Green Computing in Underwater Wireless Sensor Networks: Pressure centric Energy Modeling

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***Abstract*—Underwater Wireless Sensor Networks (UWSNs) has witnessed significant attention from both industries and academia in research and development. This is due to the dynamic increasing of the high purpose wide range applications including scientific, commercial, military and environmental. Due to the peculiar characteristics and harsh environments of UWSNs, reliable efficient communication among sensor nodes towards the network coordinator or infrastructure is one of the major challenging tasks. Therefore, design and development of routing algorithms for effective communication among sensor nodes and base station is one of the vital research topics in UWSNs. In this context, this paper proposes a localization-free Shortest Path Reliable and Energy-Efficient Pressure-Based Routing (SPRE-PBR) protocol for UWSNs. SPRE-PBR considers three parameters including residual energy, pressure and link quality for selecting the next forwarding nodes. Moreover, SPRE-PBR is designed and developed to control path selection and reduce the unnecessary forwarding based on route cost calculation and optimal shortest path algorithm. The comprehensive performance evaluation attests the benefit of SPRE-PBR as compared with the state-of-the-art techniques considering underwater networking centric metrics.**

***Index Terms*—Green computing, energy efficient, pressure-based networking, underwater wireless sensor network.**

I. Introduction

Since the beginning of the universe, humans have lived on one-third of the earth and the other two-thirds have been covered with water. Compared to land, human knowledge about the underwater world is superficial. This is due to the effect of some natural phenomena such as high pressure and harsh underwater environments. Twenty years ago, when wireless networks became a very popular and attractive research area, researchers began to show interest in using these networks to explore and gather data from underwater environments [1-3]. Underwater Wireless Sensor Network (UWSN) has been proposed as a large collection of self-organizing and autonomous sensor nodes that communicate with each other and exchange information between them.

UWSN has been defined as a group of sensor nodes and vehicles deployed in underwater environments and networked via acoustic links. Sensor nodes are scattered randomly or manually in various depth to collect the data packet from shallow or deep water. The sensor nodes then transfer the data or packets via acoustic waves to the surface (sinks that are located on the water surface). In addition, an acoustic modem is used to allow ordinary nodes to communicate with each other. Moreover, sinks that are placed on the water surface have used both acoustic and radio modems to receive data from underwater sensor nodes via acoustic waves, then transmit the data to the base station by radio waves [4, 5]. UWSN can be used to serve wide range and large marine applications such as navigation military oversight, equipment monitoring disaster prevention, undersea exploration, environmental monitoring and oceanography [6]. Various aspects interest the researcher in the development in UWSN such as security, localization, and routing protocols.

In underwater environments, employing Wireless Sensor Network (WSN) has become the main challenge because the low radio frequency requires a large antenna and the high radio frequency can be rapidly absorbed in water. Additionally, the optical waves could be scattered, so they are not efficient in underwater environments [7]. The acoustic wave is used as a wireless communication medium that has a good performance in underwater environments. However, compared to a radio wave, the acoustic wave has deficiency characteristics such as low bandwidth, high path loss, high propagation delay and high energy consumption. Moreover, other challenges include the 3D nature of underwater environments, continuous and high movement of sensor nodes with water flow and inapplicability of dealing with Global Position System (GPS) [8]. These characteristics have posed many challenges especially in designing a suitable routing protocol in UWSN.

In UWSN, underwater nodes suffer from energy problem because these nodes are equipped with a battery as the only available power supply [9]. Compared to the Terrestrial Wireless Sensor Networks (TWSNs), energy consumption regarding transmission and reception in UWSNs has been increased due to the use of acoustic waves as a communication medium [10]. Thus, packet transmission and receiving consumes most of the energy in underwater sensor nodes. Routing in underwater sensor nodes is the major part that has the responsibility to forward and receive the data packets in the network [11]. Consequently, to achieve energy

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efficiency for each routing algorithm, some procedures must be taken into account. An energy efficient routing algorithm must be designed accurately to reduce the energy consumption and select the most energy efficient and reliable nodes [12].

In this context, this paper proposes a shortest path Reliable and Energy Efficient Pressure Based Routing (SPRE-PBR) protocol. SPRE-PBR is provided to select the shortest path and reduce the unnecessary forwarding using optimal shortest path selection in order to reduce the network overhead and improve the network lifetime. The key contributions of this paper are following.

1. A lightweight information acquisition algorithm is developed for efficient knowledge discovery in the network.
2. Optimal data forwarding phase is presented to select the reliable, energy efficient and closest node to the sink in each hop based on pressure information in underwater environments to reduce energy consumption and prolong overall network lifetime.
3. An optimal shortest path algorithm is developed to layer the forwarding area and to find the shortest path based on pressure information of the neighbors.
4. Simulations are carried out in Aqua-Sim package for realistic underwater scenario consideration.

The paper is organized as follows. Section 2 qualitatively reviews location-based and location-free protocols in UWSNs. Section 3 presents the detail of the proposed SPRE-PBR protocol. Section 4 discusses experiment and evaluation, followed by conclusion in Section 5.

II. Literature Review

Opportunistic Routing (OR) has been suggested to take advantage of the broadcast nature of the wireless medium [13]. Priority for each node has been determined based on its ability to act as a best forwarding node. However, broadcasting consumes higher energy [14]. Therefore, OR should be designed carefully to reduce the energy consumption and provide high packet delivery ratio. In location-based underwater routing, the next forwarding nodes have been chosen based on location provided by GPS [15]. However, nodes waste energy in location tracking of forwarding nodes. On the other hand, location-free routing protocols did not require full location information nodes. Location free methods can be further categorized into beacon-based and pressure-based protocols. In beacon-based protocols, each node needs partial information that has been provided by the sink to select the forwarder. However, exchanging this information imposes higher energy consumption and network overhead.

In contrast, pressure-based routing protocols consist of pressure sensors that measure the depth based on water pressure locally. Thus, each node, based on calculated depth, selects the next forwarder based on depth information [16]. These protocols reduce energy consumption and overhead in selecting forwarder. Optimum forwarding hop selection is one of the major problems that has a direct impact on increasing the number of retransmissions, and energy consumption [17]. Selecting the node that has less depth than the sender in transmission range is commonly used for handling the problem of reducing the number of transmissions [18]. The main disadvantage of this is the dependency on distance between sender and receiver node without considering other network parameters. Similarly, forwarding area has been layered and the path is chosen based on location and link quality [19]. However, Opportunistic pressure-based routing suffers from a lack of efficient shortest path selection. It leads to reducing the network lifetime and higher energy consumption.

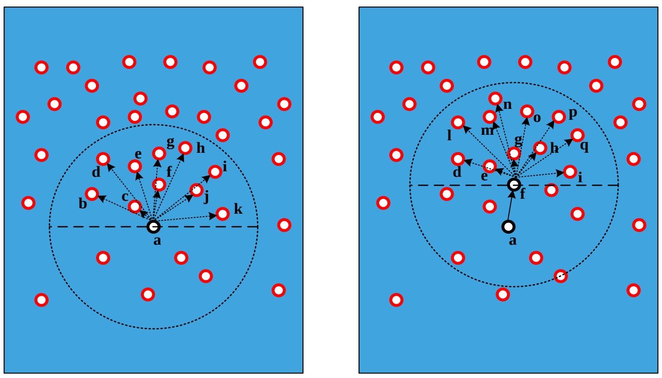
Depth Based Routing (DBR) has employed poor shortest path for handling the problem of constraint reduction [20]. It leads to consuming high energy for the selected node due to the lowest depth selection. An Energy Efficient Depth-Based Routing protocol (EEDBR) is another localization-free routing for underwater networking [21]. It has utilized the shortest path algorithm based on depth and residual energy. Similarly, HydroCast [22] and Void Aware Pressure Routing (VAPR) [23] have employed forwarding set reduction by ranking the neighbor nodes based on the distance within transmission range. The main disadvantage of the approach is the two-hop neighbor information via beacon messages resulting in high energy consumption. RE-PBR has calculated route cost based on residual energy and link quality without shortest path [24]. A vector-based data dissemination method has been suggested considering pipe dimensions in underwater network [25]. However, it has focused on vector formation majorly considering width of the pipe. The protocol is little away from the focus of our a depth-based layering of sensor nodes.

