Hindawi Publishing Corporation
International Journal of Distributed Sensor Networks
Volume 2013, Article ID 701834, 21 pages
http://dx.doi.org/10.1155/2013/701834

Review Article

Greedy Routing in Underwater Acoustic Sensor Networks: A Survey

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Received 14 March 2013; Revised 10 June 2013; Accepted 13 June 2013

Academic Editor: Yanmin Zhu

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Due to the significant advances of wireless sensor networks (WSNs), researchers are eager to use this technology in the subsea applications. Because of rapid absorption of high radio frequency in the water, acoustic waves are used as communication medium, which pose new challenges, including high propagation delay, high path loss, low bandwidth, and high-energy consumption. Because of these challenges and high movement of nodes by water flow, end-to-end routing methods used in most of existing routing protocols in WSNs are not applicable to underwater environments. Therefore, new routing protocols have been developed for underwater acoustic sensor networks (UWASNs) in which most of the routing protocols take advantage of greedy routing. Due to inapplicability of global positioning system (GPS) in underwater environments, finding location information of nodes is too costly. Therefore, based on a need for location information, we divided the existing greedy routing protocols into two distinctive categories, namely, location-based and location-free protocols. In addition, location-free category is divided into two subcategories based on method of collecting essential information for greedy routing, including beacon-based and pressure-based protocols. Furthermore, a number of famous routing protocols belonging to each category are reviewed, and their advantages and disadvantages are discussed. Finally, these protocols are compared with each other based on their features.

1. Introduction

Only less than one third of earth's surface is covered by land, and the rest is covered by water. Due to several reasons such as vast area, high pressure, and harshness of underwater environment, human presence in this area is very limited. Hence, human knowledge about underwater environment is so negligible in comparison with land. In recent decades, since the use of WSNs in different applications has brought tremendous revolution, researchers have been interested recently in using these networks for gathering data from underwater environments [1, 2]. To this end, they have proposed underwater acoustic sensor networks (UWASNs) that are composed of a number of autonomous and self-organizing sensor nodes. These nodes are manually or randomly scattered in different depths in underwater environments to collect specific data from deep or shallow water. Then, they transfer collected data via acoustic waves to the sink(s) located on water surface. In these networks, the ordinary sensor nodes are equipped with acoustic modem to communicate with each other, while sinks are equipped with both acoustic and radio modems in order to receive the data from underwater nodes via acoustic waves and transmit them to the onshore base station by radio waves [3]. UWASNs can be used for a wide range of marine applications, including oceanography, environment monitoring, undersea exploration, disaster prevention, equipment monitoring, military oversight, and navigation [1–4].

The main challenge of employing WSNs in underwater environment is that high radio frequency is rapidly absorbed in water and low radio frequency requires a very large antenna [3]. In addition, the optical waves are not efficient in underwater environments because they may be scattered [3]. Since acoustic waves have a good performance in underwater environments, they are used as a wireless communication medium [3]. Acoustic waves have high propagation delay,

high path loss, low bandwidth, and high-energy consumption in comparison with radio waves [1, 3, 5, 6]. Additionally, other challenges such as high and continual movement of sensor nodes with water flow, inapplicability of global positioning system (GPS) to this environment, and 3D nature of underwater environment increase the complexity [7]. Therefore, the major issue in this networks is that how the sensing data are routed and successfully delivered to the sinks.

A large number of routing protocols have been proposed for finding a path from source node to sink in the terrestrial wireless sensor networks (TWSNs) [8, 9]. However, these protocols are designed based on end-to-end method that are not applicable to high dynamic topology networks with high propagation delay (e.g., UWASNs) [1, 3]. Since UWASN is a very recent issue in this area of study, most researchers focus on physical layer [10, 11], link layer [12–14], and localization [15–19], whereas research on network layer is still in its infancy stage. Consequently, few routing protocols have been developed for UWASNs [1, 3, 20]. Due to the aforementioned challenges, among the different routing methods, greedy hop-by-hop routing is the most promising method in underwater environment [21]. Unlike the end-to-end routing in which a path is found from the source node to the sink in the discovery mode, the greedy routing approaches only find next hop nodes at each hop; these nodes should have positive progress towards the sink.

Although a number of review articles have been presented on the subject of routing in UWASNs, they have not focused on greedy routing techniques and classification of these routing protocols. In [22], a number of routing protocols in UWASNs are reviewed and categorized into four distinctive groups, including flooding based, multipath-based, cluster based, and miscellaneous. Then, this paper describes a number of example protocols for each category. However, it does not address the greedy routing protocols in underwater environment and the features of these protocols. In [20], majority of famous routing protocols in UWASNs are discussed and compared with each other. In addition, various taxonomies are proposed based on different parameters such as network architecture, data forwarding, and protocol operation. However greedy routing in underwater environment is the most promising technique for routing; it does not address the greedy routings, and it does not offer a classification for them in underwater environments. In [23], a number of routing protocols are examined and compared with each other in terms of different quality metrics, including successful packet delivery ratio, the average end-to-end delay, and energy consumption. However, this paper does not have any classification for routing techniques in UWASNs, and it does not focus on greedy routing techniques. In [24], a number of routing protocols proposed for UWASNs are briefly reviewed, and their advantages and disadvantages are highlighted. However, it does not address the greedy routing protocols and their features in underwater environments.

In this paper, we focus on greedy routing protocols in underwater environments and their features. Since finding location information in UWASNs is so costly due to inapplicability of GPS, we divide the greedy routing protocols into two distinctive categories based on requirement of protocols to complete location information of nodes, including location based and location-free. Furthermore, to identify the positive progress toward the sink, based on method of collecting essential information, the location-free category is divided into two subcategories: beacon based and pressure based. Then, we describe and compare a number of famous routing protocols belonging to each category based on their features and their simulation conditions.

The rest of this paper is organized as follows. In Section 2, a number of general information about UWASNs is given, including features of acoustic channel, main differences between TWSNs and UWASNs, and the reasons of inapplicability of TWSN's routing protocols to UWASNs. In Section 3, the features of greedy routing protocols in UWASNs are described, and a number of famous greedy routing protocols belonging to different categories are explained and compared with each other. Finally, the recommendations for future work and conclusion are provided in Section 4.

2. Underwater Acoustic Sensor Networks

2.1. Acoustic Communications. Communication via acoustic waves in underwater environment poses a number of main challenges, including Doppler spread, high propagation delay, multipath, noise, and high path loss. Due to these features of acoustic waves, not only the acoustic bandwidth is severely decreased in comparison with radio, but also it varies based on communication range and acoustic frequency [25]. Since the low-frequency acoustic waves should be used in long ranges to avoid the absorption in water, the bandwidth is reduced significantly which causes a remarkable increase in likelihood of error. In contrast, high-frequency waves are used in short ranges to increase the bandwidth and decrease the likelihood of error. The relation between different bandwidth and communication ranges is shown in the Table 1.

According to the direction of sound waves, the acoustic links are categorized into two categories, namely, vertical and horizontal, in which their propagation characteristics differ from each other, especially in terms of scattering, multipath spreads, and delay variance [3]. The main factors affecting the acoustic channel are described as follows.

(i) Path Loss. Attenuation and geometric spreading are the main reasons for path loss in underwater environments. The main reason for attenuation in underwater is the absorption of acoustic waves in water due to changing sound energy to thermal energy [26]. It is severely dependent on distance and frequency [27]. For instance, the amount of absorption at 12.5 KHz is less than 1 dB/Km, while it is more than 20 dB/Km at 70 KHz [2]. The amount of path loss based on distance l and frequency f is given [27]:

$$A(l, f) = A_0 l^k a(f), \tag{1}$$

where l indicates distance, f shows signal frequency, A_0 signifies a constant for a normalization, k denotes the spreading factor ($k = 2$ for spherical spreading, $k = 1$ for cylindrical spreading, and $k = 1.5$ for practical spreading),

Table 1: The available bandwidth for different ranges in underwater acoustic channel [3].

	Range (KM)	Bandwidth (KHz)
Very long	1000	<1
Long	10–100	2–5
Medium	1–10	≈10
Short	0.1–1	20–50
Very short	<0.1	>100

and $a(f)$ stands for the absorption coefficient. The empirical absorption coefficient in the Thorp's formula also is expressed as follows [27]:

$$10\log a(f) = 0.11\,\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 2.75 * 10^{-4} f^2 + 0.003, \quad (2)$$

where f is based on KHz and $a(f)$ is based on dB/Km. Equation (3) is used for frequencies above several hundred Hz. While at the lower frequencies, it can be simplified in (3) as follows [27]:

$$10\log a(f) = 0.11\frac{f^2}{1+f^2} + 0.011 f^2 + 0.002. \quad (3)$$

Furthermore, geometric spreading is a second reason for path loss. Two types of sound energy spreading exist in water, namely, spherical and cylindrical [1]. Spherical spreading is used in deep waters, while the cylindrical spreading are applied in shallow waters [3, 26].

(ii) Noise. Two types of noises directly affect the acoustic waves, including man-made noise and ambient noise. Man-made noise is usually generated by human activities in water such as shipping noise, while ambient noise is generated by natural events such as fishes, dolphins, tides, rain, and wind [1, 3, 26].

(iii) Multipath. Since multipath propagation generates Inter Symbol Interference (ISI), it may be responsible for intensive degradation of the acoustic communication signal [1]. In addition, the multipath geometry affects the link configuration. In spite of the fact that vertical channel has little time scattering, horizontal channel may have much longer multipath spreads. The depth and the distance between sender and receiver nodes play a key role in the extend of the spreading [1].

(iv) High and Variable Delay. Generally, the speed of acoustic in underwater is about 1500 m/s with a delay of about 0.67 s/km. As a result, it encounters a large propagation delay which causes a remarkable decline in the system throughput [1, 3]. A number of parameters such as temperature, salinity of water, and pressure (depth) have an influence on the velocity of sound in underwater environments. According to these parameters, the sound velocity varies between 1450 m/s to 1550 m/s. This problem should be taken into account in designing an efficient protocol. That is because an accurate estimation of round trip time (RTT) is more difficult in this situation. Whereas, this information is necessary for communication protocols [1, 3]. If the value of temperature, salinity, and pressure (depth) are obtained, the velocity can be then calculated via following empirical equation [28]:

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.010T)(S - 35) + 0.016z, \quad (4)$$

where T signifies the temperature in centigrade (°C), S shows salinity of water in parts per thousand (‰), z is depth in meters, and c denotes the velocity of sound in meter per second. This formula is valid just for $0 \le T \le 35$°C, $0 \le S \le 45$‰, and $0 \le z \le 1000$ m [28]. In this equation, if the temperature, salinity, and depth increase, the velocity of sound will increase too [28].

(v) Doppler Spread. Another factor that can affect the underwater acoustic channel is Doppler spread which causes remarkable decrease in performance of network communication in high data rate transmissions and receiving [1, 3].

2.2. Difference between TWSNs and UWASNs. As mentioned earlier, UWASN is very different from TWSN in terms of various aspects such as environmental conditions and communication medium which causes special characteristics and challenges. A number of main differences between UWASNs and TWSNs are shown in Table 2.

