A Reliable Energy-Efficient Pressure-Based Routing Protocol for Underwater Wireless Sensor Network

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Abstract

Underwater wireless sensor networks (UWSNs) are similar to the terrestrial sensor networks. Nevertheless, there are different characteristics among them such as low battery power, limited bandwidth and high variable propagation delay. One of the common major problems in UWSNs is determining an efficient and reliable routing between the source node and the destination node. Therefore, researchers tend to design efficient protocols with consideration of the different characteristics of underwater communication. Furthermore, many routing protocols have been proposed and these protocols may be classified as location-based and location-free routing protocols. Pressure-based routing protocols are a subcategory of the location-free routing protocols. This paper focuses on reviewing the pressure-based routing protocols that may further be classified into **non-void avoidance protocols** and void avoidance protocols. Moreover, **non-void avoidance protocols** have been classified into single factor based and multi factor based routing protocols. Finally, this paper provides a comparison between these protocols based on their features, performance **and simulation parameters** and the paper concludes with some **future works** on which further study can be conducted.

Keywords: Communication Void, Energy Consumption, Pressure Sensors, Reliability, Routing Protocols, Underwater Wireless Sensor Network.

1. Introduction

Generally, we can say that the humans live on a water planet because 70% of the earth is covered with water. Several reasons occupy the researchers' minds as they discover this mysterious underwater world such as the lack of knowledge about the large unexplored areas, geological and biological resources as well as human-made and natural disasters, which leads to a significant interest in many fields such as monitoring, commercial, security, environmental and military [1-3]. Due to these issues, underwater wireless sensor networks (UWSNs) have become very interesting and have much promise in this harsh environment. Moreover, many applications have been introduced such as seismic monitoring disaster prevention, ocean sampling networks, assisted navigation and undersea exploration [4-6]. Routing in UWSN is one of the major parts of network layer necessary to a build suitable route between different sensors. The design of these protocols in UWSN is a difficult and challenging task due to the aquatic environment. First, acoustic waves are more preferred as a communication medium in underwater sensor networks than optical or radio waves [7-9]. Secondly, underwater sensor nodes have a high degree of mobility from water movement, while the terrestrial sensors are mostly static. UWSN's challenges make it inapplicable to use TWSN routing protocols. Therefore, a new routing scheme must be designed and developed for UWSNs.

Many survey papers published in UWSNs by [6, 8, 10-13] presented a general review and categorizations for routing protocols. Another paper has been presented by [14] that provides an in-depth discussion of geographical routing protocols. Unlike these papers, we highlight the lack of a specific review of pressure based routing protocols. In this paper, we shed light on the pressure based routing protocols that are designed for UWSN. Moreover, we discuss the main challenges of using pressure based routing protocols in UWSN from different points of view and provide some future works in this field.

The rest of this paper is organized as follows. Section 2 provides basic information about UWSNs. Routing protocols for UWSN have been presented in section 3. Pressure based routing concept and novel classifications for pressure routing protocols with brief descriptions about the pressure protocols have been discussed in Section 4 and 5 respectively. Section 6 presents three tables of comparison of these protocols based on their features, performance **and simulation parameters** with complete dissections. Section 7 illustrates **some future works** and the conclusion of this paper.

2. Basic information about UWSNs

2.1 Network Architecture

There are two types of sensors used in UWSN namely, sink nodes and ordinary nodes [15, 16]. The former is deployed on the water's surface and uses radio waves in order to communicate between the sinks. The ordinary nodes are deployed underwater with acoustic links as a communication medium. These sensors can sense and collect data from the environment and send the sensed data to its neighbors or to the sink [17]. **Fig. 1** illustrates underwater wireless sensor network architecture.

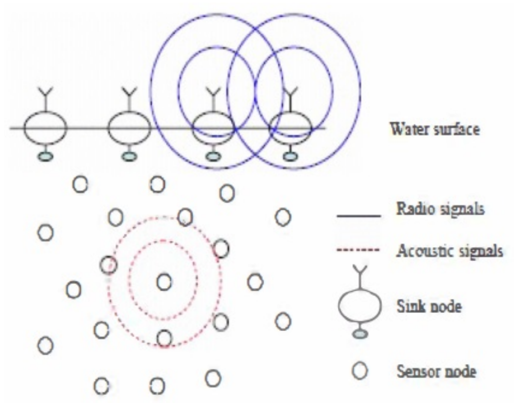

Fig. 1. UWSN architecture [17]

UWSN's architecture has been categorized into two-dimensional and three-dimensional with fixed nodes, and three-dimensional with Automatic Underwater Vehicles (AUVs) [18]. This categorization is based on the nodes' mobility and their geographical distribution. The suitable architecture used depends on the selected application.

2.2 Communication Medium

The protocols which have been proposed for TWSN use radio waves in order to communicate with each other. Underwater networks cannot use these waves because high radio frequencies are exposed to absorption and low radio frequencies requires high transmission power and a large antenna [19, 20]. This issue leads to use acoustic waves as a communication medium in underwater environments. However, the acoustic medium has five orders of magnitude higher propagation delay compared to radio waves. Moreover, changes that occur in acoustic channels leads to unsuitability of current wireless routing protocols and traditional wired protocols resulting in low network performance.

3. Routing Protocols for UWSNs

The basic idea of routing is to choose the path between the source and destination in the network. Routing protocols must have the ability to determine the best route towards the destination without pre-existing knowledge. Based on data forwarding strategies, routing protocols can be categorized as single path and multipath. Moreover, it can also be categorized based on network architecture i.e. flat, hierarchal and geographical. Centralized or de-centralized (distributed) is another categorization based on the routing operational strategy. Multipath routing protocols generate multiple paths during the routing process between source and destination. This part contributes to a better delivery ratio than single path under a specific scenario [13, 21] and also consumes more energy as multipath generation results in duplicate packets. Single path routing protocols employs only one path during the process of routing between the source and destination which contributes to simple routing tables but has poor performance if the network is disconnected.