III. The Proposed SPRE-PBR

A. *Network Architecture*

UWSNs suffers from dynamic network topology because of the movement of nodes within the water environment. Therefore, network topology consists of normal and dense areas. It changes continuously due to the flow of water highly affected by winds and weather conditions in UWSNs environments. RE-PBR employs a reliable energy-efficient next forwarding nodes selection to select the node with the high residual energy and best link quality. In this algorithm, the node with minimum route cost and less pressure than the sender is selected as a forwarder node. This algorithm works inefficiently due to the dense area in pressure-based routing protocols. In RE-PBR, during forwarding process, it does not focus on pressure level of the eligible nodes. It uses depth information to identify the shallower neighbors and then selects the path based on route cost, ignoring the pressure level of nodes. This algorithm leads to increase the number of nodes involved in the forwarding process. As a result, the probability of a useless number of transmissions increases, especially in the dense area. Therefore, the number of forwarded data packet is increased, which causes high energy consumption, leading to reduce the network lifetime.

As presented in Fig. 1 (a), it is assumed that node (a) has a data packet to forward. Therefore, it calculates the route cost for all of its neighbors in Neighbour Information Table (NIT) that have ten neighbors. More precisely, the increasing of the number of the nodes in NIT leads to increase the chance of finding many nodes with best route cost. For example, in Fig. 1 (a), route cost of node *f* and *g* are equal to 0.43 and 0.44, respectively, and considered as the best route cost values in NIT. Therefore, node *a* then chooses node *f* as the best forwarder node based on minimum route cost. Next, it embeds ID of node *f* with the data packet and then broadcasts it to its one-hop neighbors. The sender node buffers the data packet for a specific time (i.e. simulation set parameter equals to 1s). If the sender overhears the data packet within this time, it directly removes the data packets from its buffer to avoid redundant packet transmission. Otherwise, retransmission mechanism has been applied for a specific time (i.e. simulation set parameter 2-3 retransmissions) to prevent packet loss.



b 0.58	e 0.53	h 0.55	
c 0.63	f 0.43	i 0.57	k 0.48
d 0.61	g 0.44	j 0.58	

(a)

d 0.55	h 0.49	l 0.57	o 0.48
e 0.52	i 0.51	m 0.65	p 0.51
g 0.42	j 0.61	n 0.46	q 0.66

(b)

Fig. 1. Inefficiency of path selection in RE-PBR

TABLE I
Notations and definitions used in SPRE-PBR proposal

u_i: i-th sensor nodes, $1 \leq i \leq N$, $data$: The data embedded in data packet
$bestCID$: ID of the best candidate node in NIT, id: Unique node ID
$reTime$: Generated retransmission time,
C: Number of candidate neighbours in NIT, $senderID$: ID of the sender
$Pressure$: Pressure level of node, re: Residual Energy of node
OC: Number of optimal neighbours, $bestC$: Best candidate node in NIT
NIT: Neighbour Information Table, AOC: Number of OC in $OCSet$
OSPA: Optimal Shortest Path Algorithm
$OCSet$: Set of optimal neighbours in OSPA
$CSet$: Set of optimal neighbours in data forwarding algorithm

Fig. 1 (b) illustrates the packet forwarding by node *f* as it is assumed that it received the data packet successfully from node *a*. As can be seen in this figure, node *g* and *n* are the best neighbors as its route cost value are equal to 0.44 and 0.46, respectively, out of twelve neighbors available in NIT of node *f*. Therefore, node *f* then chooses node *g* as the best forwarder node based on minimum route cost. Next, it embeds ID of node *g* with the data packet and then broadcasts it to its one-hop neighbors. As can be observed, path selection in RE-PBR cannot work efficiently, especially in the dense network topology. This is because the probability of a useless number of transmissions is increased with the increases in node density. For example, node *a* chooses node *f* as a next forwarder node. Node *f* then chooses node *g* as the best forwarder, whereas node *g* is also available in NIT of node *a* and has good route cost. As a result, the number of forwarder nodes has been increased in dense areas. Moreover, the number of forwarded data packets is increased, which causes high energy consumption, leading to reduce the network lifetime.

B. *Overview of SPRE-PBR*

In this section, the RE-PBR algorithm is enhanced to deal with optimum forwarding hop and to reduce the number of nodes in the forwarding process. The enhanced version of RE-PBR is named SPRE-PBR. To handle the problem of shortest path selection in an efficient way, reliable energy-efficient data forwarding algorithm used in RE-PBR is enhanced with modifying the optimal path selection algorithm. To this end, in SPRE-PBR, the shortest path selection algorithm is designed and developed efficiently to select the reliable, energy efficient and closest node to the sink in each hop based on pressure information, in order to suppress the useless transmissions. The aim of the SPRE-PBR routing algorithm is to reduce the energy consumption and prolong the network lifetime by suppressing the unnecessary transmission, and reduction of the number nodes involved in the forwarding process.

SPRE-PBR handles two main problems efficiently, namely next forwarding nodes selection and optimum forwarding hop. SPRE-PBR consists of two phases, namely, information acquisition phase and optimal data forwarding phase. The information acquisition phase in SPRE-PBR is the same as the first phase in RE-PBR algorithm. However, the second phase, namely, optimal data forwarding phase, is designed and implemented to select the optimal node based on pressure information in order to suppress the unnecessary transmissions and reduce the number of forwarding nodes involved in the forwarding process. We do agree that link quality is a potential parameter for traditional wireless networking. However, we believe that link quality is indirectly related with depth-oriented pressure parameter for underwater networking. Thus, the framework is focused on depth-oriented layering of sensors for identifying better next forwarder nodes while information dissemination in underwater networking environments. The novel contributions of the algorithm ranges from pressure-based optimal underwater node selection to reducing energy consumption indirectly.

C. *Design Approach of SPRE-PBR*

In this section, the SPRE-PBR algorithm is explained in detail. SPRE-PBR consists of two phases, namely, information acquisition and optimal data forwarding phase. This subsection is structured as follows. First, the table and packets used in SPRE-PBR have been described. Next, the information acquisition phase is discussed in detail. Finally, the optimal data forwarding phase is described in detail. Table 1 illustrated the notations used for designing the proposed algorithm in this subsection.

1. *Table and packet Format in SPRE-PBR*

The SPRE-PBR algorithm is designed to enhance the RE-PBR algorithm to deal with optimum forwarding hop problem. In this subsection, the Neighbour Information Table (NIT) and packets have been described in detail. The NIT is one of the major parts of the proposed algorithm. Each node stores the information of its one-hop up level neighbors that can help in routing the data packets. This information is acquired through the receiving hello packets during information acquisition phase. The NIT consists of five columns including *node ID*, *pressure information*, *residual energy, the distance based the triangle metric, route cost* (see Fig.2 (a)). The first three fields of neighbors are gained from the hello packet. Also, the value of the distance based the triangle metric is estimated based on link quality algorithm. The routing cost is calculated based on route cost algorithm using residual energy and link quality during data forwarding phase.