2.3. Problem of TWSN's Routings in Underwater Environments. Since the ordinary nodes in TWSNs are stationary or have a little movement, end-to-end routing method is applied in this network. In this method, a path is found from the source node to destination node and saved in route table. Then, routing procedure is performed based on this path in hop-by-hop method. Due to high movements of nodes in underwater environment, end-to-end methods are not efficient. In general, routing protocols in TWSN can be divided into three classes: proactive, reactive, and geographical [1, 3], which are explained as follows.

(i) Proactive Routing. In proactive routing protocols, a path from each node to other nodes is initially discovered and stored in the route table. Then, the data packets are sent based on the existing paths in the table [9]. Although this method has a good performance in environments with static topology, it has not an appropriate performance in environments such as UWASNs with high dynamic topology. This is because the discovered paths can be expired quickly which causes significant increase in network overhead. In other words, due to high movement of nodes by water current, the path finding phase should be performed at short intervals of time which causes remarkable decreases in the network performance [1, 3]. Highly dynamic destination-sequenced distance-vector routing (DSDV) [29] is a famous proactive routing protocol.

(ii) Reactive Routing. Each protocol that belongs to this class has a route discovery algorithm that is known as source node

Table 2: Differences between TWSNs and UWASNs.

Feature	TWSNs	UWASNs
Architecture	Most of the time 2D	Most of the time 3D
Topology	The topology is static or low dynamic	Topology is high dynamic due to continual movement of nodes by water current
Communication media	Radio waves [1, 2]	Acoustic waves for underwater environment and radio waves for water surface [1, 3]
Deployment	Dense deployment due to cheap node price and small area which affects the network performance [2, 3]	Sparse deployment due to expensive underwater equipments and vast area [2, 3]
Position information	Available by GPS	Unavailable by GPS, because GPS uses high frequency waves which are rapidly absorbed in water [5]
Network components	Terrestrial ordinary nodes, sinks, actors, and base station	Underwater ordinary nodes, sinks, AUV or ROV, and onshore base station
Frequency	High frequency (MHz, GHz)	Low frequency (Hz, KHz) because high frequency is quickly absorbed in water [3]
Bandwidth	Not only it uses high bandwidth and high data rate, but also bandwidth is fixed in different distances	Bandwidth and data rate are low and they are dependent on distance; short distances have higher bandwidth [6]
Range	Usually used in small areas	Usually used in vast areas
Speed of medium	The speed of radio frequency in the air is $3 * 10^8$ m/s [2, 28]	Acoustic velocity in water is about 1500 m/s [2, 28]
Node movement	Almost fixed	Nodes move 1–3 m/s by water current [20]
Price	Cheap	Too expensive, for example, an ordinary sensor costs more than 100 USD [2, 48]
Propagation delay	Propagation delay is too low due to employing high speed radio waves as a communication medium	Propagation delay is high due to employing low speed acoustic waves as a communication medium.
Path loss	Low path loss	High path loss
Energy consumption	Energy consumption for sending and receiving is low and equal	Energy consumption for sending and receiving is too high and energy for sending is bigger than receiving [49]
Wave movement	Disk shape	Spherical in deep water but cylindrical in shallow water.
Simulator	Many simulators available such as NS2 [50], OMNeT++ [51], and OPNET [52].	There is not any standard simulator for UWASNs
Sinks position	Everywhere of network and it is always fixed	Located on water surface and it usually moves by water current
Routing	Since the nodes are almost stationary, the end-to-end routing is employed	Due to high movement of nodes in water current, greedy hop-by-hop routing is employed [5]
Prone to error	Links and nodes are low prone to error	Links and nodes are highly prone to error due to high propagation delay of acoustic waves and corrosion, respectively, [3]
Sensors size	Small size	Large size [48]
Hull	Usually made up of plastic	Usually made up of materials such as composite, aluminum, and titanium [48]
Energy scavenging	Usually by solar energy	Usually by kinetic energy

when it needs to transmit data from itself to the destination node. In other words, the source node in a demand method enables the route discovery algorithm. The founded path is stored in a route table for a specific time to prevent a repeat of this algorithm in this period [9]. Since this class of routing protocols floods a control packet in order to discover the path from the source node to the destination node and this path is expired in a short period of time due to high movement of nodes, it does not work efficiently in the networks with high propagation delay and high dynamic topology such as UWASNs [1, 3]. Ad hoc on-demand distance vector (AODV) [30] is a famous routing protocol in this class.

(iii) Geographical Routing. In the geographical category, it is assumed that each node knows its destination position, and routing procedure is done based on these position information. Since the next hop nodes are easily selected based on position information of source and destination

nodes, geographic routing class is a promising method for underwater environments. The main challenge for applying this class of routing in the UWASNs is that GPS cannot be used in UWASNs due to rapid absorption of high frequency in water. As a result, finding the information about nodes position in underwater environments becomes very expensive [1, 3]. Geographical and energy aware routing (GEAR) [31] is a famous routing protocol in this class.

3. Routing in UWASNs

Routing is one of the fundamental issues in any network. The majority of studies conducted on UWASNs are focused on the physical and MAC layers. However, researchers have less attention to upper layers such as the network layer, and research in this layer is still in its infancy [20]. Since the main task of the network layer is routing, designing efficient and practical routing protocols for underwater environment that consider the underwater challenges are essential. In Figure 1, the architecture of the network layer of the OSI reference model is demonstrated.

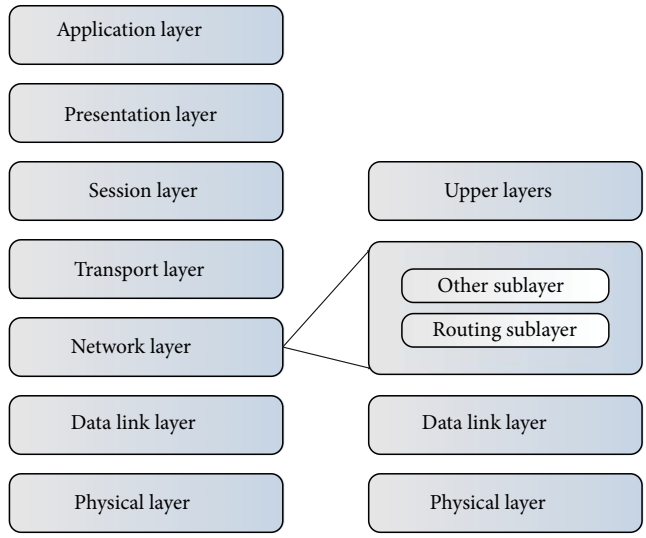

Figure 1: Network layer architecture in the OSI reference model.

According to the requirements of different applications in underwater environment, researchers have proposed various routing protocols to improve the various performance metrics in the network layer [20]. As previously mentioned, due to characteristics of acoustic channel and underwater environments, end-to-end routing approaches used in TWSNs are not applicable in the UWASNs. According to the literature, due to high movement of nodes with water currents, greedy hop-by-hop routing is the most promising routing method. This technique relies on an extremely simple forwarding strategy at every hop to transmit a data packet to a local optimal forwarder node with a positive progress towards the sink node. The greedy forwarding approaches do not always work properly. For instance, when data packets reach a node which has no neighbor with positive progress toward the sink, the greedy routing is faced with problem which is known as communication void or local maximum [32].

In the greedy hop-by-hop routing approaches, communication void is one of crucial problems which routing approaches should be able to handle. The method of handling the communication void is a technical challenge for any greedy routing protocol [32]. In general, greedy routing protocols are composed of two modes, namely, greedy mode and void handling mode [32–34]. If each node has at least one neighboring nodes with positive progress towards the sink, it works in the greedy mode; otherwise, it faces communication void and changes the mode to void handling mode.

In order to forward the data packets in the greedy mode, each forwarder node sends the data packet to a set of neighbor nodes with positive progress toward the sink. As a result, finding a set of neighbor nodes with positive progress toward the sink is a crucial problem with the greedy mode. In case of UWASNs, there are various methods introduced in the literature. Since the sinks in UWASNs are deployed in the water surface and ordinary nodes are scattered in the different depths of the underwater environment, neighbor node with positive progress toward the sink are located in the top of the forwarder node. In other words, the neighbor nodes with positive progress have less depth than the current forwarder node. According to this information, greedy routing can be employed easily in UWASNs.

Since finding location information in UWASNs is so expensive due to inapplicability of GPS to this area, we divided routing protocols into two categories: location based and location free. Moreover, the location-free category that is based on techniques used for collecting information to identify the positive progress area is divided into two subcategories, namely, beacon based and pressure based. The taxonomy of greedy routing protocols in UWASNs and a number of existing famous underwater routing protocols belonging to each category are presented in Figure 2. Here, a deep description for each category and subcategory of greedy routing protocols is provided, and a number of existing famous routing protocols proposed for them are explained.

3.1. Location-Based (Geographical) Routing. In the location-based category, it is assumed that each node knows geographical information about itself and sinks to geographically identify the positive progress area toward the sinks. Although all of the location-based routing protocols employ location information for greedy routing, they have main differences in the method of finding neighboring nodes with positive progress toward the sinks. To tackle with finding a positive progress area toward the sink, most of these protocols take into account a specific shape between forwarder node and sink node such as a virtual pipeline [7, 34, 35], cone [36], zone [37], and layer [38]. Only neighboring nodes located in these shapes can participate in the packet forwarding process. As a result, the size of this shape has a direct impact on the routing performance. If its size is too big, the number of nodes that can participate in the routing process will be increased which causes a remarkable increase in the network overhead and energy consumption; otherwise, the probability

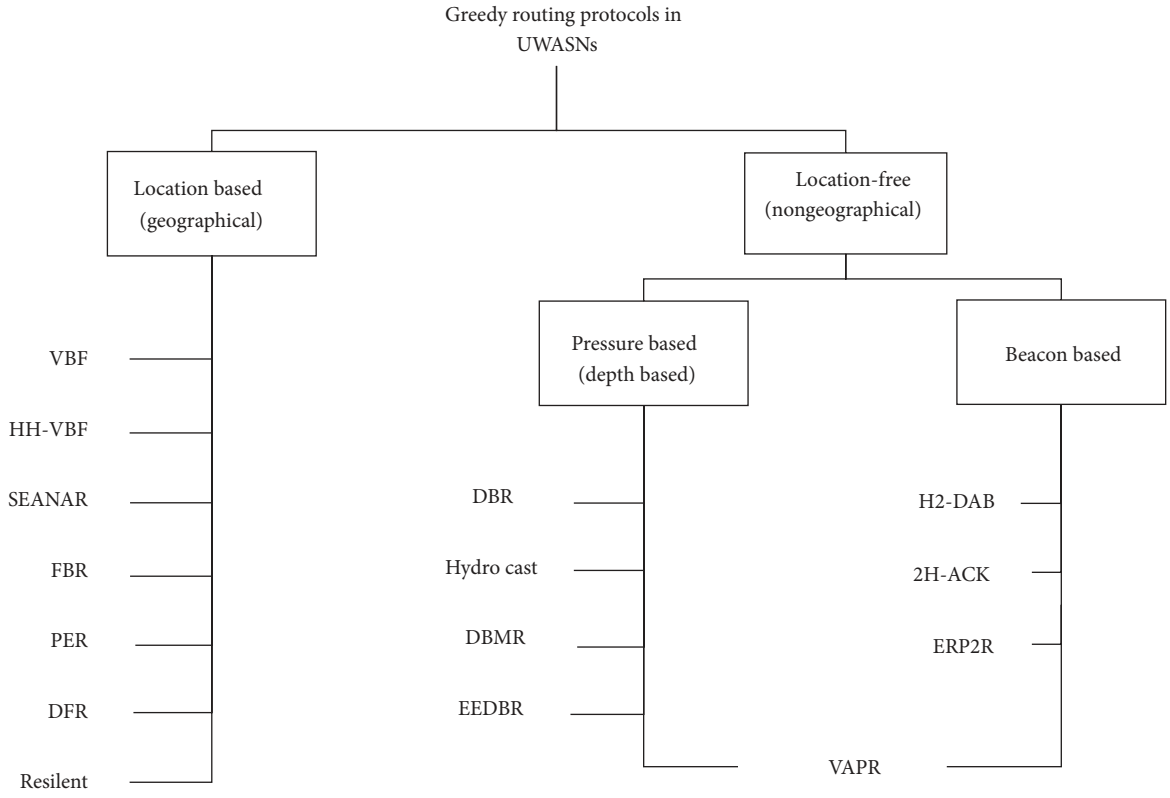

Figure 2: Taxonomy of greedy routing protocols in UWASNs.

of finding neighbor node in this area will decrease, which causes a significant increase in the probability of facing the communication void.

