



RE-PBR: A Reliable Energy-Efficient Pressure-Based Routing Protocol for UWSNs

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ABSTRACT

Recently, Underwater Wireless Sensor Networks (UWSNs) has witnessed significant attention from both academia and industries in research and development due to the growing number of applications for commercial, scientific, environmental and military purposes including pollution monitoring, tactical surveillance, tsunami warnings, and offshore exploration. Efficient communication among sensors in UWSNs is a challenging task due to the harsh environment and peculiar characteristics of UWSNs. Therefore, routing protocol design is one of the fundamental research themes in UWSNs for efficient communication among sensors and sink. In this context, this paper proposes a Location-Free Reliable and Energy Efficient Pressure-Based Routing (RE-PBR) Protocol for UWSNs. RE-PBR utilizes link quality, depth and residual energy information to balance energy consumption and reliable data delivery. In particular, link quality is estimated using triangle metric method. The performance of the proposed protocol is compared with the state-of-the-art techniques: DBR and EEDBR. The comprehensive performance evaluation attests the benefits of RE-PBR as compared to the state-of-the-art techniques in terms of energy consumption and packet delivery ratio.

Key words : energy consumption, link quality, routing, underwater wireless sensor network

1. INTRODUCTION

Recently, Underwater Wireless Sensor Networks (UWSNs) has received significant attention in research and development due to its wide range of applications for

commercial, scientific, environmental and military purposes. These applications include tactical surveillance, oceanographic data collection, seismic monitoring, assisted navigation, and pollution monitoring [1-3]. In UWSNs, usage of radio and optical signals has negative impacts on the network performance. Specifically, the usage of radio signals requires higher transmission power and larger antenna to propagate at longer distance with extra low frequencies. Usage of optical signals require higher precision for pointing the narrow laser beams and it also gets affected due to scattering [1, 4, 5]. Acoustic signals do not suffer from these limitations of radio signals. Therefore, acoustic signals are suitable as communication medium for UWSNs. However, the usage of acoustic signals in UWSNs has major challenges including limited bandwidth, longer propagation delay, and higher bit error rate [6, 7]. Moreover, sensor nodes in UWSNs contain limited energy in battery and replacement of batteries are very expensive due to the harsh environment of UWSNs [8, 9]. Thus, prolonging the overall network lifetime is a fundamental research theme in UWSNs [10, 11].

Due to the aforementioned challenges, routing protocols of terrestrial sensor network are not applicable in underwater networks, various routing protocols have been suggested for UWSNs [12]. These protocols can be broadly divided into two categories including location-based and location-free protocols. Location-based routing protocols requires complete location information about the network which is obtained by the sink using Global Position System (GPS). The harsh underwater environment and lack of synchronization reduces the applicability of location-based routing protocols in UWSNs. Therefore, location free routing protocols have witnessed more attention in UWSNs [13, 14]. The existing location free protocols suffers from the lack of effective combination of metrics resulting in selection of unstable link and higher energy consumer

nodes as next forwarder. Depth Based Routing (DBR) utilizes depth information without considering other parameters which result in selection of higher energy consumer nodes as next hop forwarder [15]. Energy Efficient Depth Based Routing (EEDBR) utilizes residual energy and depth information without considering the link quality of next forwarder resulting in wastage of energy in frequent path selection caused by unstable link selection [16].

In this context, this paper proposes a location-free Reliable and Energy-Efficient Pressure-based Routing (RE-PBR) protocol. RE-PBR utilizes three parameters, namely depth, residual energy and link quality to select next forwarding node. The major contributions of this paper are following.

- 1) Link quality calculation is derived with precise set of steps to select better quality link.
- 2) A light weight information acquisition algorithm is developed for efficient knowledge discovery in the network.
- 3) Data forwarding algorithm is designed by utilizing depth, residual energy and link quality parameters.
- 4) Realistic simulations are carried out in network simulation NS-2 with Aqua-Sim package for underwater environment.

The rest of this paper is organized as follows. Section 2.0 reviews routing in UWSNs by categorizing into location-based and location-free protocols. Section 3.0 introduces the proposed protocol RE-PBR. Section 4.0 discusses comparative performance evaluation of RE-PBR. Finally, section 5.0 concludes the work presented in this paper with some future research directions in the theme.