Node ID	Pressure	Residual Energy	Triangle metric distance	Route cost

(a)

Node ID	Pressure	Residual Energy

(b)

Packet header				
Sender ID	Forwarder ID	Packet Sequence Number	Source ID	Data

(c)

Fig. 2. Energy centric beaconing packet structure (a) neighbor information, (b) senders' hello information, (c) data reply information

The SPRE-PBR algorithm consists of two types of packets: hello and data packets. Hello packets are used periodically in information acquisition phase to share some information between neighbors without using location information. As shown in Fig. 2(b), The hello packet is composed of three fields: sender's ID, pressure information, and residual energy. Sender ID is used to determine the sender of the hello packet. Also, pressure information is used to identify the pressure value. If the hello packet is received from the node with higher pressure than the receiver node, it simply discards the hello packet. Otherwise, it extracts the information of this hello packet and saves it in NIT. Moreover, the residual energy is saved in NIT and used for route cost algorithm. Fig. 2(c) illustrates the data packet format used in the proposed algorithms. The data packet consists of two parts: packet header and data. The packet header is composed of four fields, called Sender ID, forwarder ID, packet sequence number and source ID. Sender ID is the unique ID of the sender node that has the data packet. Forwarder ID is the neighbor ID of the best selection for forwarding the data packet. Packet sequence number is the number assigned to the data packets in the source node. Source ID is the ID of the source node that generates the data packets. The last two fields are used to identify and count the data packets that are successfully forwarded or lost in the network.

2. *Information Acquisition Phase*

In this phase, similar to RE-PBR algorithm, each node identifies and exchanges specific information between its less pressure nodes. To this end, each node broadcasts a hello packet periodically to its one-hop neighbors. This hello packet includes node ID, pressure, and residual energy. After receiving the hello packets, each node extracts the pressure information embedded in the hello packet and compares it with its pressure. It saves the information in its NIT if the pressure that is embedded in hello packets is less than receiver pressure. Otherwise, it directly discards the hello packet. Once the node finishes updating its NIT, each node calls the link quality algorithm to calculate the distance based on the triangle metric for each neighbor in its NIT.

3. *Optimal Data Forwarding Phase*

In order to choose the optimal forwarder node due to unnecessary forwarding by neighbors, path selection algorithm should be enhanced. The shortest path algorithm is optimized through layering the forwarding area as an efficient criterion to improve the shortest path algorithm. This is because the use of layering criteria can reduce the forwarding area and reduce the number of eligible nodes in the forwarding process. Therefore, it is expected that the sender node selects the optimal forwarder node with minimum cost and lower pressure. Consequently, the number of transmissions are reduced, which causes low energy consumption and prolongs the network lifetime.

The data forwarding algorithm of RE-PBR is modified through enhancing its shortest path selection. In RE-PBR, each forwarder node selects the shallower node with minimum route cost based on residual energy and link quality. However, in SPRE-PBR, an optimal shortest path algorithm is designed and developed to layer the forwarding area and to find the shortest path based on pressure information of the neighbors. Algorithm 1 shows an optimal data forwarding algorithm in SPRE-PBR. As shown in this algorithm, the OSPA function (line 11) is called to reduce the number of eligible nodes and select the optimal forwarding set.

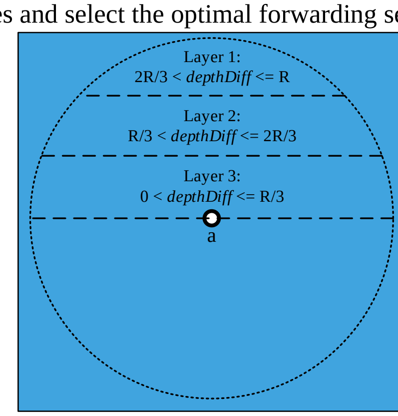


Fig. 3. Layering technique in OSPA

a) *Optimal Shortest Path Algorithm (OSPA) Design*

In this subsection, the design of optimal shortest path algorithm is discussed in detail. In the information acquisition phase, each node collects some valuable information of its neighbors and saves it in its NIT. Next, each node calculates the distance based the triangle metric for its neighbors and inserts to NIT. In the optimal data forwarding phase, the sender node calculates route cost for its neighbors based on link quality and residual energy and selects the next forwarding nodes based on the minimum route cost. The main problem in RE-PBR is that the selection of next forwarding node is based on residual energy and link quality without taking into account the position of the forwarder node, which increases the energy consumption and reduces the network lifetime by unnecessary transmission and increases of the number nodes involved in the forwarding process. To handle this issue, the transmission area should be layered. The reason of dividing into three layers is because the main goal of our algorithm is to select the closest sensor node to the sink taking into account route cost and density within transmission range. The layering techniques should be designed efficiently and carefully to keep packet delivery ratio high. Therefore, an optimal shortest path algorithm is designed in this phase to select the most reliable, energy-efficient and closest node to the sink in each hop based on pressure information to suppress unnecessary transmissions.

Algorithm 1: SPRE-PBR: Optimal data packet forwarding phase

Notations

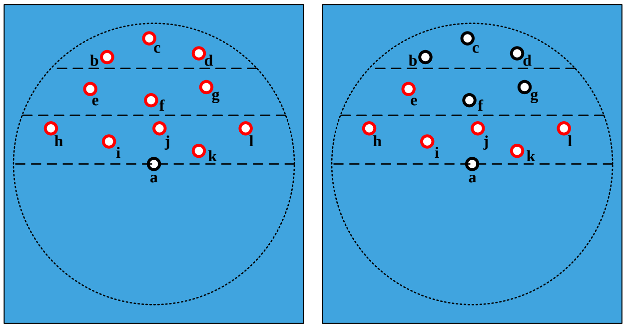
u_i: i-th sensor nodes, $1 \leq i \leq N$, $data$: The data embedded in data packet
id: Unique node ID, $bestCID$: ID of the best candidate node in NIT
C: The number of candidate neighbours in NIT, NIT: Neighbour Information Table
re: Residual Energy of node, $routcost$: The route cost field in the data packet
Δd: The triangle metric, OSPA: Optimal Shortest Path Algorithm
$CSet$: Set of optimal neighbours in data forwarding algorithm
$OCSet$: Set of optimal neighbours in OSPA, $bestC$: The best candidate node in NIT
$bestCID$: ID of the best candidate node, $reTime$: The generated retransmission time

procedure $OptimalDataForwarding\ (u_i\ , data)$
  if $id\ of\ u_i == bestCID\ in\ data\ packet$ **then**
    for $j = 1$ to C **do**
      $\boldsymbol{Compute}\ Route\ Cost(i,j) = (1 - \frac{Re_j}{Re_{max}}) + (1 - \frac{\Delta d_{(i,j)}}{\Delta d_{max}})$
      $\boldsymbol{Insert}\ Route\ Cost(i,j)\ to\ routecost$
      $\boldsymbol{Insert}\ routecost\ to\ NIT$
    end for
  Else
    Drop **(**$data$**)**
  end if
  $CSet = \boldsymbol{OSPA}(u_i)$
  for $j = 1$ to C **do**
    if $id\ of\ NIT\ is\ in\ OCSet$ **then**
      $\boldsymbol{Insert}\ routecost\ of\ NIT\ to\ bestC$
      $\boldsymbol{Insert}\ id\ of\ NIT\ to\ bestCID$
        if $routecost\ of\ NIT > bestC$ **then**
          $\boldsymbol{Insert}\ routecost\ of\ NIT\ to\ bestC$
          $\boldsymbol{Insert}\ id\ of\ NIT\ to\ bestCID$
        end if
    end if
  end for
  $\boldsymbol{Insert}\ bestCID\ to\ data\ packet$
  $\boldsymbol{Insert}\ id\ of\ u_i\ to\ data\ packet$
  $\boldsymbol{GenerateReTime}\ (data)$
  $\boldsymbol{Broadcast}\ (data)$
  if $u_i\ overhear\ data\ packet$ **then**
    $\boldsymbol{Drop}\ (data)$
  else
    $\boldsymbol{Broadcast}\ (data)$
  end if
end procedure

The transmission area in the opportunistic routing algorithms is the upper hemisphere of the sender node. In optimal shortest path algorithm, to layer the transmission area, this area is divided into three layers based on transmission range of the forwarder node. Fig. 3 illustrates how the transmission area of each forwarder node is split into three layers. The number of layers actually decides appropriateness of the next hop sensor node. However it adds additional computational complexity in next hope decision making process. We have considered three layers of design approach for next-hop sensor node selection focusing on the realistic impact of the division of transmission range of tiny sensor nodes on the depth-based energy requirement of data dissemination path via possible next hop sensor node. Communication range (R) is the key factor used to layer the transmission area. However, the maximum communication range is considered as a determining factor of the maximum transmission area. Therefore, the layering has been designed from top to down of transmission area as follows. ${2R}/{3} < Layer\ 1 \leq R$, ${R}/{3} < Layer\ 2 \leq {2R}/{3}$ and $0 < Layer\ 3 \leq {R}/{3}$, respectively.