Regardless of the mentioned challenges in the location-based category, finding the location information of nodes is the main challenge. That is because nodes move freely in underwater environment by water current, and GPS is inapplicable to underwater environment due to rapid absorption of high frequency in water [1, 20]. Consequently, finding a location information of nodes is too expensive due to using underwater localization protocols which are generally composed of three steps: range measurement, location estimation, and calibration [39]. A number of existing location-based routing protocols in UWASNs are described as follows.

3.1.1. Vector Based Forwarding Protocol (VBF). VBF [7] is proposed as a solution to two important problems in underwater environment, namely, the continual movement of ordinary nodes by water current and energy efficiency. VBF is a greedy and location-based routing protocol in which each node knows its own location and sink location. In order to identify the positive progress area toward the sink, it takes into account an assumptive routing vector between source and destination node and considers a predefined radius as a threshold. Only those nodes can participate in forwarding process that their distance to the imaginative vector is less than predefined radius. In other words, only the nodes in a virtual pipeline with a predefined radius from source node to the sink node can take part in the greedy routing. This virtual pipeline is clearly shown in Figure 3 for nodes A, B, and C. In VBF, each source node creates its own pipeline toward the sink and embeds its own location, sink location, and its location as a forwarder node in the packet and broadcasts this packet. Each ordinary node that receives the data packet calculates its distance to this vector. If the computed distance is less than the predefined radius, that means it is inside pipeline and it is eligible to forward the data packet. Therefore, it accepts and updates the data packet's forwarder node information and broadcasts the packet; otherwise, it simply discards this data packet. In order to improve the network traffic and energy consumption in dense deployments, a desirable factor and a time interval delay are calculated by each eligible node to locally identify the density and decrease the number of forwarder nodes.

VBF has some advantages; since few numbers of nodes are eligible to participate in the routing process, the network traffic and energy consumption decrease significantly. Furthermore, it handles high dynamic topology problem in UWASNs. However, VBF has a number of drawbacks; for instance, it supposes that localization information is available while finding a location of nodes is too costly due to inapplicability of GPS in underwater environment. In addition, the performance of this protocol is directly dependent on the radius of virtual pipeline, and the radius of pipeline plays the main role in the VBF. Moreover, although

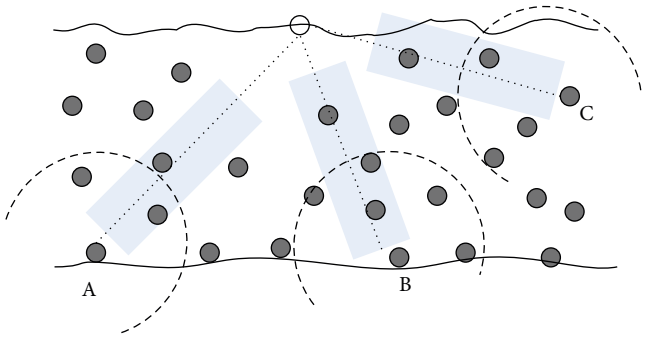

Figure 3: VBF routing protocol which uses single pipeline for each node [35].

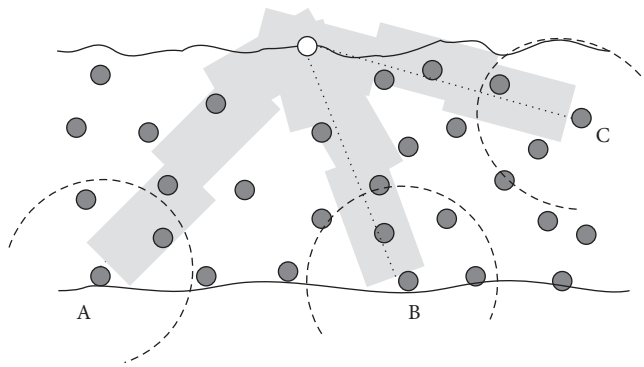

Figure 4: How virtual pipelines are created by HH-VBF [35].

the probability of happening communication void especially in sparse deployment is too high, VBF does not take into account this problem.

3.1.2. Hop-by-Hop Vector-Based Forwarding (HH-VBF). HH-VBF [35] is a greedy and location-based routing protocol. Indeed, it is an enhanced version of VBF proposed to improve the probability of happening communication void in sparse environments in order to increase the successful data delivery. In addition, it needs smaller radius than VBF for finding eligible forwarder nodes while causing an improvement in the packet delivery ratio. However in VBF, only one virtual pipeline is considered from source to sink node for finding eligible forwarder nodes, in HH-VBF each forwarder node takes into account its own pipeline toward the sink, which increases the likelihood of finding eligible forwarder nodes. As a result, the performance of HH-VBF is better than VBF especially in sparse deployments. Figure 4 obviously shows how virtual pipelines are created in each forwarder node of HH-VBF. In this figure, source nodes including A, B, and C send different data packets, and each forwarder node creates its own individual pipeline to send data packet toward the sink node.

The main advantages and disadvantages of HH-VBF are similar to VBF. It can handle high mobility of nodes in underwater environment with reasonable energy consumption, and its data delivery is improved more in comparison with VBF. Although, a remarkable decrease in the likelihood of communication void is shown in HH-VBF, it still cannot handle the communication void. The performance of HH-VBF depends on the radius of virtual pipelines; however, its dependence is significantly reduced compared to VBF. Due to dynamic topology and inapplicability of GPS, using location information of nodes is the main drawback of HH-VBF.

3.1.3. An Energy-Efficient and Topology-Aware Routing (SEANAR). In [38], an energy-efficient and topology-aware routing protocol, named SEANAR, is proposed for the UWASNs. This is a greedy and location-based routing protocol in which each node has its complete location information. The main purpose of SEANAR is to obtain a high delivery ratio with low energy consumption while handling the mobility of nodes. Therefore, each forwarder node should select the best next hop node. To this end, a special topology is proposed by SEANAR in which ordinary nodes are randomly scattered in the interested volume which can move freely in the horizontal direction by water current, and only one stationary sink is deployed in the center of water surface. The volume is divided into several spherical layers with the same thickness and density which is clearly shown in Figure 5. According to these layers, each node has three types of neighbors including neighbors in the inner, neighbors in the aside layer, and neighbors in the outer layer. The inner neighbors are closer to sink, while outer neighbors are farther to sink, and aside neighbors have almost the same distance to sink.

SEANAR is composed of two phases: neighbors information maintenance phase and data sending phase. In the first phase, each node periodically broadcasts a location message including its node ID, location, and residual energy. If the receiver node is located in the inner or aside layer, it updates its inner neighbor table or its aside neighbor table; otherwise, it simply discards the message. Consequently, the degree of each node is computed by counting the number of nodes in the inner and aside tables. In the second phase, each sender node sends a hello message including the node ID, packet sequence number, and layer information. Upon receiving the message, each node looks at the layer information. If the sender node is located in the inner layer, it simply discards it; otherwise, it replies an acknowledgment message including its node ID, distance to sink, inner degree, aside degree, and residual energy. When all acknowledgment messages are received by the sender node, it calculates their weight and selects the largest weight node as the forwarder node then sends data packet to this node. One of the significant advantages of this protocol is the fact that since the degree of nodes is used to select the next hop node, not only it has appropriate performance in sparse networks, but also it reduces the likelihood of communication void. Furthermore, it can handle dynamic topology in UWASNs. However, one of its important weaknesses is that it uses fully location information of nodes in routing, which can be so costly. In addition, it does not benefit from the advantages of multisink architecture which causes rapid drain in battery of those nodes located closer to the single sink. Since weights of neighbor nodes are calculated in each hop of data sending phase by sending and receiving messages to neighboring nodes,

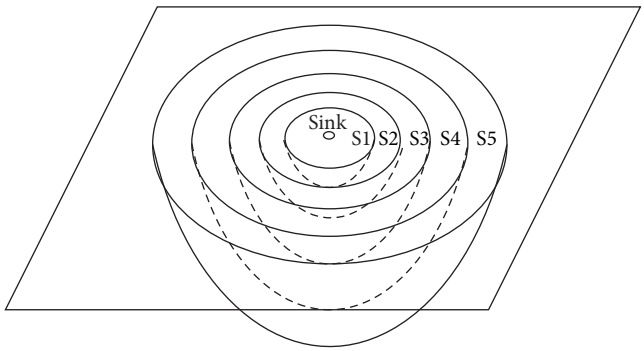

Figure 5: Division of volume into different layers in the SEANAR [38].

the end-to-end delay and energy consumption increase, especially in dense deployments. Moreover, the period of time when the first phase should be repeated has a direct impact on the protocol performance.

3.1.4. FBR: Focused Beam Routing Protocol. In [36], a greedy and location-based routing protocol, namely, beam routing protocol (FBR) is proposed for UWASNs. In this protocol, it is assumed that each node knows its own position and that of sink. Since each power level has different radius and lower power level has a smaller radius and less energy consumption, the basic idea of this protocol is the use of different power level to reduce the energy consumption per bit. As the FBR uses the power level in the routing procedure, it is considered as a cross-layer routing protocol. FBR applies 3D architecture in which four stationary sinks are deployed at the corner of interested area and ordinary node randomly scattered in the area. It uses a finite number of power levels, including $P_1, P_2, \ldots, P_n$, where P_1 signifies the lowest power level and P_n stands for the highest power level. In order to send a data packet, each node creates a cone with angle θ toward the closer sink node and sends a request to send (RTS) message with power level P_1. If the receiver node is located in the cone which is emanating from the sender node toward the sink, it replies a clear-to-send (CTS) message including its name and location; otherwise, it simply discards the RTS message. The sender node waits for specific time to receive the CTS messages. If it receives a number of CTS messages, it selects the closer one of them to the sink as the next hop node and sends data packet to the node. The next hop node acts similar to the last sender node, and data packet finally reaches the sink. Otherwise, it increases its own power level and sends a new RTS message. This procedure is repeated until a neighboring node in the cone is found or the power level increases to P_n. If there is no neighboring node in the cone with a power level P_n, the cone can be rotated to the left side or right side, and the same procedure is repeated. Figure 6(a) clearly shows how node A creates its own cone and finds the next hop node to route the data packet toward the sink B, and Figure 6(b) obviously illustrates the region of forwarder node selection in order to send data packet from node A toward the sink B in the greedy hop-by-hop method.