2. THEORETICAL

In this section, a qualitative review on routing protocols in UWSNs is presented. The routing protocols are classified into two classes including location-based and location-free routing protocols. In the next subsections, various routing protocols are reviewed in terms of major functional module, strengths and weaknesses.

2.1. Location-based

Xei et al. [17] provide a solution for one fundamental problem in Underwater Sensor Networks (UWSNs): robust, scalable and energy efficient routing. A Location-Based Routing Approach named Vector-Based Forwarding Protocol for Underwater Sensor Networks (VBF) was proposed. This protocol uses fix virtual pipeline from source nodes to the destination/sink (distance to the sink) in order to select the next forwarding nodes. Only nodes that located inside the pipeline can be selected as a forwarding node. However, this protocol

suffers from major disadvantages. VBF requires full location information of sensor nodes. Moreover, in sparse networks, the performance of the network is affected by the unavailability of sensor nodes in the predefined radius.

Nicolaou et al. [18] enhance VBF by designing an adaptive location-based routing protocol named hop-by-hop vector-based forwarding (HH-VBF). Different for VBF, this protocol employs virtual pipeline from sender node towards destination/sink with dynamic changeable pipeline based on nodes' position. However, HH-VBF also did not consider any residual energy and link quality metrics for selecting the next forwarding nodes. HHVBF solves the performance issue VBF in sparse networks by re-calculating the vector at each hop. However, HHVBF still needs an expensive full location information which is major issue in UWSNs environments.

2.1. Location-free

In this subsection, location-free routing protocols for UWSNs are reviewed. The protocols did not require full location information of the network from sink node. In [15], the first location-free routing protocol named as Depth Based Routing (DBR) has been suggested. DBR utilizes the depth information of sensor nodes as a major matric for forwarding process. The forwarding process in DBR as follows. The sender node calculates its depth and piggyback the depth information with data packet. The neighbor nodes which receive the data packets calculate their depth. After that the neighbor nodes compare their depth with the depth information attached in the data packets. The nodes with smaller depth than the depth of the sender node is eligible to participate in the forwarding process. Moreover, each node has specific holding time to hold data packets. More precisely, the node with smaller depth is the node with shorter holding time.

DBR utilizes only one matric for forwarding data packets. Therefore, the nodes having smaller depth are always involved in forwarding process. Considering this point, some nodes will die much earlier than other nodes. Thus, unbalancing energy consumption among nodes which creates routing holes or communication void in the networks. Moreover, DBR did not provide efficient next forwarding node selection due to the lake of consideration of energy and link reliability metrics. It uses depth information for forwarding and holding data packet. Furthermore, the number of redundant transmissions increases with the increase in network density due to the small differences between nodes' depths. In another word, some nodes send the data packets before overhearing the same packet from other neighbor nodes due to the expiration of holding time. This results in

redundant packet transmission, and thus, increase energy consumption.

In [16], authors have suggested an improvement of DBR named as Energy Efficient DBR (EEDBR) localization-free routing protocol. This protocol aimed at balancing energy consumption and improving network lifetime. Different from DBR, EEDBR is a sender-based routing protocol. The sender nodes choose neighbor nodes to forward data packets based on depth and residual energy. EEDBR is divided into two phases. In the first phase, all nodes broadcast Hello packet containing depth and residual energy information to their neighbor nodes. In the second phase, sender node selects a set of neighbor nodes based on their depth and residual energy to forward data packets. However, EEDBR has its downside as well. It does not handle the problem of communication void. Moreover, EEDBR utilizes only residual energy for selecting the next forwarding nodes and did not consider link quality metric.

In [19], a physical distance location-free routing protocol named as Reliable and Energy Efficient Routing Protocol (RERP2R) has been proposed as an extended version of Energy efficient Routing Protocol for UWSNs using Physical distance and Residual energy (ERP2R) presented in [20]. RERP2R aimed at improving the reliability between nodes by selecting the next forwarding nodes based on link quality. Thus, it utilizes a link reliability metric named as Expected Transmission count (ETX) [21] along with physical distance and residual energy. RERP2R consists of three phases; initialization phase, data forwarding phase and cost updating and maintenance phase. In initialization phase, sensor nodes share residual energy between neighbors and compute ETX and physical distance. Then, each node broadcast this information to their neighbors. At the end of this phase, each node has information about their neighbors in terms of physical distance, ETX and residual energy. In data forwarding phase, sender node selects the next forwarding nodes that is closer to the sink node with high residual energy and good link quality. In the last phase, physical distance between nodes is recalculated by broadcasting hello packets after a certain interval. The number of next hop count increases in dense networks resulting in higher energy consumption. Moreover, the use of only ETX as a link quality metrics is not efficient due to only packet delivery ratio.