Based on location information, routing protocols in UWSNs can be divided into two categories (i) Location-Based Routing Protocols (ii) Location-Free Routing Protocols. The former supposes that each node already has full location information about the nodes and the sink using Global Position System

(GPS). The basic idea of this category is to employ locational information in order to identify positive progress towards the sink. There are different ways to find the next selection node such as generating specific shapes between sink and nodes i.e. specific layer [22], cone [23], zone [24] and virtual pipelines [21, 25, 26]. The routing performance can be affected by the size of the shape. In other words, the number of nodes that can join the routing process will be increased if the size of the shape is increased. This increase results in more energy consumption and network overhead. Geographical information is not fully utilized in the location free routing protocols when compared to the location based category. However, in order to identify positive progress area towards the sink, information such as depth and dynamic address of the nodes are adopted. Based on data collection, this category can be further divided into beacon based and pressure based categories. In order to identify the positive progress toward the sink in the Beacon based subcategory, special information such as the dynamic address of each node is assigned by employing beacon messages [5, 9, 27, 28]. Meanwhile, to identify the positive progress area in the pressure-based subcategory, the depth information is measured locally by pressure sensor [17, 29].

4. Pressure Routing Protocols

Due to water pressure changes at different depths of the underwater environment, pressure sensors can be used to determine the depth of each node locally. Based on this idea, the sensors are equipped with an inexpensive pressure sensor for pressure-based routing to calculate the node depth locally. Thus, the ideology of greedy routing in this class is simplified. Node depths are calculated locally by each node and neighboring nodes with less depth when compared to the sender node participate in the forwarding process. In other words, all one hop neighbor nodes with a lesser depth to that of the sender node participate in the packet forwarding process and are located in the positive progress area toward the sink. The pressure-based category utilizes depth information with no extra overhead that is locally achieved when compared to both the location-based category and beacon-based subcategory. The location-based category requires expensive full location information while the beacon-based subcategory is expected to obtain expensive network information by sending beacon messages [13]. As a result, for high dynamic networks such as UWASNs, pressure-based routing guarantees a promising result when adopted.

There are many strategies used to reduce the number of candidate nodes such as residual energy, holding times and threshold nodes. Otherwise, these techniques might cause duplicating packet transmission and signaling overhead. Moreover, link quality is another important factor to ensure reliable data delivery and avoid the communication void problem [30]. In greedy approaches, the nodes that have packets to send forward do so to a single hop node that is located closer to the destination than the forwarding itself. Greedy protocols do not consider alternative paths from the source towards the destination. Source nodes could have knowledge about their neighbor nodes and can select the next forwarding nodes according to different factors in the protocols such as the nearest neighbor nodes to the destination or sink [31, 32]. Greedy routing protocols broadcast small packets (Hello packets) to provide their position and give the ability for the neighboring nodes to build a one-hop neighbor table in order to ensure that the packet is delivered from the source towards its destination. This kind of protocol is both scalable and flexible with changes in topology without the use of routing discovery and maintenance. However, these messages cause congestion problems and excessive energy consumption [33].

Most of the pressure based routing protocols employ flooding techniques. In flooding approaches, the sender node broadcasts the packet (flooding) to all one-hop neighbors to the destination i.e. they flood the data packets with their communication range. The receiver node itself checks if this node is a candidate for forwarding the packets according to specific criteria, if not it immediately drops the packet. Furthermore, because of node mobility in underwater environments, while flooding data packets sometimes the nodes' position might be changed and the nodes reach a point where they can't find any neighbor nodes. As a result, a communication void has occurred i.e. the node may not be able to find the next neighbor towards the sink [13, 34]. Therefore, there is a need to design a recovery algorithm in order to avoid this problem.

5. Classification of Pressure Based Routing Protocols

In pressure based routing protocols, the main idea is the sender nodes must have information about their neighbors without using full location information by (GPS) or expensive beaconing messages from the sink. Each protocol uses different criteria and factors to identify and choose the next hop node in order to forward the data packet. The key point in data routing is to enable the data packets to reach the sink node using the minimum number of nodes while keeping energy balanced and avoiding the communication void problem.

In this work, we focus on Void regions as a selected criteria to introduce a novel classification of protocols. In Fig 2, pressure based routing protocols are classified into two categories: Non-Avoidance Routing Protocols and Void Avoidance Routing Protocols. Furthermore, Non-Avoidance Routing Protocols can be classified into two subcategories: Single Factor Based Routing Protocols and Multi Factor Based Routing Protocols.

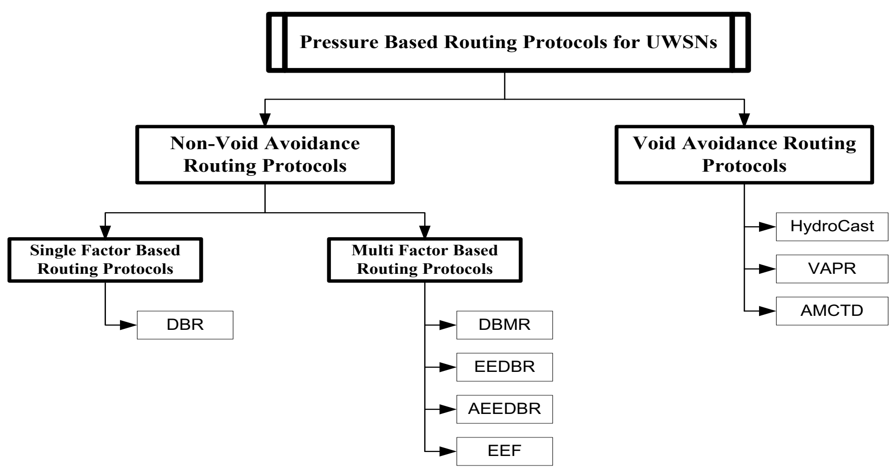

Fig. 2. Pressure Based Routing Protocols for UWSNs

5.1 Non-Avoidance Routing Protocols

This category does not take into consideration the void problem and focuses more on energy consumption as a major part in any type of wireless network; hence, it always a hot topic and draws the attention of researchers and has extensive research literature. In UWSNs, Energy Efficiency is more important than in TWSNs due to the use of acoustic waves as a communication medium. That leads to the consumption of more energy in UWSNs than in TWSNs [35]. Therefore, it is necessary to design Energy Efficient routing schemes in order to balance the energy between each single node and to decrease the communication overhead.