Each node calls the optimal shortest path algorithm. For example, u_i has data to send. First, optimal shortest path algorithm counts the number of nodes in NIT. If the counted number is less than a predefined threshold, the number of eligible nodes are kept the same. This is because the density are low and minimizing the number of eligible nodes may cause packet loss. In addition, if the counted number is greater than or equal to the threshold, the density is high, and the number of eligible nodes needs to be reduced. Therefore, the number of eligible nodes is set to the threshold. At the end of this stage, the number of optimal candidate nodes (i.e., OC) of node u_i is identified. Next, the OC nodes should be chosen among candidate nodes (i.e., C) of node u_i. To this end, an optimal shortest path algorithm chooses the ID of OC neighbor nodes among C neighbor nodes from layer 1 to 3.

The nodes that are placed in upper layer have more chance than the nodes placed in lower layer. Moreover, if there is more than one node in the selected layer, the nodes are chosen based on route cost calculated; the minimum route cost node is the highest priority nodes. OSPA utilized this way for identifying the optimal nodes for a number of reasons. First, the nodes that are placed in the higher layer (i.e., layer 1) have the lowest depth and are closer to the sink than other candidate neighbors, which reduces the number of forwarder nodes, the number of hop counts and further decreases the energy consumption. Second, the nodes in each layer have been chosen based on minimum route cost, because the route cost has been calculated based on multi-metrics, which are residual energy and link quality, to select the most reliable and energy-efficient among neighbors. Third, if the number of candidate nodes is less than the threshold, the number of optimal candidate forwarder nodes becomes equal to the number of candidate nodes and these nodes have been chosen from higher layers. As a result, the nodes that are closer to the sink (i.e., shortest path) with minimum route cost have been selected to forward the data packet in order to suppress unnecessary transmissions. In case of void or no sensor nodes in the three layers, a periodic data transmission attempts are performed after some interval time towards updated scenario.



ID	Route Cost	ID	Route Cost	ID	Route Cost
b	0.44	f	0.53	j	0.43
c	0.48	g	0.57	k	0.58
d	0.61	h	0.55	j	0.55
e	0.58	i	0.63		

OCSet = {}, AOC=0, OC=0, C=11, Threshold =5
C >= Threshold, then OC=Threshold=5

Layer 1: OCSet = {b}, AOC = 1, AOC < OC
OCSet = {b,c}, AOC = 2, AOC < OC
OCSet = {b,c,d}, AOC = 3, AOC < OC
Layer 2: OCSet = {b,c,d,f}, AOC = 4, AOC < OC
OCSet = {b,c,d,f,g}, AOC = 5, AOC = OC

Return OCSet = {b,c,d,f,g}

(a) NIT of node a (b) Optimal Candidate Set Selection of node a

Fig. 4. OSPA optimal candidate set selection

b) Optimal Shortest Path Algorithm (OSPA) Implementation

Algorithm 2 illustrates how OSPA selects the optimal candidate nodes based on predefined layers. This algorithm is consisting of one function and one procedure. First: function *OSPA* (line 13-35) is designed to select a set of optimal nodes among candidate neighbors of node u_i. It starts by identifying the number of optimal candidate that may be selected among neighbors that are available in NIT of node u_i based on a predefined threshold. Then, it starts to select the optimal candidate from the highest layer (i.e., layer 1) towards the lowest layer (i.e., layer 3) until the number of optimal candidates becomes equal to a predefined threshold. Second, procedure $LayerSelection$ (line 1-12) is called by function *OSPA* in order to select the candidate nodes based on their route cost from selected layer and then insert them to the set of optimal candidate nodes if the number of nodes is still not equal to predefined threshold.

Algorithm 2: SPRE-PBR: Optimal Shortest Path Algorithm (OSPA)

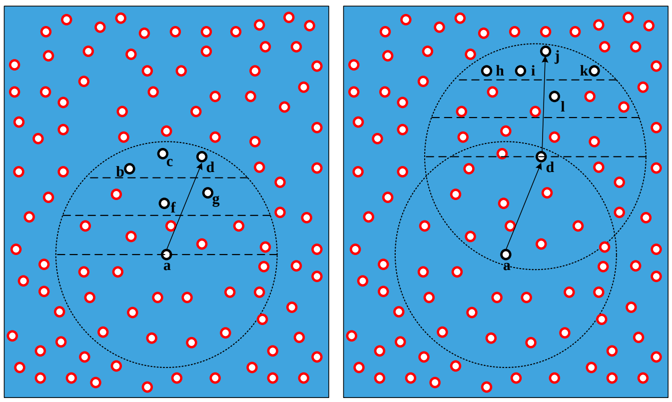
Notations

R: Transmission Range, C: The number of candidate neighbours in NIT
OC: Number of optimal neighbours, id: Unique node ID
AOC: number of OC available in $OCSet$, $Pressure$: Pressure level of node
$PressureDiff$: The difference between Pressure level of sender and receiver node
u_i: i-th sensor nodes, $1 \le i \le N$, NIT: Neighbour Information Table
$OCSet$: Set of optimal neighbours in OSPA, $routcost$: route cost field in data packet
$Threshold$: The maximum number of the optimal candidate set

1: **procedure** $LayerSelection(u_i, R1, R2, OC, AOC, OCSet)$
2: $j \leftarrow 1$
3: **while** $j \le C$ and $AOC < OC$
4: ***Compute*** $pressureDiff = pressure\ of\ u_i - pressure\ of\ NIT$
5: **if** $R1 < pressureDiff \le R2$ **then**
6: ***Add*** $AOC + 1$ to AOC
7: ***Insert*** id of NIT to $OCSet[AOC]$
8: **end if**
9: $j \leftarrow j + 1$
10: **end while**
11: **end procedure**
12:
13: **function** ***OSPA*** (u_i)
14: **Sort** NIT based on $routecost$ in ascending order
15: **Let** $OC = 0$
16: **if** $C > Threshold$ **then**
17: ***Insert*** $Threshold$ to OC
18: **else**
19: **if** $C \le Threshold$ **then**
20: ***Insert*** C to OC
21: **end if**
22: **end if**
23: **Clear** $(OCSet)$
24: **Let** $AOC = 0$
25: **if** $AOC < OC$ **then**
26: $LayerSelection\,(u_i, \frac{2R}{3}, R, OC, AOC, OCSet)$
27: **end if**
28: **if** $AOC < OC$ **then**
29: $LayerSelection\,(u_i, \frac{R}{3}, \frac{2R}{3}, OC, AOC, OCSet)$
30: **end if**
31: **if** $AOC < OC$ **then**
32: $LayerSelection\,(u_i, 0, \frac{R}{3}, OC, AOC, OCSet)$
33: **end if**
34: **return** $OCSet$
35: **end function**