The FBR has some important advantages; first, it can handle the high dynamic topology in the underwater environment. Second, it has appropriate energy consumption in the dense deployments. Third, the overhead of the network is decreased due to the limited area involved in the routing process. On the contrary, it has some serious drawbacks; it supposes that each node knows its location and that of the sinks, while GPS cannot work properly in underwater environments, and using other localization techniques is expensive. The performance of FBR is very sensitive to angle θ. In other words, the angle θ should be large enough in sparse deployments to decrease the likelihood of failure while the angle θ should be small in dense deployments in order to reduce the network overhead and energy consumption. In order to detect and handle the communication void in the FBR, each node should transmit the RTS message in all of its power level one by one, which causes high energy consumption.

3.1.5. Power-Efficient Routing Protocol (PER). In [40], a power-efficient routing protocol is proposed, called PER. It is a greedy and location-based routing protocol in which each node knows its position. In the architecture of UWASN, ordinary nodes are randomly distributed in the interested volume which can move in arbitrary directions, and the source node is deployed at the bottom of the water. In addition, a stationary sink is located in the center of the interested volume on the water surface. The transmission and receiving energy consumption by acoustic modems in UWASNs is a crucial issue since it is much higher than radio modems in the TWSNs. The main goal of this protocol is to reduce the communication energy consumption. The architecture of PER is shown in Figure 7(a). As it can be clearly seen, it is composed of two main modules, namely, forwarder node selector and forwarding tree trimming mechanism. In the first module, each forwarder node selects two appropriate next hop nodes among its neighbor nodes by employing fuzzy logic technique. Figure 7(b) illustrates the procedure of this module in detail. In this module, the fuzzifier is fed by three parameters, including distance, residual energy, and angle between two neighboring nodes in order to generate linguistic values. For example, distance values can be converted to short, medium, and long values. In the next step, the inference engine determines the linguistic value of each node according to fuzzy rules and linguistic values. Then, these linguistic values are given to defuzzifier in order to generate nonlinguistic values. Finally, forwarder node selects two best next hop nodes based on the result of defuzzifier and sends data packets to them. To prevent exponential growth of forwarding tree, the module of forwarding tree trimming mechanism is suggested to reduce the power consumption. In this module, a limitation is applied based on the number of receiving duplicate packets in each node. If the number of duplicate packets is bigger than a predefined threshold, the forwarding tree trimming mechanism is employed; otherwise, data packet is sent to the two selected next hop nodes.

The remarkable advantage of PER is that due to the selection of the two next hop node in each forwarding

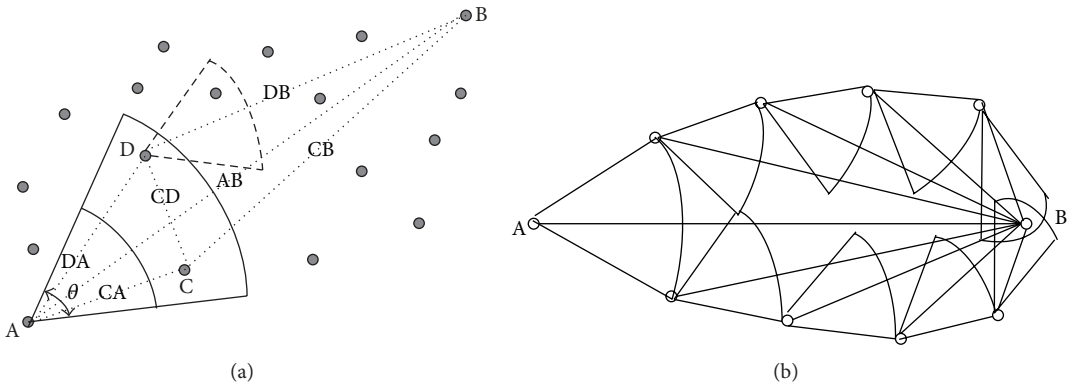

Figure 6: (a) Procedure of finding next hop node in the FBR [36], (b) The region of forwarder node selection in the FBR [36].

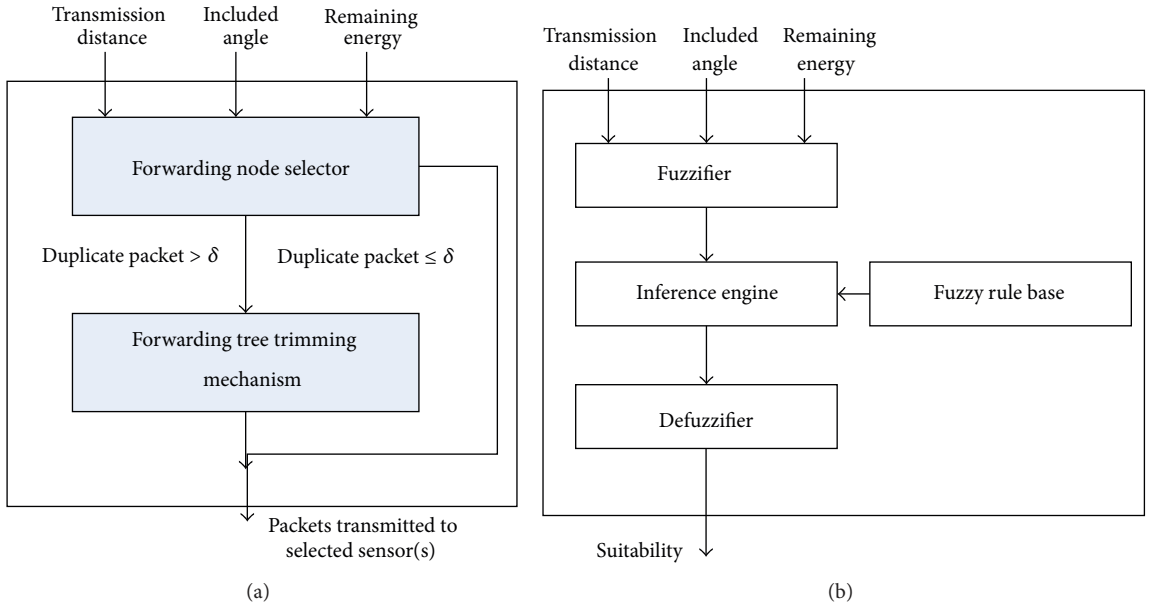

Figure 7: (a) The PER architecture [40] and (b) The fuzzy logic system in forwarding node selector module [40].

process, it has better performance in dense deployment in comparison with protocols such as VBF that floods the packet in a specific area. The forwarding tree trimming mechanism decreases the number of duplicate packets, which results in less overhead and less energy consumption. However, PER has some drawbacks; for instance, it needs geographical information, which is very expensive in underwater environments. Additionally, it employs a single sink architecture, which causes rapid drain in the battery of the nodes that are closer to sink. Although communication void is a critical problem in the greedy routing, this problem is not taken into account in PER.

3.1.6. DFR: An Efficient Directional Flooding-Based Routing Protocol. In [41], an efficient directional flooding-based routing protocol in UWASNs is proposed which is called DFR. The main goal of this protocol is to achieve higher reliability and improve data packet delivery. The DFR is a greedy and geographical routing protocol in which each node knows the location of itself and its neighboring nodes. In the DFR architecture, a number of ordinary nodes are installed in the bottom of water. In addition, a source node and an underwater sink are installed in the left end and right end of the interested area, respectively. The source node transmits the sensing data to underwater sink in hop-by-hop method, and the sink delivers this data to surface buoy.

The DFR is a flooding-based protocol in which data is transmitted to the neighboring nodes with positive progress toward the underwater sink. In order to control the flood, it employs location information and link quality of the neighboring nodes to determine the flooding zone at each hop. To this end, DFR takes into account two angles including current angle and reference angle. As Figure 8 clearly shows, the angle between FS and FD lines are called current angle in which F, S, and D are forwarder node, source node, and destination node, respectively. The reference angle is also

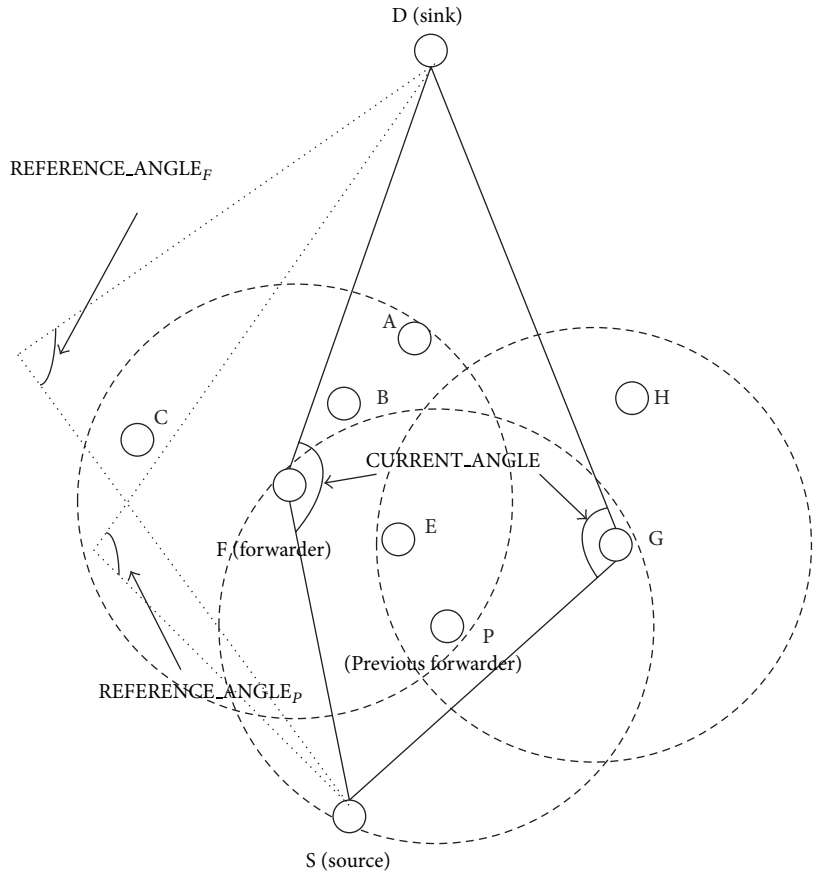

Figure 8: Packet forwarding in DFR Protocol [41].

specified by previous forwarder node based on link quality. In data forwarding process, the reference angle of the source node is initially adjusted with the minimum value. Then, the source node broadcasts its position and this reference angle to its neighboring nodes. When a neighboring node receives the packet, it compares its own current angle with the reference angle in the packet. If its current angle is less than or equal to the reference angle, in other words, the node is not located in the flood zone, it simply discards this packet; otherwise, this node participates in the packet forwarding process. To this end, each forwarder node adjusts the value of the reference angle in the packet according to the link quality and rebroadcasts the packet for its neighbor nodes and so on. It is notable that if the link quality is good, the smaller reference angle is considered to create slim-shaped zone, which results in fewer nodes participating in the packet forwarding. Otherwise, if the link quality is poor, it takes into account a larger reference angle to create a fat-shape zone, which causes more nodes to participate in the forwarding process. Furthermore, if its link quality is average, the saw-teeth shape is created.