In order to examine the effectiveness of the protocols, researchers must first have some knowledge about the factors that are used in each protocol; these factors vary depending on their impact and the methods that are being used. This information gives the researchers the ability to develop new energy efficient routing protocols. Each factor is different so researchers can use each factor according to their needs and employ different factors to reach the protocol goals. From this point of view comes the importance of knowing each factor and their impact on each protocol, and how the researchers employ these factors in developing the protocol. Therefore, we can take these factors into account to be used as selected criteria for a new sub-classification in our main category non-void avoidance routing protocols.

We further divide this category based on the number of factors into two subcategories: Single Factor Based Routing Protocols and Multi Factor Based Routing Protocols. We provide a brief description and discussion of these two subcategories with all Pressure Based Routing Protocols belonging to these subcategories separately in the next sections.

5.1.1 Single Factor Based Routing Protocols

In this subcategory, the protocol only employs one factor to find the next hop neighbor nodes. This kind of protocol is very simple as it only employs depth information in order to define the positive progress area towards the sink.

Depth Based Routing (DBR). The first pressure routing protocol recommended for the underwater environment is the Depth-based routing (DBR) [29]. Each node in this protocol is equipped with a cost effective pressure sensor used for locally calculating the depth of node. In UWASNs, DBR employs only depth information to perform greedy routing. However, multiple stationary sinks are deployed on the water's surface in the architecture of DBR, while ordinary nodes have free movement with the flow of the water and they are randomly scattered to different depths. The fundamentals of the DBR concept are very simple. Every neighboring node whose depth is lower compared to the sender node is eligible for packet forwarding.

The procedure for routing in DBR is as follows: The depth of each sender node is embedded in the data packet and broadcasted to its one-hop neighbors. Once the packet is received by the neighboring node, the depth of the node is calculated using a pressure sensor. A comparison of the calculated depth with that of the embedded depth in the data packet will be carried out. If the depth in the data packet is higher than the calculated depth, this node is located in the positive area and it is a candidate for packet forwarding; otherwise, the packet will simply be discarded. The depths of each of the candidate nodes for packet forwarding is embedded in the data packet and broadcasted to the respective one-hop neighbors and so on. The data packets are received in hop-by-hop manner by the sinks because the data packet in each hop is delivered to a node with a lower depth than the sender node.

Each forwarder computes a holding time for every data packet received based on its depth and the sender node depth in order to avoid high overhead and redundant packet transmission using equation (1) below:

$$f(d) = \frac{2\tau}{\delta}.(R - d), \delta \in (0, R] \tag{1}$$

where $\tau = {R}/{v_0}$ is maximal propagation delay for each single hop, v_0 is sound propagation speed in water, $\delta = d1 - d2$ and R is the maximum transmission range.

As a result, the holding time for each candidate node is different. Thus, each candidate node transmits its data packet only after the holding time is ended. At this stage, the node will eliminate packets received from a lower depth node if the packet is identical. DBR is on alert to prevent retransmission of identical packets by each node. Consequently, a packet history buffer receives packets that are delivered successfully.

One of the advantages of the DBR is that it does not only handle a nodes movement with water currents with ease, but also prevents high traffic and rapid battery draining of the nodes closer to the sinks by adopting a multi sink structure. Moreover, it reduces communication costs because of unused full location information and handles the mobility of nodes in water currents. The findings of the present study revealed that DBR can achieve very high-packet delivery ratios for dense networks with only small communication costs. However, DBR is characterized with a notable number of disadvantages; DBR employs depth factor without using any balancing energy factor such as residual energy which results in imbalances in energy. Moreover, in this case, it will use the same node many times because of little vertical movement between the nodes which can cause the overuse of certain nodes and decrease the networks lifetime. When the threshold is small, it will result in a communication void problem so DBR is not a recommended solution to deal with this problem. Also, DBR efforts to prevent duplicate packet from being sent are sometimes unsuccessful which may affect the protocols performance.

5.1.2 Multi Factor Based Routing Protocols

The protocols belonging to this subcategory utilize multiple factors in order to select the next forwarding nodes. Residual energy is the main factor that has a direct impact in balancing energy consumption between the nodes and further improving the networks lifetime. The researchers employ different factors and come up with novel mathematical models that can improve the overall performance of the network.

Depth Based Multihop Routing Protocol (DBMR). In [17], the use of a greedy and depth-based multi hop routing (DBMR) was proposed to improve energy consumption. DBMR selects a single node as the next hop node for the reduction of communication overhead unlike in DBR where the data packet is flooded by sender nodes to its neighboring nodes. DBMR is comprised of two phases namely route discovery and sending packets. The next hop node of each node is discovered in the first phase. Consequently, the depth of each node is measured by pressure sensor. Also, the node ID and depth information is broadcasted as a control message which waits for a specific time duration to receive a reply message. The depth of the control message received by each neighbor node is compared with the depth of the node. If the depth of the control message is higher than that of the node, the weight of the node is computed based on its depth and residual energy **using equation (2) below.**

$$F(ID) = \frac{E_r}{d_r} \tag{2}$$

where E_r is the residual energy of the selected node and d_r is the depth of the node. Thus, the node ID and weight in the message is embedded before it is replied. Otherwise, the control message is discarded. Once the waiting time is completed, the largest weighted node is selected by each node as the next hop node and is then saved in the routing table. Data packet forwarding is carried out in the second phase. Here, the next hop node from the routing table is retrieved by each node before the data packet is transmitted to the node to avoid high communication overhead.

The major advantages of the DBMR is its ability to deal with high node movement through water currents and the likelihood of decreasing traffic in the nodes located closer to the sinks by employing a multi sink structure. It also provides a longer lifetime for the network and a reduced communication overhead by adopting a single-next hop strategy. However, it has some shortcomings such as high packet loss due to its inability to handle the communication void problem. Due to high node movement resulting from water currents, the discovery phase should be done at short intervals in order to increase network overhead. Knowing that DBMR does not take link quality into consideration for selection of next hop node and the unreliable nature of acoustic links, there is a significant increase in the amount of packet retransmission, which in turn increases energy consumption remarkably.