Fig. 4 provides an example of OSPA in data forwarding process. As shown in Fig. 5(a), it is assumed that node *a* is a sender node. This node has eleven shallower neighbors in its NIT, namely nodes {*b, c, d, e, f, g, h, i, j, k, l*} with (*C=11*). To forward the data packet using shortest path, node (a) calls the OSPA function to select the optimal candidate node. These nodes are sorted based on route cost value. Moreover, the threshold value is set to 5 (i.e., the maximum number of the optimal candidate set). Fig. 4(b) illustrates how node *a* selects the optimal candidate set among its candidate neighbors. First, node *a* identifies the exact number of optimal candidate (i.e., OC) neighbors that should be inserted into optimal candidate set. Given that C is equal to 11 and greater than the predefined threshold, the size of optimal candidate set is equal to the threshold (i.e., OC=5). Next, it selects the optimal candidate neighbors among candidate neighbors from the highest toward the lowest layer. The selection of the nodes starts from layer 1. Three nodes exist in this layer, which are nodes {*b, c, d*}, where the route cost of node *b* is lower than that of node *c* and node *d*. Therefore, node *b* is selected first and inserted into optimal candidate set (i.e., OCSet= {*b*}), and the number of candidate nodes in the optimal candidate set is increased to 1 (i.e., AOC=1).

Since the number of optimal candidate nodes in the optimal candidate set is less than the exact number of optimal candidate neighbors (i.e., AOC < OC), and node *c* has lower route cost than node *d*, node *c* is selected and inserted into OCSet (i.e., OCSet= {*b, c*}) and the value of AOC is increased to 2. Since the number of optimal candidate nodes in the optimal candidate set is less than the exact number of optimal candidate neighbors (i.e., AOC < OC), node *d* is selected and inserted into OCSet (i.e., OCSet= {*b, c, d*}) and the value of AOC is increased to 3. Given that AOC < OC and there are no more candidate neighbors in layer 1, the selection of optimal neighbors is moved to layer 2. Three nodes are available in this layer i.e., nodes {*e,f,g*}, where the route cost of node *f* is lower than that of node *e* and node *g*. Thus, node *f* is selected and inserted into optimal candidate set (i.e., OCSet= {*b*, *c*, *d*, *f*}), and value of AOC is increased to 4. Since the number of optimal candidate nodes in the optimal candidate set is less than the exact number of optimal candidate neighbors (i.e., AOC < OC), and node *g* has lower route cost than node *e*, node *g* is selected and inserted into OCSet (i.e., OCSet= {*b*, *c*, *d*, *f*, *g*}) and value of AOC is increased to 5. Since AOC and OC have the same value equal to 5, OSPA is stopped and returns the optimal candidate set, OCSet to the optimal data packet forwarding algorithm.



(a) **(b)**

Fig. 5. The optimal data packet forwarding in SPRE-PBR

Since a sender node has a data packet to send, it uses an optimal data packet forwarding algorithm. In this algorithm, an OSPA function is called to select the optimal candidate forwarding set. Fig. 5 illustrates an example of the optimal data packet forwarding in SPRE-PBR. The threshold value is set to 5 (i.e., each node selects maximum 5 nodes as a candidate forwarding set by calling OSPA function). As shown in Fig. 5(a), node *a* is a forwarder node. Therefore, it calls OSPA function to select the optimal candidate set among its neighbors in NIT. The exact number of nodes that should be selected among neighbors is set to 5, because the number of neighbors is more than a predefined threshold, which are nodes {*b*, *c*, *d*, *f*, *g*}. Node *a* then retrieves the nodes' ID that is placed in the optimal candidate set and selects node *d* among these five nodes because it has the minimum route cost among them, and is considered as an optimal shortest path towards the sink. As illustrated in Fig. 5(b), node *d* calls OSPA to select the optimal candidate set, which are nodes {*h*, *i*, *g*, *k*, *l*}. Then, node *b* selects the optimal candidate node among the optimal candidate sets which is node *j* based on its position to the sink and minimum route cost. Next, it updates the data packet by adding the ID of the optimal candidate node i.e., node *j* and broadcasts it. This process is repeated until data packet reaches the sink.

IV. Performance Evaluation

A. *Simulation Sitting*

This section provides a brief explanation of the simulation framework that has been used in this study in order to simulate the proposed algorithms using Aqua-Sim. Aqua-Sim is an underwater supportive package that is attached in NS-2 and works in parallel with Communication Management Unit (CMU). Moreover, Aqua-Sim provides real and accurate simulation result due to the employment of underwater MAC protocols and acoustic channel in MAC layer and physical layer in Aqua-Sim. Therefore, similar to DBR and RE-PBR, Aqua-Sim over NS-2 has been selected as a standard simulator in this study. Regarding benchmark, in this study, DBR [20], EEDBR [21] and RE-PBR [24] have been considered among existing pressure-based routing algorithms. The proposed SPRE-PBR algorithm is compared with DBR algorithm, which is considered as a standard energy-efficient and reliable opportunistic pressure-based routing algorithm. DBR is used as a benchmark by researchers in existing algorithms. Moreover, EEDBR employs reliable energy-efficient next forwarding node selection based on residual energy. Therefore, EEDBR has been selected along with DBR to compare them with SPRE-PBR algorithm. On the other hand, RE-PBR has been selected along with DBR and EEDBR that is the latest existing depth-based algorithm that can deal with next forwarding nodes selection.

The performance evaluation of the proposed algorithm in this paper is built based on standard variables and settings that are applied and employed in experiments based on most related algorithms. A 3-D network model architecture is used as a mobile 3-D architecture as deployed in [24]. Communication range is set to 250*m*. Moreover, a different number of underwater wireless sensor nodes (50-400) in 3-D area size of 1250*m* * 1250*m* * 1250*m* in random topology has been used. On the other hand, the horizontal movement speed of nodes is 0-3 *m/s*, whereas the vertical movement speed is negligible [10]. Moreover, a different number of sinks is set based on the number of nodes (3-7) is deployed on the water surface to receive the data from underwater sensor nodes via acoustic waves and forward it to the base station via radio waves. The hello packet interval is set to 100*s*. Therefore, exchanging hello packet information such as pressure and residual energy among neighbors is done each 100*s*. The source node generates a data packet in application layer with the size of 64 *bytes*. The acoustic speed is equal to 1500 *m/s* whereas the bandwidth is considered equal to 10*Kbps*. The initial energy of sensor nodes is set equal to 100*J*. Also, the amount of total energy consumption regarding transmission, receiving and idle is considered equal to 2*w*, 0.75*w*, and 10*mw*, respectively. Moreover, the Broadcast MAC protocol is used as an underlying MAC protocol. The MAC layer interference is handballed effectively in our Aqua-Sim based simulations where every node maintains a local copy of incoming packets and collision of packets are identified using the difference in received power levels locally. Therefore, the effect of collision only remains on local copies of a node and does not impact the copies of other nodes. The results have been averaged from 50 runs to increase the accuracy of the simulation results. Lastly, simulation time is set to 1500*s*. it is highlighted that the experimental area considered for carrying out simulations is based on the number of different simulation environment settings including number of underwater nodes, movement speed, total simulation time, number of message exchange and size of messages. We believe that for our simulation environment settings the 3D network area of 1250mX1250mX1250m was large enough for carrying out the simulations. Table III illustrates the simulation set up parameters used in this study.

In contrast, the proposed algorithm and the existing algorithms are developed using a C++ programming language in network layer in Aqua-Sim as a formal routing protocol. Next, different simulation scenarios have been developed using TCL programming language. Then, results have been extracted from trace files using AWK script language and these results are saved in a normal text file. Lastly, Matlab and X-graph are used to extract the final result from the extracted text file.