Since DFR is a greedy routing, it may face the void problem. Two types of void problem are addressed in DFR; first, a new flooding zone is established without forwarder node. To deal with this problem, the authors take into account a flood zone that should be big enough to cover at least one relay node. Second, if there is no closer node to sink compared to the current node, an algorithm is enabled to discover a detour path to the sink.

The DFR has important benefits; due to employing the controlled flooding zone based on link quality, not only it has been improved in successful data packet delivery, but also the network reliability shows a good growth. Furthermore, it handles the two types of the communication void problem. The main disadvantages of DFR are that it needs nodes location information, while achieving to this information is a major problem in underwater networks due to inapplicability of GPS. Since the next hop nodes are selected from the flood zone and link quality has a direct impact on the size of the zone, the protocol performance is tied directly to link quality.

3.2. Location-Free (Nongeographical) Routing. Unlike the location-based category, location-free routing protocols do not employ the fully geographical information for greedy routing. In this category, other information such as depth of nodes and dynamic address of nodes are used for identifying the positive progress area toward the sink. Based on data

collection methods, this category can be divided into two subcategories: beacon based and pressure based. Beacon-based subcategory employs beacon messages to assign special information such as dynamic address to each node in order to identify the positive progress toward the sink, while in pressure-based subcategory only the depth information measured locally by pressure sensor can be used for identifying the positive progress area. A deep description of these subcategories is provided in the following subsections.

3.2.1. Beacon-Based Routing. In the beacon-based subcategory, the positive progress area toward the sink is identified based on special information about the network such as address which is obtained by sending periodical beacon messages from the surface of water to the bottom. The various information is employed in different protocols to identify the positive progress toward the sink. For example, in [21, 42], dynamic address is used to identify the neighboring nodes with positive progress toward the sink, while the distance to sink is employed in [43]. These protocols usually composed of two phases, namely, information acquisition phase and data forwarding phase. In the first one, the surface buoys periodically send beacon message to the bottom of water. The beacon message is received by each neighbor node of surface buoy, and it updates its information and beacon message. Then, the node broadcasts the updated message to its neighbor nodes and so on. Finally, all nodes earn the desired information. In the second phase, the information obtained in the previous phase can be used for identifying the neighbor nodes with positive progress toward the sink and employing greedy routing method in UWASNs. It should be noted that due to high mobility of nodes by water current in underwater environments, the information acquisition phase should be done in short intervals, which causes a significant increase in the network overhead. As a result, obtaining desired information for greedy routing can be too expensive in high dynamic topology networks such as UWASNs. A number of protocols belonging to this category are described as follows.

Hop-by-Hop Dynamic Addressing-Based Routing (H^2-DAB). In [21], hop-by-hop dynamic address-based routing protocol is proposed for UWASNs, which is called H^2-DAB. It is the first greedy and address-based routing protocol in underwater environments. Since the most of greedy routing protocols in UWASNs employ the location information or additional hardware, the main goal of H^2-DAB is to design a greedy routing protocol, which does not need any additional hardware and location information. In the architecture of the protocol, several stationary sinks are located on water surface, while source nodes anchored at the bottom of the ocean. The ocean depth is divided into different levels, and ordinary nodes are equipped with buoyancy control and deployed in different depth levels between bottom and surface water. These nodes can move freely in the horizontal direction while their movement in the vertical direction is very little.

H^2-DAB is composed of two phases, namely, assigning dynamic address to mobile nodes and data delivery. In the first phase, a dynamic hop ID is allocated to all floating nodes whose initial hop ID is equal to 99. To this end, sinks start to send hello packet toward the bottom of water. Each node that receives the hello packet should update its hop ID according to the number of hops to the sink. The result of this process is that the closer sensors to sinks have smaller hop ID. This process is clearly demonstrated in Figure 9, in which each node can save the hop distance to two sinks. For instance, the hop ID of node N13 is equal to 34 that indicates its hop distance from one sink is equal to 3 while its distance to another sink is equal to 4. In the second phase, the data is delivered to the sinks. To this end, each forwarder node sends an inquiry request message to its neighboring nodes. Nodes located within the communication range receive the message and send an inquiry reply message including their node ID and their hop ID. Since the nodes with smaller hop ID are closer to the sinks, the forwarder node selects a node with smallest hop ID as a next hop node. It is notable that hop ID should be updated after an interval of time due to movement of nodes.

This protocol has a number of advantages; not only it handles the node movement by water flow, but also it employs the multisink structure, which reduces the congestion at closer nodes to sink. Furthermore, it works without geographical information of nodes, extra hardware, and complex routing tables. The H^2-DAB has some drawbacks as follows. Since the mobile nodes should be deployed in special depth levels, deployment process is more difficult than random deployment. Although communication void is a critical problem in greedy routing, this protocol does not consider this problem. Due to the high mobility of nodes in underwater environments, the first phase should be done in a short interval of time, which decreases the network performance. This protocol employs a single forwarder node strategy at each hop without any consideration to the link quality of the nodes, which results in an increase in the number of packet loss and low reliability.

A Reliable Address-Based Routing Protocol (2H-ACK). In [42], a greedy and reliable address-based routing protocol is proposed to guarantee the successful data delivery in UWASNs. This protocol is called two-hop acknowledgment reliability model (2H-ACK). Indeed, this protocol is an enhanced version of H^2-DAB, which improves the network reliability. Similar to H^2-DAB, its architecture is composed of several sinks on water surface and a number of ordinary nodes; source nodes are stationary and anchored at the bottom of water, while mobile nodes are deployed in different depth levels of water and can move in the horizontal direction. 2H-ACK is composed of two phases, namely, assigning dynamic address to mobile nodes and data packet forwarding. Similar to H^2-DAB, in the first phase, an address is assigned to mobile nodes based on their hop distance to the sink; nodes that are closer to the sink obtain a smaller address. In the second phase, a 6-step data forwarding strategy is employed in this paper, in which two copies of data packets are stored in the network in order to achieve high reliability. These steps are shown in Figure 10. In the first step, the sender node sends

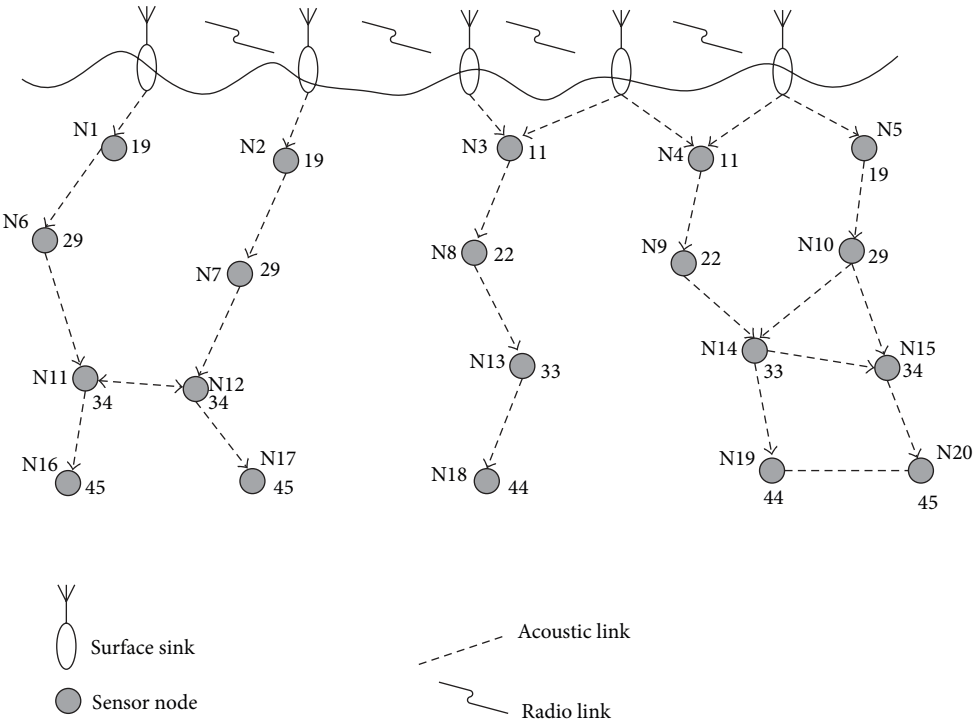

Figure 9: Hop ID assigning process [21].

an inquiry request in its own communication range as shown in Figure 10(a). Only the neighboring nodes with smaller hop ID in comparison with the sender node transmit an inquiry reply message to sender node. This process is illustrated in the Figure 10(b). After receiving inquiry replies, the sender node selects a forwarder node and sends a data packet to this node. In step (d), before sending an acknowledgment message to sender node, the forwarder node sends an inquiry request to its neighboring nodes to find its own next hop node. In step (e), the forwarder node waits to receive the inquiry replay from its neighbors that are closer to the sink. In the last step, it selects its own next hop node and sends a data packet to the node. In addition, an acknowledgment packet is sent to the sender node. This process is demonstrated in Figure 10(f).

This protocol has some advantages; due to using the dynamic address for greedy routing, it does not use location information, extra hardware, and complex routing tables. It can handle the node movement by water current and employ a multisink structure to alleviate the traffic in the nodes located closer to the sinks. Since two copies of each data packet are stored in the network, the amount of packet loss and duplicate packet are decreased significantly. The 2H-ACK has some weaknesses; first, it uses a special deployment that nodes should be placed in the specified depth levels. Second, it does not consider the void problem, while the likelihood of facing communication void is so high in the greedy routing approach. Third, the first phase should be done in short interval of times to tackle with the high mobility of nodes, which causes high overhead.

An Energy-Efficient Routing Using Physical Distance and Residual Energy (ERP^{2}R). In [43], a distance-aware and energy-aware routing protocol, called ERP^{2}R is proposed for UWASNs. It is a greedy and beacon-based routing protocol. The ERP^{2}R employs a 3D architecture in which the multiple sinks are located on water surface and ordinary nodes are scattered randomly in different depths under water. It is composed of two phases: cost establishment and data forwarding. The main goal of the first phase is assigning a cost to each node based on their physical distance to sink. For this purpose, the sinks broadcast a hello packet including sender ID, residual energy, and cost (physical distance to sink) to their neighboring nodes. When a node receives the message, it calculates its distance to sink using time of arrival (ToA). Then, it updates the residual energy and physical distance to sink in hello packet and rebroadcasts it to its neighboring nodes. Each node that receives this rebroadcasted hello packet computes its distance to sender node using ToA. In order to obtain the cost, the distance to the sender node is summed with cost in the hello packet and so on. Finally, each node obtains a physical distance to the sink as a cost. Since each node may receive several hello packets from different nodes, it only saves the neighboring nodes with minimum distance to sinks. Since hello packets contain the residual energy, each node achieves information about the residual energy of its neighboring nodes.