In this paper, similar to DBR and EEDBR, depth information is utilized to distinguish between the lower and higher depth neighbors. However, our proposed protocol is different and beneficial from DBR and EEDBR. The difference and benefits are as follows.

1) DBR employs only depth information to select the next forwarding nodes. In addition, EEDBR balances energy consumption by utilizing one metric residual energy to select the next forwarder. In contrast, our proposed protocol employs residual energy metric along with link quality to select the energy efficient and reliable link among neighbors.

2) DBR uses holding time that all neighbors hold the data packet based on depth information, whereas EEDBR hold the data packet based on residual energy to choose the forwarding node based on energy information. In contrast, in our proposed protocol, only one node accepts the packet and forward it directly, whereas the sender nodes hold the packet for certain time which have direct impact on reducing the energy consumption, improving packet delivery ratio and prolonging network lifetime.

3. THE PROPOSED PROTOCOL

In this section, the proposed routing protocol RE-PBR is presented in detail including network architecture, link quality calculation, information acquisition phase and data forwarding phase.

[1] 3.1. Network Architecture

Fig. 1 below shows UWSNs' architecture used in most of related works. In this figure, all sink nodes are deployed at water surface connected to each other by radio frequency links. All ordinary sensor nodes are deployed randomly under water surface from top to bottom at different depths. It assumed that sink nodes are utilized with acoustic link (communication with underwater sensor nodes) and radio link (communication with sinks and data center). Sensor nodes send the data packets from source node to the sink/destination by relying the data packets through sensor nodes placed near to sink. More precisely, the sensor nodes placed at bottom of deployment region (higher depth) forward the data packet by moving the data packet through sensor nodes placed at top of deployment region (lower depth).

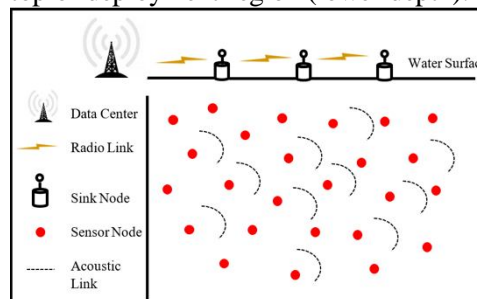


Figure 1: Standard Network Architecture

[2] 3.2. Link Quality Metrics

Link Quality estimator is one of the best criteria that have direct impact on the performance of minimizing the energy consumption, maximizing delivery ratio and

throughput. To our knowledge, only two protocols [19, 22] in UWSNs measure the Link Quality in their forwarding process which is based on calculating ETX between sender node and next forwarder node. Moreover, no one have been used Link Quality in depth-based routing protocols. For that purpose, our proposed protocol is the first depth-based routing protocol that measures the Link Quality. We have taken The Triangle Metric [23] into account out of many Link Quality estimators that haven't been tested yet in UWSNs. An important advantage of The Triangle Metric is that can obtain fast assessment, reliable estimation and minimizing traffic overhead. The Triangle Metric is a geometrically combination of the strength of PRR, SNR and LQI. The Triangle Metric is robust, quick and reliable estimation. Moreover, it obtains good result in both static and dynamic environments.

The Triangle Metric further is a combination of PRR, LQI and SNR in order to guarantee reliable and fast Link Quality estimation by calculating mean LQI and mean SNR. The formal equation of The Triangle Metric can be described as n packets with m successfully received packets where $(0 < m < n)$. The SNR and LQI for each successfully packet i are denoted by SNR_i and LQI_i . The sender node broadcast 10 probe packets in specific time to its neighbor nodes. After receiving the packets, the receiving nodes calculate mean SNR and mean LQI using the equations below:

$$\overline{SNR} = \frac{\sum_{k=1}^m SNR_k}{n} \quad (1)$$

$$\overline{LQI} = \frac{\sum_{k=1}^m LQI_k}{n} \quad (2)$$

The receiver node then calculates the distance to the origin (length of hypotenuse) characterized by a point $(\overline{SNR}, \overline{LQI})$ and the origin $(0,0)$ using the following equation based on equation (1) and (2):

$$\Delta d = \sqrt{\overline{SNR}^2 + \overline{LQI}^2} \quad (3)$$

Based on the calculated distance, the sender node estimates the Link Quality for the link between sender and receiver node on the base of large distance the best Link Quality. In our proposed protocol, each node computes the Link Quality based on The Triangle Metric for all of its neighbors in the table.