Energy Efficient Localization Free Routing Protocol (EEDBR). In [36], the authors proposed an energy efficient localization free routing protocol (EEDBR) for the greedy pressure-based routing group of UWASNs. The aim of the protocol was balancing node energy and improving the lifetime of the network. In EEDBR, selection of the sets of next hop nodes by the sender node is based on their depth and residual energy which makes it a sender based routing protocol unlike the DBR which is a receiver-based routing protocol.

EEDBR composes of two phases which are knowledge acquisition and data forwarding. The depth and residual energy of each node is broadcasted as a Hello packet to its neighboring nodes. Therefore, the neighboring nodes' information is collected and saved by all the nodes. The second phase involves the selection of forwarder nodes based on their depth information and residual energy. In other words, the next hop node candidate selected is a group of neighboring nodes with smaller depths than that the sender node characterized by suitable residual energy. A list of the selected nodes ID in the data packet is embedded by the sender node and forwarded. The residual energy of the nodes on the list shows their priorities and is considered when sorting them. Each candidate node considers a holding time based on its residual energy and priority in order to prevent redundant data packet forwarding in which a shorter holding time is assigned to a node with more residual energy.

Fig. 3 shows five different scenarios for selection of the next forwarding node where n is the source, n1 and n2 are the next neighbors' candidate nodes with 90J and 80J values considered as their residual energy. In (a), node n1 and n2 are located at the same depth. However, node n2 has higher residual energy than n1 so it forwards the packet. In (b), n2 now is a source node while node n3 and n4 are the next neighboring candidate nodes with residual energy of 90J for both of them. However, node n4 has a lower depth than n3 which leads to the selection of n4 as the next forwarding node. In (c), n4 is a sender node with n5 and n6 as neighboring nodes. Node n5 is the farthest to the sink but is has less residual energy than n6. Node n5 is the next forwarding nod and it will transmit the packet because its residual energy is higher than n6. In (d), it is possible that two or more nodes have the same depth and residual energy. In this case, the node is selected based on its priority value and holding time since the holding time is different between each two nodes. Then, the node with best holding time and priority value transmits the packets and the second one will drop the packets when overhearing the transmission of the same packets.

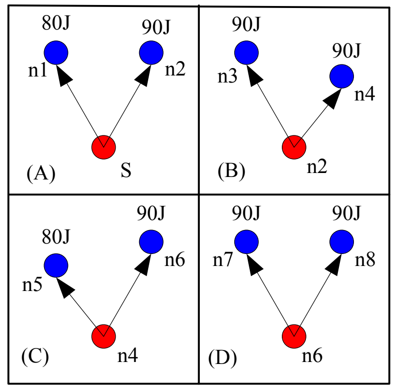

Fig. 3. Next forwarding node selections in EEDBR [36]

In addition, the priority of nodes with similar residual energy differs which result in different holding time T for these nodes calculated using equation (3) below:

$$T = \left(1 - \left(\frac{current\ energy}{initial\ energy}\right)\right) \times \max\_holding\_time + p \quad (3)$$

where max_holding_time is the maximum holding time for data packet calculated locally by node and p is the priority value.

The major advantages of EEDBR are listed below:

1. It handles the movement of nodes with water flow.
2. Rapid battery drain in the nodes closer to the sink is prevented by adopting the advantages of multi sink structure.
3. Only uses depth information and residual energy which does not require obtaining expensive full location information or beacon messages.

EEDBR have been simulated by Network Simulation 2 (NS2) [37] in order to validate the results. It shows that EEDBR contributed to performance improvements in terms of energy consumption, end-to-end delay and network lifetime. However, the major setback of this protocol is that it requires the knowledge acquisition phase to be repeated within a short time interval as nodes move with the water currents resulting in high overhead. Moreover, this protocol does not provide a good solution if the nodes have the same depth information and residual energy. Additionally, due to unreliable acoustic links, the link quality of nodes is a vital parameter in the underwater environment. Furthermore, it cannot handle the void problem which is a critical problem in greedy routing. Finally, due to data storage and list of forwarding nodes in EEDBR there are delays.

A New Advanced Energy Efficient Routing Protocol (AEEDBR). A simple enhancement of (EEDBR) has been proposed in [38] called A New Advanced Energy Efficient Routing Protocol in order to enhance the nodes located near the sink. The nodes that are located near the sink are equipped with bigger batteries and depths less than 70 meters. The rest of this scheme is almost the same using the same architecture and platform of EEDBR except on some major points such as there is no method to choose the next forwarding nodes if the depth information and residual energy for the candidate nodes are the same. Moreover, this protocol uses the table that contains only depth information and residual energy without any priority factor in the top of the table list. In other words, all the nodes have to wait until the holding time finishes to forward the data packets. However, there is a difference between residual energy for the nodes in their protocol and the residual energy that used in the simulation scenario. Thus, we cannot accurately determine if the simulation results are the same as the real results for the performance of AEEDBR. We can only consider the performance of this protocol if a fair comparison is implemented with the same scenario. Otherwise, this protocol only contributes to balancing energy consumption when compared to EEDBR and DBR.

Energy Efficient Fitness Based Routing Protocol (EEF). In order to reduce the end-to-end delay and the energy consumption of the network, a new pressure based routing protocol named energy efficient fitness based routing protocol (EEF) [39] has been proposed which uses the same architecture as DBR while utilizing more than one parameter (i.e. depth) for packet forwarding. If a node has a packet to send, it adds its fitness value based on the equation given below and adds its own location value, destination location value, packet sequence number, source ID and then broadcasts it. When neighboring nodes receives this packet it will check if its energy is greater than the threshold, the node calculates its fitness value by the equation (4) given below. Otherwise it immediately discards the packets.

$$f(n_f) = \frac{E_r^f x\ depth_{diff} x\ d_{sf}}{d_{fd}} \quad (4)$$

where E_r^f is the residual energy, $depth_{diff}$ is the difference in depth between the sender and forwarder in terms of vertical distance from the sink, d_{sf} is the distance between sender and forwarder node and d_{fd} is distance between the forwarder node and the sink. When a node has a higher fitness value than the fitness value of sender node that received the packet header, it considers itself a candidate for forwarding the packets. While the fitness value is higher, the holding time becomes shorter in order to reduce the number of forwarding nodes.