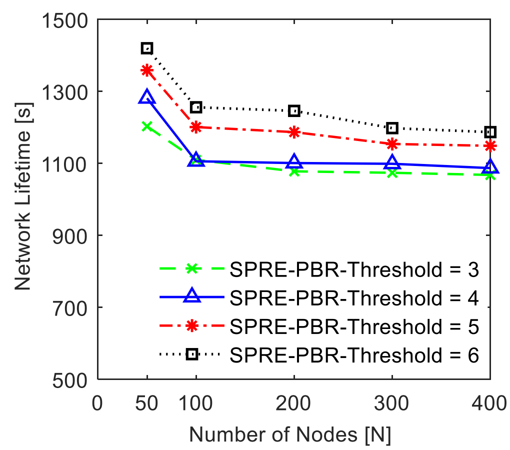
TABLE III
Simulation parameters

Simulation Parameter	**Value**
Network Topology	Random
Deployment Area (in meter)	1250*m* * 1250*m* * 1250*m*
Number of Sinks	3 – 7
Number of Nodes	25 – 400
Transmission Range (in meter)	250 *m*
MAC Protocol	Broadcast MAC
Initial Energy (in Joule)	100 *J*
Communication Medium	Acoustic Waves
Bandwidth (in Kilobits per second)	10 *Kbps*
Signal Velocity (in meter per second)	1500 *m/s*
Node Movement	0 – 3 *m/s*
Energy Consumption (in watts)	2*w*, 0.75*w* and 10*mw*
Data Packet Size	64 *byte*
Hello Packet Interval (in second)	100 *s*
Simulation Time	1500 *s*
Number of Runs	50

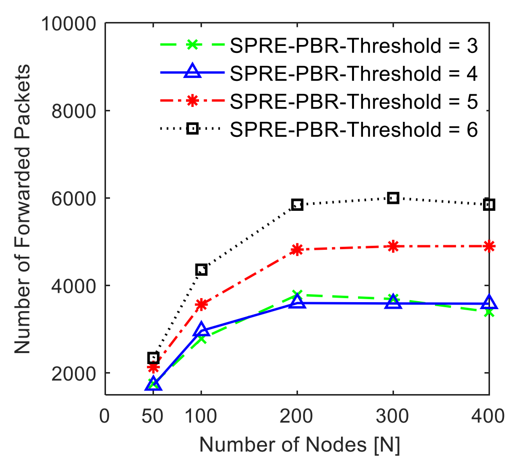
B. SPRE-PBR: Performance Evaluation and Comparison

In order to evaluate the performance of the SPRE-PBR algorithm, several experiments have been conducted. As mentioned earlier, the SPRE-PBR algorithm can deal with two main issues in opportunistic pressure-based routing protocols, namely next forwarding nodes selection and optimum forwarding hop. Therefore, different scenarios are conducted to evaluate the performance of SPRE-PBR. In these experiments, four different scenarios have been employed in OSPA algorithm by increasing threshold value (i.e., 3 to 6). These tests have been evaluated with increasing the number of nodes (i.e., 50 to 400) in terms of network lifetime, energy consumption, packet delivery ratio and the total number of data packets forwarded. The impact of increasing the number of nodes in the SPRE-PBR is provided as it can handle the selection of next forwarding nodes and optimum forwarding hop in terms of network lifetime, energy consumption, the total number of data packets forwarded and packet delivery ratio. Therefore, SPRE-PBR is compared with the well-known related pressure-based routing algorithms, which are DBR, EEDBR, and RE-PBR. In this test, the residual energy and link quality are set with the same rate in route cost calculation. Threshold value is set to 4 in OSPA in data forwarding phase.

The impact of changing the threshold value of SPRE-PBR on the network lifetime is shown in Fig. 6(a). The result indicates that the network lifetime is slightly increased with increasing the threshold value. Moreover, the network lifetime with a small threshold value (i.e., 3 and 4) decreases in comparison with a higher threshold value. This is because when the threshold value is small, the optimal candidate set is small. Therefore, the probability of selecting the same nodes increases, which leads to increasing the energy consumption of the nodes that are placed in the higher layers. As a result, the network lifetime is decreased. In contrast, when the threshold value is high (i.e., 5 and 6), the network lifetime is almost at the same level. For instance, in an SPRE-PBR algorithm with threshold 5 and 6, the network lifetime in 50 nodes is increased slightly, approximately 2 %, whereas the network lifetime with increasing the number of nodes (i.e., 200-400) is approximately 8 %, which is much higher than the lower threshold (i.e., 3 and 4). This is because an optimal number of nodes has been involved in the candidate set and the probability of high residual energy is increased and the selection of the candidate nodes still from the upper layers. As a result, the use of threshold value 5 is fair enough for improving the network lifetime. This is because the number of optimal candidate nodes becomes fair sufficient to save the network lifetime, by selecting the shortest path with a high probability of selecting the shortest path with high residual energy and best link quality.



(a)

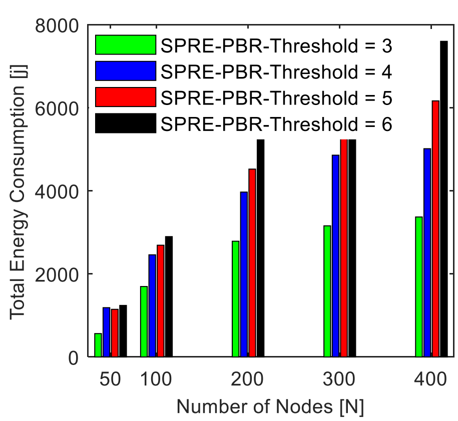


(b)

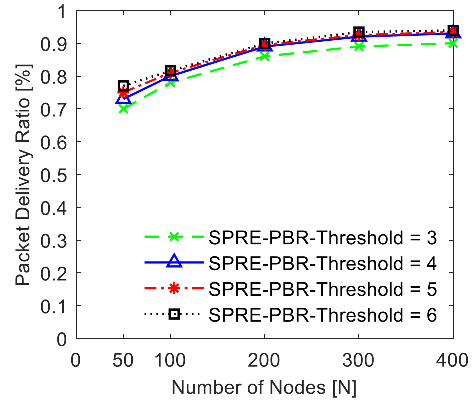
Fig. 6. Effect of changing threshold (a) network lifetime (b) forwarded data

Fig. 6(b) demonstrates the impact of increasing the number of nodes with changing threshold value in terms of the total number of forwarded data packets. The illustrated result indicates that with increasing the threshold value, the total number of forwarded data packets is dramatically increased. This is because threshold value has the main responsibility for setting the number of the optimal candidate set. Therefore, with increasing the threshold value, the probability of selecting the optimal nodes as the next forwarding node closer to the sender node rather to the sink increases. As a result, the number of forwarded data packets is increased. For instance, with a higher number of nodes (i.e., 300), the total number of forwarded data packets with different threshold values (i.e., 3, 4, 5 and 6) are 3691, 3589, 4896 and 5999.

In contrast, the number of forwarded data packets with a threshold value equal to 3 is decreased compared to the threshold value 5 and 6. This is because with increasing the number of nodes, the probability of selecting the optimal nodes from top layers is high. Therefore, the efficiency of finding the shortest path with minimum route cost is increased, and the number of hops is further decreased. On the other hand, with a threshold value equals to 4, the total number of forwarded data packets is increased with increasing the nodes density (i.e., 100-200) and it slightly lower if the number of nodes is more than 200. Therefore, the probability of selecting the nodes from all layers is slightly higher since the number of neighbors becomes high. As a result, the efficiency of OSPA algorithm is reduced, which leads to increase the total number of forwarded data packets. Moreover, with increasing the number of nodes to 400, there are more neighbors. Thus, the probability of finding the shortest and reliable energy-efficient node from the upper layers is highly increased, resulting in reducing the number of data packets forwarded. Furthermore, with increasing the value of the threshold to 5 and 6, the efficiency of OSPA algorithm is dramatically reduced. Therefore, the number of optimal candidate set could be selected from lower layers, which results in increasing the total number of forwarded data packets as compared with SPRE-PBR with the threshold value set to 4. Therefore, from both the results in Fig. 6, it can be concluded towards optimally selecting the threshold value to enable effectively longer lifetime as well as larger number of forwarded packets.