[3] 3.3. Information Acquisition Phase

In this phase, each node broadcast a hello packet periodically to its one hop neighbors after a specific time. This hello packet includes node ID, depth and residual energy as shown in Figure 2. After receiving the hello packets, each node extracts the depth information that embedded in the hello packet and compare it with its depth. It saves the information in its NIT if the depth that embedded in hello packets is less than receiver depth. Otherwise, it directly discards the hello packet. More precisely, each node collects information from its less depth neighbors and save it in its NIT. Once the node finish updating its NIT, each node calls the link quality algorithm to calculate the distance based the triangle metric for each neighbor in its NIT as mentioned in the previous section by broadcasting very small probe packets including node ID only. Finally, the distance for each node have been inserted in NIT and the information is sorted based on the highest distance the highest rank.

Node ID	Depth	Residual Energy
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Figure 2: Hello Packet format

At the end of this phase, each sensor nodes become aware of their neighbors' information such as depth, residual energy and distance based the triangle metric. Algorithm 1 describes Information Acquisition Phase in detail.

Algorithm 1 Information Acquisition Phase

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1:  procedure GenerateHello
2:    Add id, depth, residual energy to hello packet
3:    Broadcast (hello packet)
4:  end procedure
5:
6:  procedure ReceiveHello
7:    if |node.depth| > |hello packet.depth| then
8:      if hello packet.id not in node.table then
9:        add hello packet information to node.table
10:     else
11:       update information in node.table
12:     end if
13:     Call Link Quality based the Tringle Metric (node)
14:   else
15:     Drop (hello packet)
16:   end if
17: end procedure
    
```

[4] 3.4. Data Forwarding Phase

In this phase, data packets are forwarded from source node to the destination/sink. The next forwarding node should be closer to the sink, with high residual energy and

best link quality. All of the nodes that closer to the sink are eligible to forward data packets. However, and different from [19] that calculated minimum cost based on residual energy and ETX, we calculates The Route Cost based on residual energy and distance based the triangle metric to choose the next forwarding node. Therefore, the Route Cost can be calculated between two nodes (x,y) using Equation (4)

$$RouteCost = \left(1 - \frac{Re_y}{Re_{max}}\right) + \left(1 - \frac{\Delta d_{(x,y)}}{\Delta d_{max}}\right) \quad (4)$$

Where Re_y is the value of the residual energy of node y , Re_{max} is a total energy of a node, Δd_{max} is a system parameter value and set according to the environment i.e. we choose the max Δd after simulating different underwater scenario, $\Delta d_{(x,y)}$ is the Link Quality value of the link that computed between sender and forwarder nodes x, y . This equation calculates the route cost based on two different metrics, that is, residual energy and link quality. Based on Equation (4), it is expected that the node that placed at lower depth than sender with higher residual energy and best link quality will have minimum route cost. Thus, this node will be selected as a next forwarding node to forward data packets.

Fig. 3 shows how source node can select the next forwarding nodes. As seen from this figure, the data packets' forwarding process is as follows. The sender node (i.e., node a) firstly retrieve all neighbor's information from the neighbor information table (i.e., node b, c and d) and computes route cost based on Equation (4). The sender node then selects the nodes that have minimum routing cost. Given that (node c) is the minimum routing cost, node (c) is the best candidate node and it have been selected as a forwarder node. The sender then embeds the ID of the selected node with the data packets and then broadcast it to its one hop neighbors. Upon receiving the packet, the receiving nodes compares its ID with ID that embedded with the packets. Therefore, only the node that matches its ID with the ID that embedded with the packets accept the data packets, whereas it discarded by all remaining nodes. This process is continuously repeated until data packets reaches one of the sink nodes. In addition, the sender nodes tries to transmit the data packets with good link quality, but the link quality in UWSNs is not stable [12]. Therefore, is it possible that the data packets might not reach its destination/next forwarding node successfully because of packet loss.

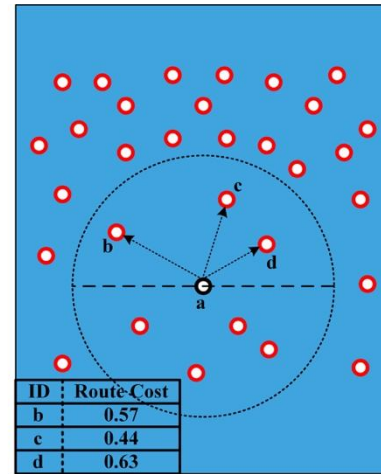


Figure 3: Next forwarding node selection

Our proposed protocol utilizes a sender overhear that it tries to overhear the data packets that transmitted by next forwarding node. Therefore, the sender node buffers the data packets for a certain time (i.e. in our simulation scenario we set 1s) and upon overhearing the same data packets from its receiving node, the forwarding node removes the data packets from its buffer. Otherwise, retransmission mechanism has been applied to retransmit the data packets again (i.e. in our simulation scenario we set 2 retransmissions). Algorithm 2 below shows our protocol's data forwarding phase.

Algorithm 2 data forwarding phase