On the other hand, each node does not directly forward the packet; it waits for the holding time based on the fitness value and the packet transfer time from itself towards the sink node. This gives the ability to the nodes closer to sink to broadcast before the nodes that are located further away from the sink. Thus, nodes that are further away from the sink can overhear the transmission before their waiting time finishes and then drop the packets. Also, EEF significantly improves energy consumption and contributes to better end-to-end delay than DBR. Moreover, it handles the underwater dynamic topology efficiently.

However, it faces some major problems. First this protocol did not provide any solution for the communication void problem. Moreover, more nodes will receive packets and further broadcast it with its greedy nature in dense deployments, and the continuous calculation of fitness values at every hop will result in poor utilization of the limited available bandwidth. Also it does not keep the history of sent packets which could cause the extra transmission of the same packets. And lastly, it chooses the nodes with a higher depth forwarder without considering link quality, which can have substantial effects on the network.

5.2 Void Avoidance Routing Protocols

In this scenario, some areas may not be covered by the network due to node failures and underwater hurdles. Since communication void is a major problem, the routing protocol should be able to deal it. In addition, the method of handling communication void is a technical challenge for any greedy routing protocol [26]. If any node reaches some void region it directly changes to the void handling mode. In pressure based routing protocols, three protocols have been published in this subcategory. Next we provide an in-depth description of these protocols with their techniques and how they deal with the communication void problem.

Pressure Routing for UWASNs (HydroCast). In [40], an improvement in the reliability of networks and void problem handling was proposed by adopting a pressure routing for underwater sensor networks (HydroCast). In HydroCast, the movement of ordinary nodes with flow of water is without restraint because they are scattered in the underwater environment. The depths of these nodes are measured locally through an inexpensive pressure sensor. Multiple mobile sinks are also deployed on the water's surface whose movement is with the flow of water. Only depth information is employed by the protocol which is determined by water pressure measurement at different depths in order to identify positive progress areas towards the sink.

HydroCast has two modes; greedy routing and void handling. An opportunistic forwarding mechanism is adopted in the first mode. In order to maximize the greedy progress, a subset of neighboring nodes with positive progress toward the sink is selected in this mechanism as a next hop candidate. The expected packet advance (EPA) metric is considered in this process when selecting the higher link quality neighboring nodes and hidden terminal problem in order to prevent the nodes in the subset from redundant packet forwarding. Nodes closer to the sink in this subset tend to have a higher priority. Candidate nodes IDs are embedded in the data packet and broadcasted by each forwarder node which is then received by a neighboring node in order to retrieve the list of the IDs present in the data packet. However, the packet whose IDs are not listed are simply removed. Otherwise, the holding time is calculated and the data packet is sent based on this holding time. Furthermore, if the same packet from a higher priority node in the holding time is received by the neighboring node, the data packet forwarding is contained to prevent redundant packet forwarding.

In order to tackle the void communication problem, a void handling mechanism is utilized in the second mode. When a node lacks any neighbor with a lower depth when compared to its depth, greedy routing cannot be utilized. Thus, such node is regarded as a local maximum node. To this end, a void handling mechanism is enabled 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 **Fig. 4.** As seen from the figure, LM1 is a local maximum node which locates a detour path with a lesser depth to its own (i.e. LM2) and send the data packet to such a node. Given that LM2 is a local maximum, it locates another node with a lower depth such as S and transmits their data packet. Once the data packet reaches a non-local maximum node, this node will send the data packet in greedy mode.

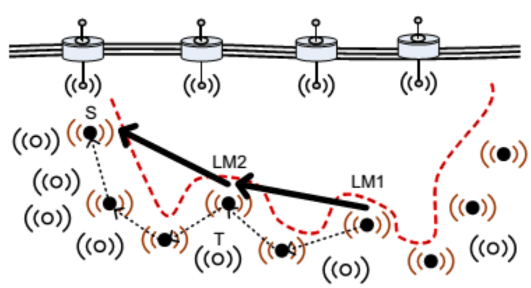

Fig. 4. Void handling mode in HydroCast [40]

Some advantages of HydroCast are highlighted as follows:

1. It can deal with the void problem.

2. Depth information is utilized rather than using high-cost full location information and beacon messages.
3. It can handle the high mobility of nodes with the water flow.
4. A multi sink structure is used to deal with a rapid battery drain in the nodes closer to the sink.

However, it has a number of problems which cannot be overlooked. For example, how is the distance information from two-hop neighboring nodes calculated in greedy mode to choose a set of forwarder nodes, while measuring two-hop neighboring nodes' distance by ToA causes a high communication overhead. The expiry period of the detour path discovered by a local maximum becomes shorter due to the rapid movement of nodes in underwater environments. Consequently, communication overhead and energy consumption can be increased by repeating the process of finding the detour path in the local maximum nodes.

Void-Aware Pressure Routing (VAPR). The communication void problem has been identified as one of the most critical setbacks in greedy routing as stated earlier. If at least one neighboring node with progress towards the sink is not present as a forwarder, the communication void problem will be encountered [26]. In [41], a void-aware pressure routing (VAPR) is proposed to handle the void problem in this category of greedy routings. Multiple sinks are deployed on the water surface in this protocol while ordinary nodes whose movement is based on water currents that use the Meandering Current Mobility (MCM) model are scattered in the undersea area. Existing 3D void handling methods in UWASNs identify the detour path by adopting a flooding technique. A periodical beacon message is employed by the VAPR 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 which are enhanced beaconing and opportunistic directional data forwarding. In enhanced beaconing, a beacon message is broadcasted by each sink. Such messages include the depth of sender node, the sequence number, number of hop counts to sink, and the direction of the current node toward the sink. The received message is updated by the node and broadcasted to its neighboring nodes. The direction of update is upwards if the beacon message is received from a node whose depth is less than that of the receiver node. Otherwise, it updates downwards. **Fig. 5** is a representation of the procedure of the enhanced beaconing component in two directions. For instance, since the packet data received by node a is from a node with less depth, it will have an upward direction. Meanwhile the direction of node e is downwards because the beacon message it receives is 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.