(a)



(b)

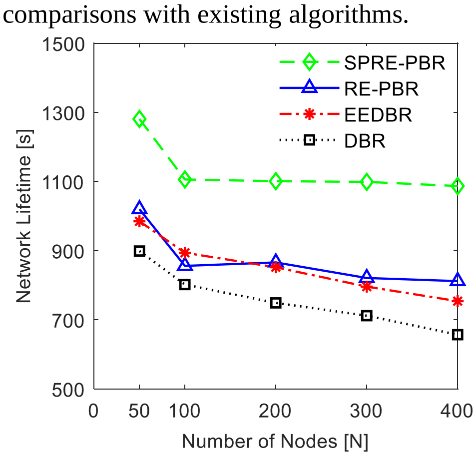
Fig. 7. Effect of changing the threshold value (a) energy consumption, (b) delivery ratio

Fig. 7(a) demonstrates the impact of changing the threshold value in SPRE-PBR in the total energy consumption. The obtained results indicate that with increasing the threshold value, the total energy consumption is increased. This is because SPRE-PBR uses a threshold value to determine the number of the optimal candidate set. Therefore, with increasing the threshold value, the number of the optimal candidates set are incremented, leading to increasing the number of forwarded data packets and further increase in energy consumption. For instance, with increasing the number of nodes (i.e., 300-400), the total amount of the energy consumed with threshold values 3-6 are equal to 3156, 4856, 5846 and 6698 J and 3369, 5012, 6163 and 7596 J, respectively. More precisely, by setting the threshold value to 6, the energy consumption is increased around 45 % more that the low threshold values (i.e., 3 and 4).

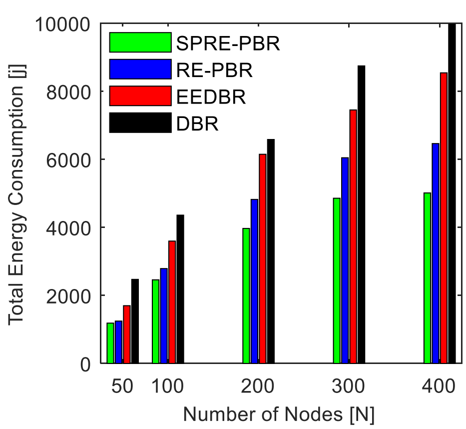
As mentioned above, the total energy consumption is dramatically increased with increasing the number of nodes in most of the threshold values. The main reason is that once increasing the number of nodes, the number of forwarded data packets is increased, resulting in increasing the amount of consumed energy. On the other hand, by increasing the number of nodes, the total energy consumption is significantly reduced by reducing the threshold value (i.e., 3). This is because the total number of forwarded packets are reduced, whereas the total energy consumption is dramatically increased by increasing the threshold value (i.e., 5 and 6). As a result, the energy consumption is highly affected by the threshold value. For instance, with different threshold values (i.e., 3-6), the total amount of energy consumed with setting the number of nodes equals to 50 are 562, 1186, 1146 and 1240 J, respectively. Moreover, the total amount of energy consumed with setting the number of nodes equals to 400 are 3369, 5012, 6163 and 7596.

The impact of changing the threshold value in SPRE-PBR in the packet delivery ratio is illustrated in Fig. 7(b). The illustrated results indicate that the packet delivery ratio is slightly increased with increasing the threshold number. In lower density, the packet delivery ratio is highly increased with increasing the threshold value, whereas the packet delivery ratio is slightly increased with increasing the number of nodes. On the other hand, once setting the threshold value to 4, 5 and 6, the obtained packet delivery ratio has almost the same values, while their network lifetime and energy consumption are different. For instance, when the number of nodes is equal to 300 and the threshold value 4, 5 and 6, the packet delivery ratio is about 92.5%, whereas their network lifetime is 1099, 1154 and 1198, respectively, and the total energy consumption is 4856, 5846 and 6698, respectively. In contrast, when the threshold value is equal to 3, the packet delivery ratio is the lowest compared to higher threshold values. The reason is that the optimal forwarding hops is too short, especially in the low-density network, which leads to packet loss. As a result, the packet delivery ratio is decreased.

In addition, with taking into account the network lifetime, energy consumption and packet delivery ratio, the best threshold value is the value of 4. This is because by setting the threshold value to 4, the packet delivery ratio is almost the same as threshold values 5 and 6, whereas the packet delivery ratio is better than packet delivery ratio with a threshold value equals to 3. Moreover, by setting the threshold value to 4 , the network lifetime is a little bit lower than threshold values 5 and 6, whereas network lifetime is lower with the threshold value equals to 3. Furthermore, the energy consumption with threshold values 4 and 3 are significantly lower than the amount of energy consumed with higher threshold values. As a result, in the next sections, the threshold value is set to 4 for further comparisons with existing algorithms.



(a)



(b)

Fig. 8. Comparison of (a) network lifetime, (b) energy consumption

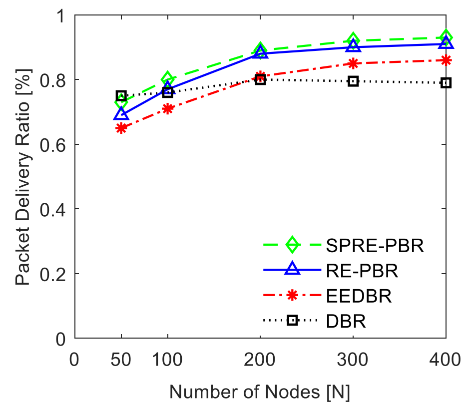
Fig. 8 (a) demonstrates the impact of increasing the number of nodes in DBR, EEDBR, RE-PBR and SPRE-PBR in terms of network lifetime. The illustrated result proves that SPRE-PBR performs highest network lifetime significantly compared to the other algorithms. This is because route cost calculation utilizes residual energy to balance the energy consumption and link quality that can optimize the network lifetime. Moreover, the use of layering in OSVA algorithm helps in selecting the shortest path taking into account the route cost for each node, which leads to reduce the energy consumption and further improves the network lifetime. Therefore, the data packets reache the sink using shortest path with balancing the energy consumption. As a result, the network lifetime is totally improved.

As shown in Fig. 8(a), the network lifetime is decreased with increasing the number of nodes in DBR, EEDBR, and RE-PBR. This is because DBR employs depth information only to select the shortest path without taking into account residual energy, thus the nodes with the highest depth is always selected, leading to finish its energy soon and then reducing the network lifetime. EEDBR obtains higher network lifetime than DBR by utilizing the residual energy in selecting the next forwarding node, but it has lower network lifetime compared to RE-PBR and SPRE-PBR. This is because EEDBR suffers from a lack of short path selection, leading to increasing the number of hops and further reducing the network lifetime. On the other hand, RE-PBR obtains higher network lifetime than DBR and EEDBR and lower than SPRE-PBR. This is because RE-PBR uses route cost mechanism for selecting the shortest path. In contrast, SPRE-PBR obtained more stable network lifetime with increasing the number of nodes compared to other algorithms. This is because OSPA algorithm with all number of nodes can work efficiently by selecting the shortest path without ignoring the energy of nodes. As a result, the energy is balanced by utilizing the residual energy, the number of hops is reduced by using link quality and layering the forwarding area. Therefore, the network lifetime is increased.