```

1: procedure data forwarding
2:   if node.id = forwarding id in data packet then
3:     Calculate RouteCost for neighbors
4:   else
5:     Drop (data packet)
6:   end if
7:   Select forwarder based on min RouteCost
8:   Add node.id to data packet
9:   Broadcast (hello packet)
10:  If node overhear data packet then
11:    Drop (data packet)
12:  else
13:    Rebroadcast (data packet)
14:  end if
15: end procedure
    
```

4. PERFORMANCE EVALUATION

In this section, we present our protocol's performance evaluation. We compare our protocol against an existing pressure-based routing protocols called DBR and EEDBR.

[5] 4.1. Simulation Environment

In this subsection, we evaluate the performance of our proposed protocol using Network Simulator 2 (NS2) with Aqua-Sim package for underwater [24]. A random

topology with different number of sensor nodes have been performed (i.e. 25, 75, 100, 250 and 400) in deployed area of 1250m * 1250m * 1250m. In grid topology, the distance between each sensor nodes are fixed at 100m. The transmission range for both of topologies are set to 250m and the initial energy is set to 100 J. data packet generation time is set to 15s by each source node with 64 bytes fixed data packet size. We also set hello packet interval to 100s. Therefore, every 100s, depth and residual energy are shared among neighbors and distance based The Triangle Metric are calculated. In terms of energy consumption, we use the energy model that used in [17]. The total amount of energy consumption in terms of transmitting, receiving and idle listening is set to (2w, 0.75w and 8mw). We use the 802.11-DYNAV [25] as an underlying media access control protocol (MAC) and the result have been averaged from 50 runs for both topologies.

[6] 4.2. Performance Metrics

In order to evaluate the performance of our proposed protocol, we use major two metrics that have been used for most of well-known routing protocols in UWSNs. These metrics have been described below:

- 1)Energy Consumption: the total amount of energy that consumed by sensor node for the data packets that transmitted successfully.
- 2)Packet Delivery Ratio: the ratio of the successful data packets that reach the sink node to the number of data packets that transmitted by the sender node.

[7]4.3. Simulation Results

We measure the Energy Consumption for DBR, EEDBR and RE-PBR in this subsection and the result have been shown in Fig. 4. DBR didn't utilize any energy factor which only use depth Information for choosing the next forwarding node and it considered as a main reason for increasing the energy consumption continuously. Moreover, the redundant packet's transmission in DBR causes high energy consumption. Furthermore, the increasing of the number of nodes will increase the number of nodes that involved in forwarding process. This causes high energy consumption because it utilizes depth Information only. On the other hand, EEDBR consumes less energy consumption than DBR. This is because EEDBR utilize residual energy along with depth Information for choosing the next forwarding nodes. Moreover. EEDBR reduce the number of packet transmission and balance the energy consumption between nodes. In contrast, RE-PBR achieves better energy balancing and the energy consumption is totally reduced comparing to DBR and EEDBR for many reasons. RE-PBR employ single node to forward the data packets which avoid the redundant packets' transmission.