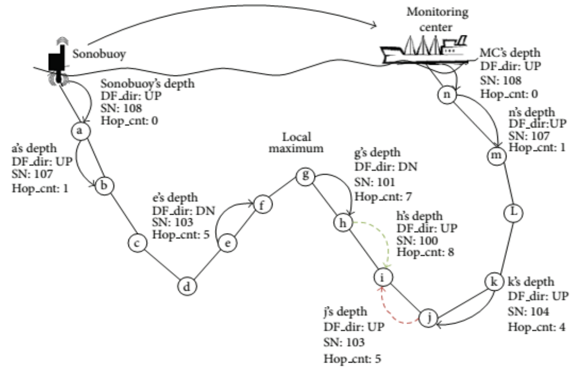

Fig. 5. Enhanced beaconing in VAPR [41]

One of the major advantages of VAPR is that it prevents rapid battery drain in the nodes closer to the sinks by employing a multi sink structure. Additionally, it can handle the movement of nodes with the flow of water. It can also handle the void problem with a heuristic method unlike HydroCast where a recovery path has to be discovered; hence VAPR reduces communication overhead and end-to-end delay, which turns out to be its biggest advantage. The results of the present study showed that the extensive simulation results of VAPR outperform existing solutions. However, the notable letdown of VAPR is that it requires a repetition of the enhanced beaconing component within short time intervals which results in the high movement of nodes in UWASNs, thus significantly increasing the network overload.

Adaptive Mobility of Courier nodes in Threshold-optimized DBR Protocol **(AMCTD).** Another idea proposed in [42] based on the depth of sensor nodes is known as depth based routing protocol (AMCTD). AMCTD have been presented to achieve two goals, (i) employ courier nodes for data collection and data transferring in order to balance energy consumption (ii) minimize delay. Death from frequent usage of nodes causes the communication hole problem and this protocol comes up with a solution to this problem. It assigns a depth threshold with an efficient weight calculation function that changes with the change in topology and density of the network in order to prolong the network lifetime. Furthermore, AMCTD minimizes the load on the nodes that are closer to the sink. First, AMTCD assigns a depth threshold of 60 meter i.e. nodes having a depth difference of 60 meter from the source are an eligible forwarder. Second, AMTCD consists of three phases. In the initialization phase, nodes send their residual energy and weight information to each other and record this **information using equation (5) given below.**

$$W_i = \frac{Priority\ Value \times R_i}{Depth\ of\ Water - D_i} \quad (5)$$

where R_i and D_i is residual energy depth of Node i respectively and priority is a constant value. According to this equation, the node with high depth or energy is preferred as this will help in minimizing the load on the nodes that are closer to the sink. In other words, AMTCD doesn't utilize opportunistic routing techniques since it works to increase network lifetime. The data forwarding phase starts when a source node has a packet to send. It compares the weight information that is received from hello packets and then chooses the node with the highest weight value. And lastly, the source nodes will forward the data packets. When the node receives this packet it waits until their holding time is finished. If a node overhears the same packet from some other neighbor nodes it simply discards the data packet. When the courier node receives this packet, it will send an acknowledgement to their neighbors to stop forwarding this packet or discard it if the same message has been received from any other neighbor of the source node. Moreover, AMCTD checks for communication holes by looking for dead nodes every 50 rounds. In the last phase, it will update the weight only when the number of dead nodes increased by 2% using equation (6) given below.

$$W_i = \frac{Priority\ Value \times D_i}{R_i} \tag{6}$$

As the above equation shows, makes the nodes with high residual energy insignificant rather nodes with high depth are preferred forwarders. This helps in using nodes with more depth rather than nodes with high energy as selected nodes to forward the data packets. However, to handle communication holes, the authors employed courier nodes strategically floating at different depths if the number of dead nodes reaches 80%. Also, to prolong network life time, it changes the weight function that selects the nodes with more residual energy in lower densities. To keep a number of eligible nodes available for the next hop they minimize the depth threshold value with increases in the number of dead nodes.

AMCTD prolongs the network lifetime by employing all the nodes at higher depth by minimizing thresholds according to topology changes. Furthermore, while filling in communication holes courier nodes are also helpful for reducing communication void issues and the burden of ordinary sensor nodes is reduced with the help of courier nodes. On the other hand, simulation result shows that AMCTD has better performance than DBR and EEDBR in terms of network lifetime higher throughput.

However, the use of hello packets for exchanging information among neighbors in AMCTD causes high energy consumption. Another major drawback of this protocol is large end-to-end delay. This is because when a sender selects the most appropriate forwarder by comparing the weight of its neighbors, this will have a direct increase in waiting time during packet reception by its neighbors. However, it still cannot avoid duplicate packet transmission due to the use of short area of threshold in the start (60m) to avoid flooding, Finally, AMCTD do not handle nodes mobility.

6. Comparison Study

In the previous section, we have categorized all pressure based routing protocols. **In the discussion of Non-Void Avoidance Routing Protocols**, single factor routing protocols only rely on depth information and do not need full location information. Hence, it is an inexpensive approach that only works on vertical depth difference. The main advantages of this protocols is that not only handle nodes movement easily through water current, but also by adopting a multi sink structure it prevents high traffic and rapid battery draining of the nodes closer to the sinks. Moreover, it reduces communication costs because full location information is not used. These kinds of protocols however only utilize depth factors without balancing for energy consumption such as residual energy. As a result, in this situation, some nodes may die early because the continuous use of the same node many times consumes more energy. Also, although it tries to avoid sending duplicate packets, a number of duplicate packets are sent which affects the protocols performance. Moreover, single factor routing protocols do not provide any solution to solving the communication void problem.

Multi factor routing protocols employs multiple factors to select the next hop nodes. One of the main factors in this sub-classification is residual energy; it has a direct impact in balancing the energy consumption between nodes and also improves the networks lifetime. On the other hand, researchers utilize different factors and provide some new novel models that can improve the overall performance of the network. However, the major setback of this category is that it requires the repetition of the initial phase in a short interval time due to high node mobility with water currents which results in high overhead. Moreover, most of them did not provide a good solution in the protocol when nodes have the same residual energy and depth information. Additionally, due to unreliable acoustic links, the link quality of nodes is a vital parameter in the underwater environment. None of these protocols utilized this parameter with residual energy. Furthermore, it cannot handle the communication void problem which is considered a major problem in pressure routing. Finally, delays might occur due to the use of tables which included a list of forwarding nodes.