In the data forwarding phase, each forwarder node embeds a sorted list of its neighbors' IDs and broadcasts it to its neighbors. This list includes only the ID of those

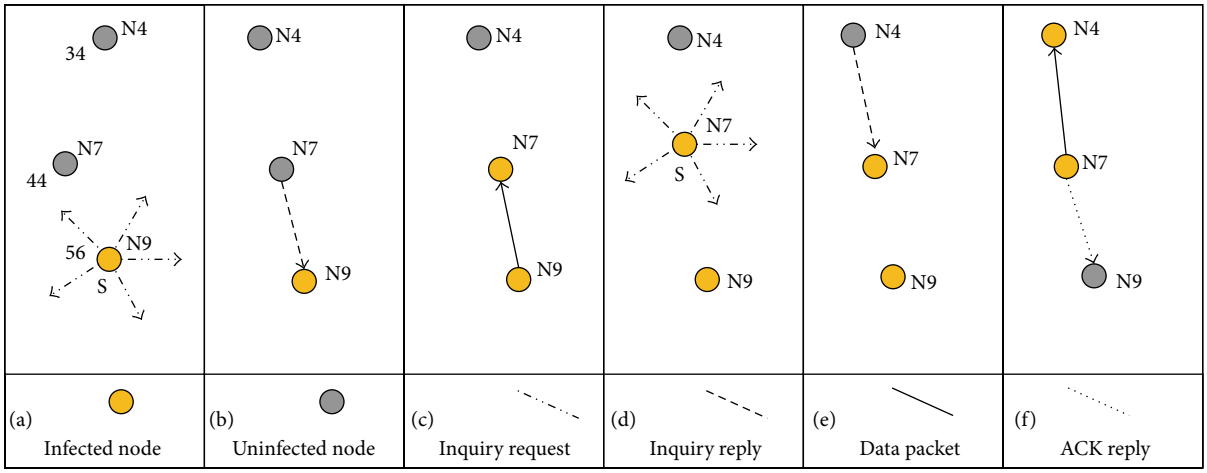

Figure 10: The steps of data packet forwarding in 2H-ACK [42].

neighboring nodes whose cost is smaller than forwarder node cost. In other word, the list contains a group of forwarder nodes which are closer to the sink. The list is ordered based on the residual energy in which each node with more energy has higher priority. According to the priority, a holding time is assigned to these list of nodes so that holding time of the node with the highest priority could be equal to zero and the other nodes' holding time is also computed. If the same data packet is received during holding time by each candidate node, this node does not participate in data packet forwarding. Instead, it forwards the data packet when the holding time is over.

The ERP^{2}R has advantages highlighted as follows. It does not require the fully location information of nodes for greedy routing. It employs the multisink structure to prevent rapid battery draining in the nodes located closer to the sink. The ERP^{2}R has also some drawbacks; due to movement of nodes through water currents, the first phase should be repeated in short interval of times, which results in an increase in network overhead. The number of the next hop candidate is increased remarkably in dense networks, which causes an increase in the energy consumption. Although communication void is a critical problem in greedy routing, this protocol does not take it into consideration.

3.2.2. Pressure-Based Routing in UWASNs. Since the pressure of water changes in different depths of underwater environment, the depth of each node can be calculated locally through measuring the pressure of water by a pressure sensor. Based on this idea, in the pressure-based routing protocols each node is equipped with an inexpensive pressure sensor to calculate locally the depth of the node. The main idea of greedy routing in this class is very simple. Each node calculates its depth locally, and only the neighboring nodes with less depth in comparison to the sender node can participate in the forwarding process. In other words, all one-hop neighbor nodes with a depth less than that of the sender node are located in positive progress area toward the sink, and they can take part in the packet forwarding process. Unlike the location-based category that needs expensive full location information and beacon-based subcategory that requires to gain expensive information about network by sending beacon messages, pressure-based category only uses depth information that can be achieved locally without any extra overhead. Consequently, the greedy pressure-based routing is the most promising method for high dynamic networks such as UWASNs. Here, the existing pressure routing protocols in UWASNs are explained.

Depth-Based Routing for UWASNs (DBR). Depth-based routing (DBR) [44] is the first pressure routing protocol proposed for underwater environment. In this protocol, each node is equipped with an inexpensive pressure sensor to calculate locally the depth of the node. DBR only employs depth information for performing greedy routing in UWASNs. In the architecture of DBR, multiple stationary sinks are deployed on water surface, while ordinary nodes are randomly scattered in different depths, and they can move freely with water flow. The basic idea in DBR is very simple. Each neighboring node with a lower depth than sender node is a candidate node for packet forwarding. The routing procedure in DBR is as follows. Each sender node embeds its depth in the data packet and broadcasts it to its one-hop neighbors. Once a neighboring node receives the packet, it calculates its depth via pressure sensor and compares to the embedded depth in the data packet. If its depth is less than the depth in the data packet, this node is located in the positive progress area and it is a candidate for packet forwarding; otherwise, it simply discards the packet. All candidate nodes for packet forwarding embed their depth in the data packet and broadcast the packet to their one-hop neighbors and so on. Since in each hop, the data packet is delivered to a node with a lower depth than the sender node, the sinks receive the data packets in hop-by-hop manner. In order to prevent high overhead and redundant packet transmission, each forwarder node computes a holding time for each received data packet based on its depth and the sender node depth. Therefore, different candidate nodes have different holding time. Each

candidate node waits until the holding time is over, then it transmits the data packet. During this period, if the same packet is received by the node from a lower depth node, it removes the packet from its sending queue. DBR is careful to avoid the same packet retransmission by each node. To this end, each successfully delivered data packet is added to the packet history buffer.

The DBR has some advantages highlighted as follows. Not only it can handle easily the high movement of nodes through water current, but also it employs a multisink structure to avoid the high traffic and rapid battery drain in the nodes closer to the sinks. It has also a number of remarkable disadvantages explained as follows. First, however the communication void problem is a common problem in greedy routing, DBR does not suggest a solution to tackle this problem. Second, although DBR tries to avoid sending duplicate packet, yet a number of duplicate packets is sent, which affects the protocol performance.

Depth-Based Multihop Routing for UWASNs (DBMR). In [45], a greedy and depth-based multihop routing (DBMR) is proposed to improve the energy consumption. Unlike DBR in which each node floods the data packets for its neighboring nodes, in the DBMR, only one node is selected as the next hop node to reduce the communication overhead. In the architecture of DBMR, several stationary sinks are deployed on water surface, while ordinary nodes are equipped with an inexpensive pressure sensor and scattered randomly in underwater environment. They move based on the random walk pattern. DBMR is composed of two phases: route discovery and send packets. In the first phase, the next hop node of each node is discovered. To this end, each node measures its depth by pressure sensor and broadcasts its own ID and depth information as a control message. It waits to receive the reply message for a specific period of time. Each neighbor node which receives the control message compares the depth in the message with its own depth. If its depth is less than the depth in the control message, it calculates its weight according to its depth and residual energy, then it embeds its ID and weight in the message and replies it; otherwise, it readily discards the control message. When the waiting time is over, each node selects the largest weight node as the next hop node and saves it in the routing table. The second phase is responsible for data packet forwarding. To this end, each node retrieves the next hop node from the routing table and transmits the data packet to this node in order to avoid the high communication overhead.

The main benefits of DBMR are that it handles the high mobility of nodes through water current and it employs a multisink structure to decrease the likelihood of traffic in the nodes located closer to the sinks. It applies a single-next hop strategy to reduce the communication overhead and increase the network lifetime. However, it has some remarkable drawbacks; for instance, it cannot handle the communication void problem, which causes high packet loss. Due to the high mobility of nodes by water current, the discovery phase should be done at short intervals, which results in an increase in the network overhead. Since acoustic links are unreliable and DBMR does not consider link quality for selecting the next hop node, the amount of packet retransmission increases significantly, which causes a remarkable increase in energy consumption.

Pressure Routing for UWASNs (HydroCast). In [33], a pressure routing for underwater sensor networks (HydroCast) is proposed to improve the reliability of the network and handle the void problem. In HydroCast, ordinary nodes are randomly scattered in underwater environment, and they can move freely with water flow. These nodes are equipped with an inexpensive pressure sensor to measure their own depth locally. Multiple mobile sinks are also deployed on water surface, which move with water flow. In order to identify positive progress area toward the sink, this protocol employs only depth information which is calculated by measuring pressure of water in different depths. HydroCast has two modes, including greedy routing and void handling. In the first mode, an opportunistic forwarding mechanism is used. To this end, this mechanism selects a subset of neighboring nodes with positive progress toward the sink as a next hop candidate to maximize the greedy progress. In this process, it takes into account the expected packet advance (EPA) metric to select the higher link quality neighboring nodes and hidden terminal problem to suppress the redundant packet forwarding by the nodes in the subset. In this subset, the nodes that are closer to the sink have higher priority. Each forwarder node embeds the ID of candidate nodes in a data packet and broadcasts it. After a neighboring node receives the data packet, it retrieves the list of IDs in the data packet. If its ID is not on the list, it simply discards the packet. Otherwise, it calculates a holding time and sends a data packet based on this holding time. It should be noted that if it receives the same packet from higher priority node in the holding time, it suppresses the data packet forwarding to prevent the redundant packet forwarding.

In the second mode, void handling mechanism is employed in order to deal with the communication void. When a node does not have any neighbor with a depth lower than that of itself, it cannot employ the greedy routing; therefore, this node is considered as a local maximum node. In this condition, it enables a void handling mechanism to deal with this problem. In this mechanism, each local maximum node finds and stores a detour path to a node with a depth lower than that of itself and transmits the data packet to this node. The procedure of this mechanism is illustrated in Figure 11. As can be seen, LM1 is a local maximum node. It finds a detour path to a node with a depth lower than that of itself (i.e., LM 2) and sends the data packet for this node. Since LM2 is a local maximum, it finds other node with a lower depth such as S and transmits the data packet for this node. Finally, the data packet reaches a node that is not a local maximum node, and this node sends the data packet in greedy mode.

The HydroCast has some advantages highlighted as follows. First, it can handle the void problem. Second, it only employs the depth information instead of using high-cost full location information and beacon messages. Third, it can handle the high mobility of nodes with the water flow. Finally, it uses the advantage of the multisink structure to tackle

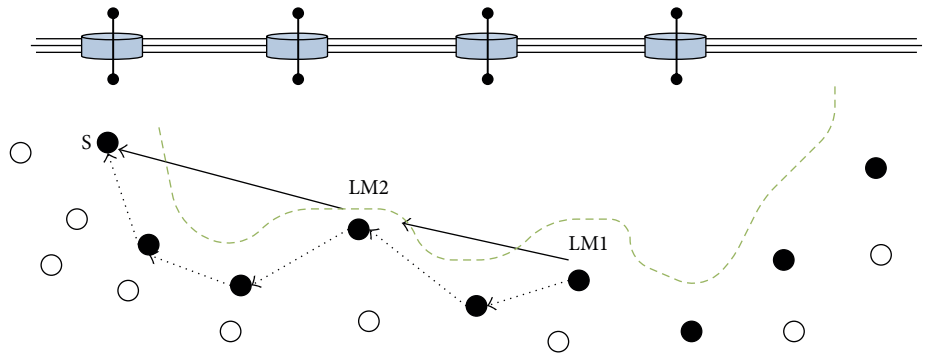

Figure 11: Recovery mode in HydroCast [33].

with a rapid battery drain in the nodes closer to the sink. However, it has a number of serious problems; for example, it calculates the information of distances from two-hop neighboring nodes in greedy mode to select a set of forwarder node, while measuring two-hop neighboring nodes' distance by ToA causes high communication overhead. Due to the high mobility of nodes in underwater environments, detour path discovered by a local maximum node is expired in a short period. Consequently, the finding detour path in the local maximum nodes should be repeated, which increases the communication overhead and energy consumption.