Moreover, our protocol utilizes Residual Energy metric with Link Quality metric which can balance the energy consumption between nodes with best Link Quality. Thus, based on all of these reasons, our protocol achieves lower energy consumption comparing to DBR and EEDBR.

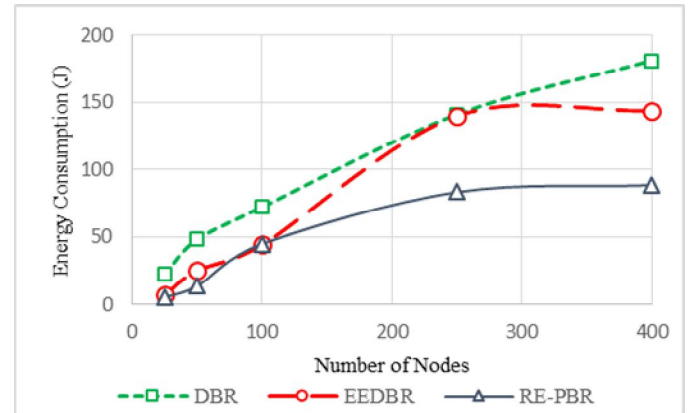


Figure 4: comparison of energy consumption Packet Delivery Ratio for DBR, EEDBR and RE-PBR have been shown in Fig. 5. The redundant packets' transmission in DBR make the data packets being transmitted using multipath which reduce packet loss and resulting in high delivery ratio in DBR comparing to EEDBR with a smaller number of nodes. But this way consumes more energy comparing to EEDBR. On the other hand, EEDBR obtain less delivery ratio with less energy consumption comparing to DBR because it provides energy balancing but didn't utilizing any link quality metrics. In contrast, RE-PBR achieves the highest packet delivery ratio using less expensive methods. Therefore, the use of retransmission mechanism helps in minimizing packet loss if the nodes didn't forward the data packets which leads to high packet delivery ratio. Moreover, RE-PBR utilize The Triangle Metric which obtain more reliable and stable links which resulting in reduce the packet loss and then resulting in high delivery ratio.

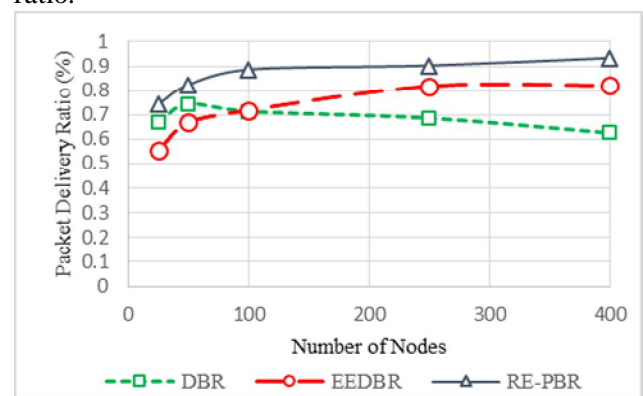


Figure 5: comparison of packet delivery ratio

5. CONCLUSION AND FUTURE WORK

In this paper, we proposed Reliable Energy-Efficient Pressure-Based Routing Protocol for UWSNs (RE-PBR). Our protocol is the first pressure routing protocol that take the Link Quality into account along with Residual Energy to choose the reliable and energy-efficient next forwarding node among neighbors. The use of Residual Energy helps in balance the energy consumption between nodes. The Link Quality helps in select most reliable links between sender and receiver nodes which can improve the delivery ratio. Thus, ER-DBR combines these factors to calculate the Route Cost. This Route Cost have been used to choose the next forwarding nodes. At the end, our protocol employs a sender overhear and retransmission mechanism to suppress redundant packet transmission and avoid packet lose.

We evaluate the performance of RE-PBR using NS-2 Simulator with Aqua-Sim package for underwater. Moreover, we compare it against DBR and EEDBR. Based on simulation results, RE-PBR achieves better result than DBR and EEDBR in terms of Energy Consumption and Packet Delivery Ratio. In Future Work, we are working on modifying The Triangle Metrics to combine more link quality metrics in order to obtain more stable and reliable links. Moreover, we are investigating the communication void in UWSNs and working in designing a void aware RE-PBR. Next, selecting the shortest path is another important issue that being taken into account for designing shortest path RE-PBR. Furthermore, delay sensitive is another important issue needs to be investigated in future works.

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