In Void Avoidance Protocols, if any node reaches a void region it directly changes to the void handling mode which can deal with this problem. Methods of handling communication voids are the main challenge for any pressure routing protocol. In addition, a greedy approach consists of two modes: greedy mode and void handling mode. The former works when a node has at least one neighboring node with less depth than the sender. Otherwise, it faces a communication void and directly changes to the latter mode. However, few studies have taken into consideration void handling. Moreover, the existing recovery algorithm utilizes a flooding approach in order to decide the detour path which causes high network overhead.

Pressure Routing Protocols have been described in detail with their strengths and drawbacks in the previous section. **Table 1** provides a complete comparison in the features of the protocols, which includes a summary of the major behaviors of all protocol discussed above. **This summarization is based on the dependent factors that are used to forward data including number of copies, number of next hops, whether they take advantage of opportunistic routing, reliability, whether the sender or receiver based and advantages/disadvantages.**

In the dissection of table 1, DBR [29] is the first pressure routing protocol which employs depth information only in order to find the next forwarder nodes. The first enhancement of DBR named DBMR [17] is a multihop depth based routing protocol which employs depth information with residual energy and assigned node IDs in order to find best single path towards the sink. Moreover, EEDBR [36] is another enhancement of DBR which utilize depth information with residual energy and calculates a priority value for each of the forwarder nodes. EEF [39] is also another enhancement of DBR which calculate a fitness value for each forwarder node using a new formula using residual energy and depth information. Unlike these protocols, HydroCast [40] and VAPR [41] utilize link quality for their void handling mode to finding a detour path as VAPR uses an enhanced beaconing in the first mode and employs a hop count and sequence number during forwarding process. Finally, AMCTD [42] employs a courier node with residual energy, depth and weight value in order to choose the next forwarding nodes. From this dissection, employing different parameters such as residual energy, link quality, hop count and node ID may have a direct effect on the performance of the network such as network lifetime, reliability, end-to-end delay and packet delivery ratio.

In routing procedures, the number of next hop nodes has a significant impact on the overall performance of the protocols. According to the number of next hop nodes, routing protocols can be split into two parts, multi-next hop and one-next hop. In the first part, a group of next hop nodes have been selected with positive progress towards the sink by protocols while taking advantage of opportunistic routing [29, 36, 38-42]. In an opportunistic technique, each sender node floods the packets to its neighbor nodes while taking into account that only neighbor nodes with positive progress towards the sink can participate in forwarding process in order to decrease communication overhead. The main disadvantage of this group is that multiple nodes forwards the same packets which causes high communication overhead. Moreover, a holding time is assigned to each next hop nodes in opportunistic techniques to forward the packets at different times and avoid forwarding same packets. This technique cannot prevent redundant data packet forwarding. In the

second part, DBMR [17] selects only one next hop node in order to decrease energy consumption and communication overhead. The main disadvantage of this group is that the number of retransmission packets has been increased due to high path loss in UWSNs which causes a large decrease in overall routing performance.

Based on the node that chooses the next forwarder node, routing protocols can be divided into two groups, namely, receiver based and sender based. In the first group, the receiving nodes can decide if it can forward the data packets or not [29, 39, 40, 42]. This approach suffers from redundant packet transmission during the routing process which causes high energy consumption. In the second group, the sender nodes decides the next forwarder nodes based on parameters such as residual energy [17, 36, 38, 41]. This approach significantly reduces the number for forwarding nodes which can balance the energy consumption between nodes and improves the networks lifetime.

Table 2 presents an overview of protocol performance (Energy Consumption, End-to-End Delay, and Data Delivery Ratio) based on their simulation results and communication method computation i.e. use of node ID and priority value, types of holding time, packet collision rate, processing time for the packets at each node, etc., **and Table 3 illustrates a number of simulation parameters such as simulator name, area, transmission range, node speed, bandwidth, data generation rate, energy consumption, single or multisink and node deployment/node movement.**

Table 1. Features and performance of Pressure based Routing Protocols in UWSNs

	Features									
	Protocols	**Factors**	**Single/ multiple copies**	**Number of next hop**	**Opportunistic**	**Sender based/ receiver based**	**Reliability**	**Advantages**	**Disadvantages**
Non-Void Avoidance Routing Protocols	**DBR [29]**	Only Depth	Multiple	Multi	Yes	Receiver based	NO	• Reduce cost (didn't use full location information). • Use multisink (reduce battery drain and high traffic)	• Use only one parameter (depth information). • Decrease network lifetime (using the same node many time as a next forwarder node). • High energy consumption (redundant packet transmission). • High end-to-end delay. • Communication void.
	DBMR [17]	Depth Node ID Residual energy	Single	One	No	Sender based	NO	• Reduce energy consumption (using single best path).	• Communication void (high packet loss). • Didn't use link quality. • Reduce throughput.
	EEDBR [36]	Depth Residual energy Priority value	Multiple	Multi	Yes	Sender based	NO	• Provide energy balancing (use residual energy with depth information) • High delivery ratio.	• Communication void. • Delay (adding list of forwarding along the packets). • Didn't use link quality.
	AEEDBR [38]	Depth Residual energy	Multiple	Multi	Yes	Sender based	NO	• Provide energy balancing (employ residual energy).	• Communication void. • Delay (adding list of forwarding along the packets). • Didn't use link quality.
	EEF [39]	Depth Residual energy Fitness value	Multiple	Multi	Yes	Receiver based	NO	• Less energy consumption. • Reduce end-to-end delay.	• Communication void. • Didn't use link quality. • Transmission of same packets (didn't update history of sent packets)
Void Avoidance Routing Protocols	**HydroCast [40]**	Depth Link quality	Multiple	Multi	Yes	Receiver based	NO	• Reduce end-to-end delay. • High delivery ratio. • Void handling (using recovery path).	• High energy consumption (repeating the process of finding detour path). • High overhead (using two hop neighboring nodes).
	VAPR [41]	Depth Hop count Sequence number Link quality	Multiple	Multi	Yes	Sender based	NO	• Reduce end-to-end delay. • Void handling (directional opportunistic data forwarding algorithm). • Use multisink (reduce battery drain and high traffic).	• High energy consumption (enhance beaconing).
	AMCTD [42]	Depth Courier node Residual energy	Multiple	Multi	No	Receiver based	Yes	• Reduce communication void (courier nodes). • High throughput.	• High energy consumption (extra use of hello packets). • High end-to-end delay (increase the waiting time).