An Energy Efficient Localization-Free Routing (EEDBR). In [46], the authors proposed an energy efficient localization-free routing protocol (EEDBR) for the greedy pressure-based routing group of UWASNs. The aim of this protocol is to balance the energy of nodes and improve the network lifetime. In the architecture of EEDBR, multiple sinks are deployed on the water surface and equipped with radio and acoustic modems, while ordinary nodes are randomly scattered in the area of interest. They can move freely through water flow, and they are equipped with acoustic modem. Unlike DBR that is a receiver-based routing protocol, EEDBR is a sender-based routing protocol in which sender node selects a set of next hop nodes based on their depth and residual energy. EEDBR is composed of two phases: knowledge acquisition and data forwarding. In the first one, each node broadcasts its own depth and residual energy as a Hello packet to its neighboring nodes. Therefore, all nodes collect and save their neighboring nodes' information. In the second phase, a subset of forwarder nodes is selected based on their depth information and residual energy. In other words, a group of neighboring nodes with a depth smaller than that of sender node that have suitable residual energy are selected as next hop node candidates. The sender node embeds a list of selected nodes ID in data packet and forwards it. The nodes on the list are sorted based on their residual energy, which shows their priorities. In order to prevent redundant data packet forwarding, each candidate node considers a holding time according to its residual energy and priority in which a shorter holding time is assigned to a node with more residual energy. In addition, the nodes with the same residual energy have different priority which result in different holding time for these nodes.

The major advantages of EEDBR are as follows. First, it can handle the mobility of nodes with water flow. Second, it uses the advantages of multisink structure to prevent the rapid battery drain in the nodes closer to the sink. Third, only depth information is used in the greedy routing procedure, and it does not require to obtain expensive full location information and to send the beacon messages. The main drawback of this protocol is that knowledge acquisition phase should be repeated in a short interval of time due to high movement of nodes with water current, which causes high overhead. In addition, EEDBR does not take into account the link quality of nodes, while it is an important parameter in underwater environments due to unreliable acoustic links. Furthermore, it cannot handle the void problem, whereas it is considered as a critical problem in greedy routing.

Void-Aware Pressure Routing (VAPR). As mentioned earlier, the communication void problem is one of the most critical problems in greedy routing. If a forwarder node does not have at least one neighboring node with positive progress toward the sink, it encounters this problem [32]. In [47], a void-aware pressure routing (VAPR) is proposed to handle the void problem in this category of greedy routings. In this protocol, multiple sinks are deployed on water surface, while ordinary nodes are randomly scattered in the undersea area, and they move with water current based on Meandering Current Mobility (MCM) model. However existing 3D void handling methods in UWASNs use the flooding technique to identify the detour path, VAPR employs periodical beacon messages to identify the direction of each node in a heuristic manner. This direction is used for packet forwarding. Since VAPR employs depth information and information acquired from beacon messages, it belongs to both pressure based and beacon based categories.

VAPR is composed of two components, namely, enhanced beaconing and opportunistic directional data forwarding. In the first one, each sink broadcasts a beacon message including depth of sender node, the sequence number, number of hop count to sink, and direction of the current node toward the sink. After a node receives

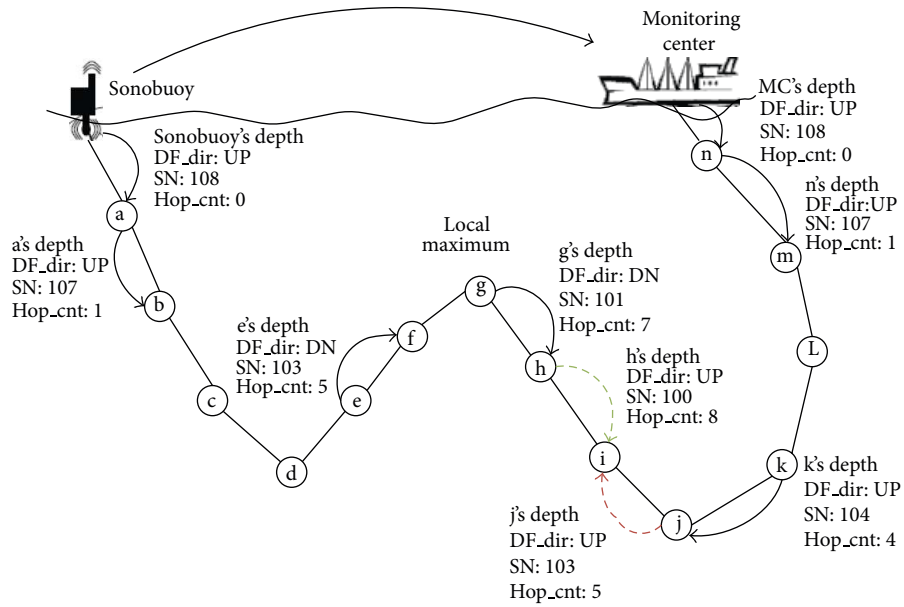

Figure 12: Enhanced beacon reception in two directions [47].

the message, it updates the message and broadcasts the updated message to its neighboring nodes. It is notable that if the beacon message is received from a node with a depth smaller than the receiver node, the direction of node is updated to up; otherwise, it updates to down. Figure 12 demonstrates the procedure of the enhanced beaconing component in two directions. For example, since node *a* receives the packet from a node with less depth, its direction is up, while the direction of node *e* is down because it receives the beacon message from a node with more depth. In the second component, a directional opportunistic data forwarding algorithm is proposed to forward the data packet toward the sinks. In this algorithm, each node employs the direction information to forward the packet and avoids the communication void.

The main advantages of VAPR are that it employs a multisink structure to prevent from a rapid battery drain in the nodes closer to the sinks. Furthermore, it can handle the mobility of nodes with water flow. It can handle the void problem with a heuristic method. The important drawback of VAPR is that due to the high movement of nodes in UWASNs, the enhanced beaconing component should be repeated in the short intervals of time, which causes a significant increase in the network overhead.

3.3. Comparison between Greedy Routing Categories and Protocols. The location-based category uses geographic information to carry out the greedy routing. The main benefit of location-based category is that positive progress area toward the sinks can be found and controlled easily, which helps to deliver the data packets to sink in an almost direct route. However, the major drawback of this category is that due to inapplicability of GPS in underwater environment and high mobility of nodes by water current, finding the location information of nodes by localization techniques is too costly.

Since location-free category does not employ geographical information for routing, there is no need for costly localization techniques to find the geographical information. Location-free category is composed of two subcategories: beacon-based, and pressure-based. In the beacon-based subcategory, sinks periodically broadcast a beacon message from the surface of water to the bottom in order to assign a specific information to each node. The main advantages of this category is that it does not require the expensive geographical information of nodes. However, the main drawback of this category is that due to high movement of nodes by water current in UWASNS, this special information must be updated in a short period, which causes high overhead of the network. In the pressure-based subcategory, each ordinary node is equipped with an inexpensive pressure sensor to measure locally the pressure of water and calculate the direct distance of node from water surface. The main advantage of this category is that it only uses the depth information in routing process and does not require expensive location information and high overhead beacon messages. The main shortcoming of this category is that they are equipped with pressure sensor that is costly. Table 3 compares the features of the protocols discussed in this paper, and Table 4 demonstrates a number of simulation conditions such as simulator name, the size of simulation area, communication range, node speed, sound speed, energy consumption in different modes, and node deployment.

Regardless of the information used to identify positive progress area in the greedy routing, a number of other routing parameters including residual energy, link quality, node degree, and number of hop count are employed by routing protocols to improve the efficiency of protocols. These parameters directly affect different network metrics such as reliability, network lifetime, and end-to-end delay. For example, residual energy of node is used in [38, 43, 45] to

Table 3: Features of greedy routing protocols in UWASNs.

		Protocol	Single/multiple copies	Positive progress area	Number of next hops	Single/multiple sink	2D/3D	Additional request	Forwarder node criteria	Opportunistic	Handle void	Sender based/receiver based	Compared with
Location based		VBF [7]	Multiple	Virtual pipeline	Multi	Single	3D	Location info.	Distance	Yes	No	Receiver based	—
		HH-VBF [35]	Multiple	Virtual pipeline	Multi	Single	3D	Location info.	Distance	Yes	No	Receiver based	VBF
		SEANAR [38]	Single	Inner and aside layers	One	Single	3D	Location info./power control	Distance/energy/node degree	No	No	Sender based	VBF, GF
		FBR [36]	Single	Cone	One	Multiple	2D	Location info.	Distance	No	Yes	Sender based	Min. Power
		PER [40]	Multiple	Distance	Two	Single	3D	Location info.	Distance/energy	No	No	Sender based	DBR
		DFR [41]	Multiple	Angle	Multi	Single	2D	Location info./link quality	Distance/link quality	Yes	Yes	Receiver based	HH-VBF, VBVA
Location free	Beacon based	H^2-DAB [21]	Single	Lower address	One	Multiple	3D	—	Address	No	No	Sender based	—
		2H-ACK [42]	Single	Lower address	One	Multiple	3D	—	Address	No	No	Sender based	HbH-ACK
		ERP^2R [43]	Multiple	Physical distance	Multi	Multiple	3D	—	Physical distance/energy	Yes	No	Sender based	DBR
	Pressure based	DBR [44]	Multiple	Lower depth	Multi	Multiple	3D	Pressure sensor	Depth	Yes	No	Receiver based	VBF
		DBMR [45]	Single	Lower depth	One	Multiple	3D	Pressure sensor	Depth/energy	No	No	Sender based	DBR
		HydroCast [33]	Multiple	Lower depth	Multi	Multiple	3D	Pressure sensor/two hop cluster	Depth/link quality	Yes	Yes	Receiver based	DBR
		EEDBR [46]	Multiple	Lower depth	Multi	Multiple	3D	Pressure sensor	Depth/energy	Yes	No	Sender based	DBR
		VAPR [47]	Multiple	Lower depth	Multi	Multiple	3D	Pressure sensor	Depth/direction/hop count./seq. no.	Yes	Yes	Sender based	DBR, HBR, HydroCast

Table 4: Simulation conditions of greedy routing protocols in UWASNs.