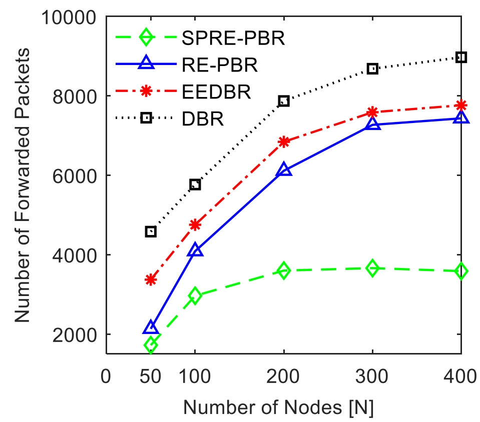
Fig. 8(b) demonstrates the effect of increasing the number of nodes on the total energy consumption. As shown from the result, the amount of energy consumed is increased in the DBR, EEDBR, and RE-PBR algorithms with increasing the number of nodes. The illustrated result shows that SPRE-PBR performs lower energy consumption compared to DBR, EEDBR, and RE-PBR. This is due to two reasons. First, SPRE-PBR employs route cost calculation based on the residual energy and link quality that can select the energy efficiency and reliable node among neighbors, whereas DBR selects the next forwarding node based on the depth information only and EEDBR selects the next forwarding node based on the residual energy only. Second, the OSPA algorithm in SPRE-PBR helps in reducing the energy consumption compared to RE-PBR. This is because reducing the number of optimal candidate nodes leads to the decreasing number of forwarded data packets, which leads to reducing the energy consumption. For instance, with the number of nodes equals to 200, the energy consumption of SPRE-PBR is about 41%, 29% and 11% less than DBR, EEDBR, and RE-PBR, respectively.

As mentioned previously, the amount of consumed energy is increased in the DBR, EEDBR, and RE-PBR algorithms with increasing the number of nodes. Nevertheless, the energy consumption in SPRE-PBR is slightly increased compared to DBR, EEDBR, and RE-PBR. This is because the use of layering in OSPA algorithm helps in selecting the optimal and reliable energy-efficient candidates set among the neighbor nodes, leading to decreasing the number of forwarded data packets. As a result, the data packets forwarding is optimized for sparse and dense networks with slight increasing in the energy consumption. However, the total energy consumption in DBR and EEDBR dramatically increase with increasing the number of nodes. This is because these algorithms do not handle optimum forwarding hop. For instance, DBR does not employ residual energy, while EEDBR does not balance the energy efficiently and does not provide any solution for selecting the shortest path among the neighbors. RE-PBR slightly increases the energy consumption compared to SPRE-PBR. This is because it balances the energy consumption using residual energy and link quality. However, it does not provide any solution for selecting the shortest path among the neighbor nodes. Therefore, the number of nodes that joins the forwarding process is increased with increasing the number of nodes, leading to increasing the total number of forwarded data packets and further increasing the total energy consumption. For example, the total amount of energy consumed by setting the number of nodes to 100 for DBR, EEDBR, RE-PBR and SPRE-PBR is about 4359, 3597, 2789 and 2458, respectively, whereas by setting the number of nodes to 400, the total energy consumption is about 9968, 8541, 6463 and 5012, respectively.

Fig. 9(a) shows the impact of increasing the number of nodes in SPRE-PBR in packet delivery ratio and compare it with DBR, EEDBR, and RE-PBR. The obtained result indicates that the packet delivery ratio increases with increasing the number of nodes in DBR, EEDBR, RE-PBR and SPRE-PBR. However, DBR increases slightly with the increasing number of nodes. DBR obtains almost the same packet delivery ratio. This is because, with increasing the number of nodes, the number of candidate nodes increases due to the lack of efficient forwarding algorithm. Moreover, holding time calculation is not efficient because it bases on the depth information only and it is a receiver based routing approach, leading to increasing unnecessary forwarding. As a result, the probability of packet loses is high. On the other hand, SPRE-PBR obtains highest packet delivery ratio compared to other algorithms. This is because SPRE-PBR works efficiently with success packet delivery by employing link quality in route cost calculation and reliable energy-efficient short path selection. For instance, in route cost calculation, the selection of the node with high residual energy and best link quality, leads to balance the energy consumption, obtain stable links and ensure data packets delivery. The optimal shortest path algorithm is to select the shortest path and suppress the unnecessary forwarding, leading to reduce the total number of forwarded data packets with a reasonable packet delivery ratio.



(a)



(b)

Fig. 9. Comparative study (a) packet delivery ratio (b) forwarded packets

As illustrated in Fig. 9(a), the packet delivery ratio by setting the number of nodes to 100, SPRE-PBR improves about 6%, 11% and 4% compared to DBR, EEDBR, and RE-PBR, respectively. Also, increasing the number of nodes to 400, the packet delivery ratio for SPRE-PBR is about 93.6%, meaning that, SPRE-PBR obtained higher packet delivery ratio than DBR, EEDBR, and RE-PBR with 14%, 7%, and 3%, respectively. Moreover, the illustrated result indicates that RE-PBR obtained high packet delivery ratio and almost near to SPRE-PBR, whereas SPRE-PBR in the same scenario, obtained approximately 31% less energy consumption than RE-PBR.

Fig. 9(b) demonstrates the impact of simulating a different number of nodes for DBR, EEDBR, RE-PBR and SPRE-PBR in terms of the total number of forwarded data packets. The illustrated result, shown in Fig. 9(b), proves that SPRE-PBR performs lower forwarded data packets than the DBR, EEDBR, RE-PBR algorithms. This is because the OSPA algorithm controls the number of optimal candidate nodes efficiently by layering the sending area and selecting the efficient shortest path that is closer to the sink taking into account its residual energy and link quality. Therefore, the data packet reaches to the sink using shortest path and reliable energy-efficient node, as well. As a result, fewer hops are used in forwarding process taking into account energy balancing and quality of the links.

From the result shown in Fig. 9(b), the total number of forwarded data packets increases with increasing the number of nodes in DBR, EEDBR, and RE-PBR. The reason is that DBR employs depth information only to select the shortest path without taking into account other metrics and EEDBR select the next forwarding node based on the residual energy, leading to increasing the number of hops and further increasing the number of forwarded data packets, while RE-PBR utilizes residual energy and link quality for selecting the shortest path. However, with high-density networks, the efficiency of selecting the best forwarding nodes is lower, leading to increasing the number of forwarded data packets. On the other hand, SPRE-PBR obtained almost the same as the forwarded data packet with a different number of nodes (100 to 400), but it increases in low density (50 to 100). This is because with fixing the predefined threshold, with fewer nodes, the number of optimal candidates and the number of neighbors is low, leading to select the optimal nodes from all layers. Thus, the number of forwarded data packets increases by the increasing the probability of selecting the best nodes placed closer to the forwarder than the sink and then increasing the number of hops. Also, with increasing the number of nodes (high-density network), the number of neighbor nodes to be selected as an optimal candidate group increased. The probability of selecting the optimal candidate set from the upper layers is higher, thereby reducing the number of hops, the unnecessary forwarding and further reducing the number of forwarded data packets. On average, the total number of forwarded data packets is about 51%, 33%, and 21% less compared to DBR, EEDBR, and RE-PBR.

V. CONCLUSION AND FUTURE WORK

In this paper, a Shortest Path Reliable Energy-Efficient Pressure-Based Routing protocol for underwater wireless sensor networks has been presented. The optimal data forwarding algorithm for selecting the next optimal forwarding node significantly enhances the performance of SPRE-PBR in terms of higher network lifetime, durable packet delivery ratio, lower end-to-end delay and energy consumption, when compared with the state-of-the-art techniques. Optimal shortest path algorithm reduces network overhead, which results in significance performance improvement of the routing protocol in UWSNs. In future, authors will enhance path selection algorithm in UWSNs focusing on recent alternative technologies such as Visible Light Communication (VLC) and Free-Space Optics (FSO) for underwater networking.

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