Table 2. Performance Evaluation for Pressure based Routing Protocols in UWSNs

Protocols	Performance Evaluation		
	Energy Consumption	**End-to-End Delay**	**Packet Delivery Ratio**
DBR	High	High	Medium
DBMR	Medium	High	Medium
EEDBR	Low	Low	High
AEEDBR	Medium	Medium	Medium
EEF	Low	Medium	Medium
HydroCast	Medium	Medium	High
VAPR	Medium	Low	High
AMCTD	High	High	High

Table 3. Simulation Parameters for Pressure based Routing Protocols in UWSNs

Protocol	Simulator	Area	Trans. range (m)	Node Speed (m/s)	Bandwidth	Data generation rate	Energy Consumption				Sink	Node deployment/ Node movement
							Initial	Send	Rec.	Idle		
DBR	Ns2 (Aqua-Sim)	500 * 500 * 500 m^3	100	1-5	10 kbps	1 per second	n/a	2w	0.1w	10mw	Multi (fixed)	Random/ Random walk
DBMR	VC++	500 * 500 * 500 m^3	100	n/a	n/a	n/a	n/a	n/a	n/a	n/a	Multi (fixed)	Random/ Random walk mobility pattern
EEDBR	Ns2	n/a	250	n/a	n/a	1 per second	70 J	n/a	n/a	n/a	Multi (fixed)	Random and grid/ Random
AEEDBR	MATLAB	100 * 100 * 100 m^3	35	n/a	n/a	n/a	70 J / 110 J	n/a	n/a	n/a	Multi (fixed)	Random/ Random walk
EEF	Ns2 (Aqua-Sim)	500 * 500 * 500 m^3	100	1-10	10 kbps	2 per second	n/a	3w	3w	3w	Multi (fixed)	Random/ Random
HydroCast	Qualnet	1000 * 1000 * 1000 m^3	250	0.3	50 kbps	1 per 60 seconds	n/a	n/a	105 dB re µPa	n/a	Multi	Random/ Mobile
VAPR	Qualnet	1500 * 1500 * 1500 m^3	250	0.3	50 kbps	1 per 50 seconds	n/a	n/a	105 dB re µPa	n/a	Multi (fixed)	Random/ Mobile MCM model
AMCTD	MATLAB	500 * 500 * 500 m^3	100	n/a	n/a	1 per second	70 J	2w	0.1w	10mw	Multi (fixed)	Random/ Random walk

7. Future Work and Conclusion

7.1 Future Works

Energy efficiency in UWASNs is a major challenge due to the use of acoustic waves as a communication medium that consumes more energy than radio frequencies [35]. Therefore, it is essential to design and develop energy efficient routing protocols that balance the energy consumption between nodes and improve the networks lifetime. Moreover, a new energy algorithm should reduce the number of transmissions in order to reduce communication overhead and improve the networks lifetime. It should have some mechanisms that can convert other types of energy such as kinetic energy to electrical energy to supply the nodes with energy.

In UWSNs, instead of radio waves, acoustic waves are used as a communication medium. However, most popular network simulators such as QualNet [43], JSim [44], OMNeT++ [45] and NS2 [37] cannot utilize and support acoustic waves. Moreover, NS2 only supports 2D environments while the underwater environment is 3D in nature. Therefore, most of the existing simulators need to change some features and capabilities to support underwater environments. Also, other protocols use other simulators with different languages such as C++ and Matlab [46]. Therefore, it is necessary to develop a standard simulator for UWASNs in order to cover all of the underwater environment's features.

Due to the 3D nature of the underwater environment, the communication void problem is a major issue in pressure routing protocols [30]. However, the existing recovery algorithms in TWSNs are not applicable for use in UWASNs. Moreover, most of the existing void recovery techniques in UWSNs try to find the detour path between nodes by apply applying a flooding approach. Therefore, it is necessary to design a new recovery algorithm than has the ability to handle the communication void problem in underwater environments.

The high error prone nature of underwater wireless links is another major issue and a challenge in UWSNs [5]. The use of poor link quality in the process of transmitting the data packets leads to increased data packet loss [47, 48]. Thus, it requires retransmitting the data packets again. As a result, energy consumption and delays might be increased. Therefore, improving the mechanism of selecting reliable links with good link quality has a direct impact on reducing data packet losses, delays and energy consumption.

The existing routing protocols are mostly proposed to handle small-scale UWSNs. However, a number of specific applications require large-scale routing protocols. Therefore, it is very important to design a new routing protocol applicable for use in large-scale networks in UWSNs.

Secure communication between nodes is one of the main challenges in many UWSNs applications [49]. However, the existing routing protocols still fail to address this issue. As a result, designing a secure routing protocol for UWSNs with the ability to tackle security issues is encouraged.

7.2 Conclusion

The main idea for designing a new routing protocol is to take into consideration specific requirements and goals. The development of pressure based routing protocol for UWSNs is considered as a vital research area that will have a direct impact on the efficiency and reliability in these networks. In this paper we provide a comprehensive survey of the various pressure based routing protocols in UWSNs. We classify the pressure routing protocols according to void regions into two categories: **Non-Void Avoidance** and Void Avoidance. Moreover, we categorized **Non-Void Avoidance** based on a number of factors into two subcategories: Single Factor based Routing Protocols and Multi Factor based Routing Protocols. We provide an in-depth description of all pressure based routing protocols with their advantages and disadvantages. Furthermore, we present a comparison between these protocols based on their features. Also, a performance comparison of the most relevant routing protocols has been provided in terms of Energy Consumption, End-to-End Delay and Packet Delivery Ratio **followed by a table of simulation parameters comparing all pressure based routing protocols.**

The most promising goals for designing pressure routing algorithms is to embed security mechanisms, enhance reliability and improve the energy consumption of the networks. This full review of the protocols could contribute in a better understanding of the direction of current research on pressure based routing protocols for UWSN and is useful for the researchers for understanding the current issues and protocols in order to design more efficient and reliable pressure routing protocols.

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