	Protocol	Simulator	Area	Range (m)	Node speed (m/s)	Bandwidth	Data generation rate	Sound speed (m/s)	Energy consumption				m65Nodes deployment and movements	
									Init.	Send	Rec.	Idle	Ordinary	Sinks
Location based	VBF [7]	n/a	$100 * 100 * 100\ m^3$	20	0–5	n/a	2 per sec	n/a	n/a	n/a	n/a	n/a	Uniform/mobile random walk	One/fix on surface
	HH-VBF [35]	NS2	$1000 * 1000 * 500\ m^3$	100	n/a	10 Kbps	1 per 10 sec	n/a	n/a	2 w	0.75 w	8 mw	Random/mobile horizontal 2D	One/fix on surface corner
	SEANAR [38]	C++	$240 * 240 * 120\ m^3$	30	0–2	Fix	n/a	n/a	1000 J	60 mj/bit	3 mj/bit	n/a	Random/mobile horizontal 2D	One/fix on surface corner
	FBR [36]	Python	$200 * 200\ km^2$	n/a	n/a	n/a	0.0005 per sec	1500	—	—	—	—	Random/mobile	Multi/fix on surface corner
	PER [40]	C++	$500 * 500 * 500\ m^3$	100	1–5	4 Kbps	n/a	n/a	n/a	n/a	n/a	n/a	Random/mobile random walk	One/fix on surface corner
	DFR [41]	NS2	$3000 * 4000\ m^2$	500	0–3	30 KHz	1 per 30 sec	1500	—	—	—	—	Two methods, random and grid	One/fix on surface
Location free — Beacon based	H^2-DAB [21]	NS2	$1500 * 1500 * 1500\ m^3$	500	n/a	n/a	1 per sec	1500	n/a	n/a	n/a	n/a	Bottom fix/special depths mobile with horizontal 2D	Multi/fix on surface
	2H-ACK [42]	NS2	$350 * 350 * 350\ m^3$	100	2-3	n/a	n/a	1500	n/a	n/a	n/a	n/a	Bottom fix/special depths mobile with horizontal 2D	Multi/fix on surface
	ERP^2R [43]	NS2	n/a	250	n/a	n/a	1 per 15 sec	n/a	70 J	n/a	n/a	n/a	Two methods, random and grid	Multi/fix on surface
Location free — Pressure based	DBR [44]	NS2	$500 * 500 * 500\ m^3$	100	1–5	10 Kbps	1 per sec	n/a	n/a	2 w	0.1 w	10 mw	Random/mobile random walk	Multi/fix on surface
	DBMR [45]	C++	$500 * 500 * 500\ m^3$	100	n/a	n/a	n/a	1500	n/a	n/a	n/a	n/a	Random/mobile random walk	Multi/fix on surface
	HydroCast [33]	Qualnet	$1000 * 1000 * 1000\ m^3$	250	0.3	50 Kbps	1 per 60 sec	n/a	—	105 dB re μPa	—	—	Random/mobile	Multi/mobile
	EEDBR [46]	NS2	n/a	250	n/a	n/a	1 per 15 sec	1500	70 J	n/a	n/a	n/a	Random and grid/mobile horizontal 2D	Multi/fix on surface
	VAPR [47]	Qualnet	$1500 * 1500 * 1500\ m^3$	250	0.3	50 Kbps	1 per 50 sec	1500	n/a	105 dB re μPa	n/a	n/a	Random/mobile with MCM model	Multi/fix on surface

balance the energy consumption and improve the network lifetime.

The number of next hop nodes involving in routing procedures has a direct impact on the protocol performance. According to the number of nodes selected as the next hop nodes, the greedy routing protocols can be divided into two groups, namely, one-next-hop nodes and multinext-hop nodes. In the first group, the protocols select only one next hop node at each hop [21, 36, 38, 45] in order to decrease the communication overhead and energy consumption. The main drawback of this group is that likelihood of data packet retransmission increases due to high path loss in UWASNs, which causes a significant decrease in routing performance. In the second group, protocols select a set of next hop nodes with positive progress toward the sink [7, 35, 41, 44] in order to take advantage of opportunistic routing. In opportunistic routing, each node floods the data packets to its neighboring nodes, and only the neighbors with positive progress toward the sinks can participate in the routing process to decrease the communication overhead. The main drawback of this group is that the communication overhead increases significantly due to involving multiple nodes in forwarding the same data packet. Although in opportunistic routing technique, a holding time is assigned to each next hop node to forward the data packet in different times and prevent from forwarding the same packet by different next hop nodes, this technique cannot prevent completely the redundant packet forwarding.

4. Future Work and Conclusion

4.1. Future Work. UWASN is a new area of research that has recently emerged in field of wireless sensor network. However, many studies have been conducted on the lower layers of OSI model such as physical and data link layers; the research on upper layers such as network layer is still in its infancy stages. In recent years, a number of routing protocols have been proposed to solve the problems related to underwater environment. However, most of these routing protocols cannot completely handle the problems and a number of issues still have not been addressed. A number of open issues in the network layer of UWASNs are explained as follows.

(i) Most of the existing routing protocols have been proposed for small-scale UWASNs, while a number of special applications require large-scale routing protocols. As a result, it is necessary to develop a new routing protocol for large-scale networks in underwater environment.

(ii) The acoustic wave is used as a communication medium in UWASNs instead of radio waves, while common network simulators such as OMNeT++, JSim, QualNet, and NS2 cannot support the acoustic wave. Furthermore, the underwater environment has 3D nature. However, famous networks simulator such as NS2 only support 2D environments. Therefore, a number of existing routing protocols use existing simulators and change some features on the simulator to be adapted with features of UWASNs, while other protocols use a customize simulator with different languages such as C++, Perl, Peyton, and Matlab [53]. It seems crucial to develop a standard simulator for UWASNs to cover all features of underwater environment.

(iii) The underwater networks suffer from lack of a realistic model for node mobility. Most of the routing protocols apply random walk mobility, and a number of them employ other mobility models such as MCM [47]. However, these mobility models are not suitable for undersea environments. Therefore, designing a new mobility model for undersea environments is essential.

(iv) In many UWASN applications such as military applications, a secure communication between nodes is one of the main challenges. However, the existing routing protocols have not addressed this issue. Consequently, it is essential to design a secure routing protocol for UWASNs with capability of tackling with underwater challenges.

(v) Congestion is a common issue in applications that use event-driven data reporting models. However, existing routing protocols do not take into account this issue. Since congestion in node and link creates high packet loss, which results in a significant decrease in network performance, designing a new routing protocol to address this issue seems an essential research.

(vi) Communication void is a crucial problem in greedy routing protocols. Due to 3D nature of underwater environment, the existing void handling techniques in TWSNs are not applicable to UWASNs. Since most of the existing void handling techniques in UWASNs employ flooding techniques to find the detour path, designing new void handling techniques with low overhead is essential for using in underwater environment.

(vii) Energy efficiency in UWASNs is more important than that of TWSNs. This is because underwater networks employ acoustic as a communication medium, and energy consumption by acoustic is much more than radio frequency [54]. Therefore, it is necessary to design an energy efficient routing protocol that is able to balance the nodes energy and decrease the communication overhead. Furthermore, new energy scavenging methods should be designed to supply the energy of nodes by converting the other types of energy such as kinetic energy to electrical energy.

(viii) Most of existing routing protocols take into account the sound speed equal to 1500 m/s in underwater environment, while the sound speed is varied with salinity, pressure, and temperature, which have

a direct impact on network performance. Consequently, there is still room to consider this issue in designing routing protocols for UWASNs.

4.2. Conclusion. As mentioned earlier, greedy routing method is the most promising routing approach in UWASNs. A routing protocol in underwater environment faces different challenges such as high movement of nodes by water flow, 3D environment, high path loss, low bandwidth, and high propagation delay. Since none of the routing protocols can tackle with all of the issues, each protocol takes into account a few ones of these issues to handle. In this paper, the basic issues of an acoustic communication and its challenges were presented. Then, the architecture of an underwater node and its components was explained in detail. Next, features of some recent commercial and scientific acoustic modems were expressed. The main differences between TWSNs and UWASNs were explained, and the reasons of low performance of TWSN's routing protocols in underwater environment were discussed. After that, a survey was given on greedy routing protocols proposed for UWASNs. According to information required for identifying the positive progress area toward the sink, we divided the greedy routing protocols into two categories: location based and location-free. The location-free category, in turn, was composed of two subcategories, namely, beacon based and pressure based. For each category, a number of famous routing protocols were briefly described, and their advantages and disadvantages are explained. Furthermore, these protocols were compared to each other based on their features and their simulation conditions. Finally, we provide an outlook on open issues in underwater routing protocols.

Acknowledgments

This work is supported by Universiti Teknologi Malaysia (UTM). The authors would like to thank the Research Management Center (RMC) for the partial funding and Pervasive Computing Research Groups (PCRG) of the Faculty of Computing for the support and insightful comments in making this study a success.

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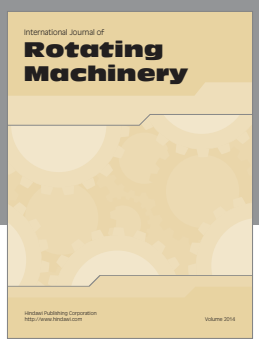

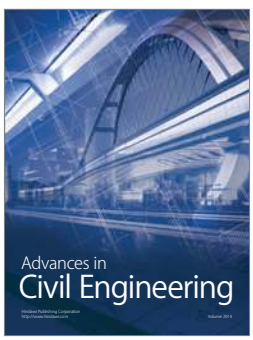

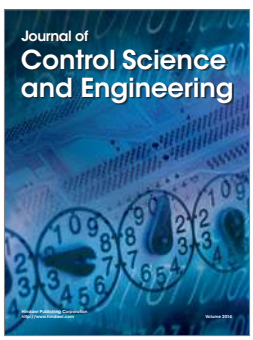

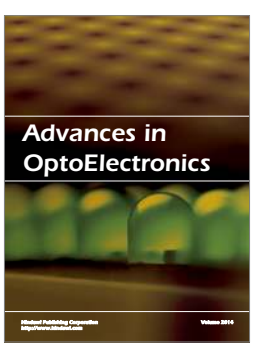

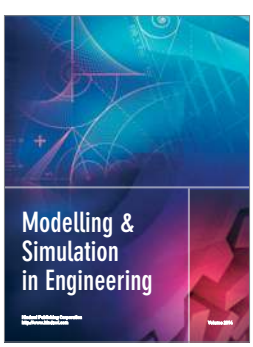

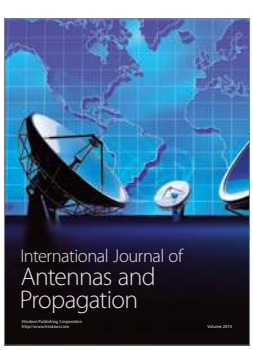

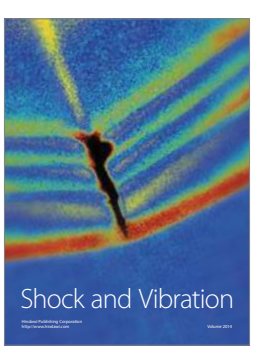

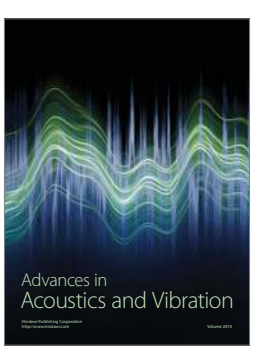

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