
LCAD (Anupama et al., 2008)	Fair	Low	Fair	Fair	Low	Low	Low
LASR (Carlson et al., 2006)	Fair	Low	Fair	Fair	Fair	High	Fair
Adaptive (Zheng et al., 2008)	High	Fair	Flexible	Flexible	Flexible	n/a	Fair

underwater environments like AUVNetsim (The AUVNetsim Simulator) was used in Jornet et al. (2008). Some custom simulators written in different languages have also been implemented, including VC++ (Liu and Li, 2010) and C++ based simulator DEVCES (Choi et al., 2000) used in Carlson et al. (2004).

Although the discussed simulators play an important role for developing and testing new protocols for UWSNs, there are always some kind of risk involved as simulation results may not be accurate due to unrealistic underwater characteristics like continuous mobility in a 3d volume. In order to analyze a protocol more effectively, it is important to know different available tools and understand the associated benefits and limitations. Due to different performance requirements according to specific applications, a general tool for underwater acoustic networks is still lacking at present.

## 6. Current issues and potential research areas

Underwater wireless sensor networks are becoming increasingly important in underwater data communications for the years to come due to its significance scalability and flexibility as compared to traditional ocean monitoring approaches. From all discussions in the preceding sections, it seems that UWSNs have received much attention with sufficient solutions proposed. However, harsh underwater environment, hardware limitations, and complicated application scenarios still pose many challenges to many UWSN researchers. Based on the literature surveyed above, the following potential directions may deserve the attention of the current and future researchers interested in UWSN.

We cannot neglect the issue of continuous node mobility, especially in the large scale UWSNs. Many techniques, such as those in Melodia et al. (2010) and Creixell and Sezaki (2007) have been proposed for mobility prediction and handling in terrestrial mobile and sensor networks. However, these techniques are not suitable for handling underwater mobility due to UWSN's 3d nature. Mobility prediction is an important issue even more critical for clustered base routing, which is required to control the network topology. On other notes, the mobility models like Gauss-Markov Mobility Model and Boundless Simulation Area Mobility Model are used for evaluating different ground based algorithms, which are

not suitable for underwater environment due to its unique characteristics. Although in Zhou et al. (2011a) the authors have accepted this challenge and proposed a mobility prediction model for underwater environments and in Caruso et al. (2008) a mobility model was also proposed, the mobility prediction problem is still worth some further investigation. More efforts are needed from the UWSN research community so that we can present more realistic conditions for better evaluation methods.

Cross layer design helps increase the performance of WSN by optimizing the interaction between different layers and in fact many cross layer techniques have been proposed for the terrestrial sensor networks. However, for UWSN it requires further optimization, especially in the physical layer where the communication channel is often of poor quality. While research carried out so far on underwater communication protocols has followed the traditional layered approach but performance can be improved by adopting the cross layer design. The objective of this approach is to overcome the shortcomings of traditional layered architecture that lacks the information sharing option across different layers by forcing the network to operate in a suboptimal mode. Presented in Pompili and Akyildiz (2010) is the only published work where the authors have explored the cross layer design to make the efficient use of the bandwidth-limited acoustic channel. Motivated by their works, this emergent design trend is worth to be followed up in order to ascertain better underwater wireless communication performance.

Testing is an important issue and most of the evaluations for UWSNs are conducted through simulation due to expensive hardware cost. Until now, very few specialized tools similar to those in Peng et al. (2009) are available to present more accurately the underwater phenomena. The well funded research groups must consider the importance of these tools so as to present the underwater scenarios in a more realistic way. Even when these tools are available, whenever possible it is still necessary to conduct real experiments because of their realistic empirical importance. It is thus deemed necessary to develop inexpensive transceiver or modems for underwater communications in the future (Pompili, 2007).

Moreover, following issues are also suggested for near future research. With poor quality channel and long propagation delays, data link protocols and its related issues like optimization of data packet size and data packet segmentation can play a vital role.

Unfortunately, very little published work like [Stojanovic \(2005\)](#) and [Basagni et al. \(2010\)](#) related to packet size optimization and [Basagni et al. \(2010\)](#) on packet fragmentation is available and more researches are required in order to maximize the channel utilization. Different models like Urick propagation model ([Vuran and Akyildiz, 2008](#)) and Rayleigh fading model ([Haykin, 1994](#)) can be helpful to understand and analyze the acoustic channel characteristics like reflection, diffraction, and scattering of sound. Optimized architecture, possibly of hybrid type, is preferred for efficient data collection, and retrieval of large data volumes from these environments is a research issue still left to be resolved. Integration of routing protocols with other system functions including navigation, localization, data collection, compression, etc. can help improve their efficiency. For example, the protocols proposed in [Peng et al. \(2007\)](#), [Seah and Tan \(2006\)](#), and [Zheng et al. \(2008\)](#) use multiple copies of a data packet to increase the reliability and delivery ratios. These proposed protocols are targeted for resource scarce underwater environment, where some of the mechanism suggested can be very useful to the destination node after receiving a data packet to inform those intermediate nodes that have the remaining copies.

## 7. Conclusion

In this paper, we have presented an overview of state of the art of routing protocols in underwater wireless sensor network. Routing for UWSN is an important issue, which is attracting significant attention from the researchers. The design of any routing protocol depends on the goals and requirements of the application, as well as appropriateness, which depend on the availability of network resources. The development of routing techniques suitable for these environments is therefore regarded as an essential research area, which will make these networks much more reliable and efficient. We have discussed the unique characteristics of UWSN, the protocols proposed for these environments and highlighted the advantages and performance issues of each scheme. Finally, we have compared and classified these techniques according to their attributes and functionalities. In summary, it is not possible to conclude that any particular routing technique is the best for all scenarios as each of them has some definite strengths and weaknesses, and suitability for specific situations. The ultimate objective of this study is to encourage new researchers in the area by providing a foundation on the routing protocols proposed to date. The field of underwater sensor networks is rapidly growing, and still there are many challenges that need to be explored.

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