Energy Efficient Opportunistic Routing Protocol (EE-OR) for Underwater Wireless Sensor Network

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Abstract. The surface of the earth consists of 71 percent water. In recent years, research has focused on using underwater sensor networks (USN) to monitor and manage these aqueous environments. Research on the communication protocols in Terrestrial sensor networks (TSN) has been well investigated and various protocols proposed. In contrast with terrestrial wireless sensor networks, the characteristics of acoustic communication lead to challenges in deploying fully functional and operational USNs. In our proposed architecture, we present a new energy efficient opportunistic routing protocol (EE-OR). The proposed protocol is a novel energy-efficient opportunistic routing algorithm for USNs. The protocol deals with the issue of ranking of nodes during candidate set selection while reducing energy consumption and keeping the packet delivery ratio at a satisfactory level. In order to evaluate the performance, we used two common metrics that have been used for routing protocols in USNs; energy consumption and packet delivery ratio. Simulations were carried out in NS-2 with Aqua-Sim. The performance of the proposed protocol is compared with the standard DBR protocols. The comprehensive performance evaluation attests the benefit of EE-OR as compared to the mentioned protocol in terms of energy consumption, end-to-end delay and packet delivery ratio.

1. Introduction
The surface of the earth consists of 71 percent water. However, most of the underwater environment remains unexplored due to its vastness and harsh environment. In the last decade, there have been significant interests in monitoring the underwater environments for scientific, commercial exploration and military operations. These applications range from aquiculture monitoring, environmental monitoring, disaster prevention, oil extraction monitoring, and tactical surveillance [1, 5, 11, 13]. In recent years, companies and governments has focused on using underwater sensor networks (USN) to monitor and manage these aqueous environments. With the cost of sensors dropping and the development of smart sensors, USN offers an alternative method to better sense and acquires these data.

Terrestrial sensor networks (TSN) have been well investigated and research conducted on the communication protocols have been proposed and reported often. However, the characteristics of USN differ to that of the TSN. In USN, a number of autonomous and self-organizing sensors nodes are deployed at different depths to collect information and forward them to a destination. Groups of sensor nodes are anchored to the bottom of the ocean. Others sensor nodes act as a relay to one or more sinks.
nodes by means of wireless links. When deployed in an underwater environment, the channels attenuation or loss of signal for electromagnetic waves is 45 times the square root of the frequency decibels per kilometer. Even though optical waves do not suffer from high attenuation, the problem of scattering still affects them [16]. Therefore, in contrast with terrestrial wireless sensor networks, USN uses acoustic communication, where the attenuation is several magnitudes lower and no occurrence of scattering effects [14].

The characteristics of acoustic communication lead to challenges in deploying fully functional and operational USNs [4, 5]. First, the acoustic communication channel is severely impaired, especially due to multipath and fading. Second, acoustic communication operates below 30 kHz, thus the available bandwidth is limited depending on both range and frequency due to absorption. Third, acoustic communication experiences high bit error rate and temporary losses of connectivity. Forth, unlike electromagnetic communication, the propagation delay is five times magnitude higher than radio frequency in TSN. Fifth, an underwater sensor networks require 100 times more power when transmitting data, as compared to the power required when receiving it [10]. Consequently, USN nodes needs to reserves energy consumption to prolong the network lifetime. Lastly, USN has to contend with mobile nodes either due to their dynamical capability or due to random motion caused by ocean currents [6, 11, 12].

An underwater sensor network consists of many autonomous and individual sensor nodes that perform forwarding, storing and collecting data. The main issues involved is deploying USN are the cost, computational power, memory, communication range and limited source of energy at each individual sensor node. The main energy source of USN are batteries, and since the replacement of the batteries are in harsh underwater conditions, the process becomes challenging and expensive [8, 15]. Over time, the number of sensor nodes that expire due to energy loss increases, which in turn decreases the USN coverage area.

An underwater sensor node consumes more energy when transmitting a packet compared to when receiving one [2]. In order to reduce energy consumption, the number of unnecessary transmissions needs to be reduced. Energy efficient routing protocols developed for TSN cannot be applied directly to underwater sensor networks. One possible solution to overcome these problems is by implementing appropriate routing algorithm adapted to underwater environments. Recently, opportunistic routing (OR) has been proposed as an alternative routing protocol. Opportunistic routing protocols are able to handle issues associated with USN [3]. The protocol is the preferred method with use in USNs compared to other as it guarantees higher data rate [7].

Therefore, the main goal of this research is to propose a novel energy-efficient opportunistic routing algorithm for mobile USNs in order to deal with the issue of ranking of nodes during candidate set selection and communication void while reducing energy consumption of nodes and keeping the packet delivery ratio at a satisfactory level.

2. Methodology

In our proposed protocol, energy efficient opportunistic routing (EE-OR), two types of nodes are deployed i.e. sink node and ordinary/sensory node. Sink nodes are equipped with both acoustic modem and RF modem while ordinary node contains an acoustic modem only. In sink nodes, the acoustic modem is used to communicate with ordinary nodes while RF modem is used for communication between two sink nodes or from sink node to onshore data centre. In ordinary nodes, the modem is used to communicate with each other and with sink nodes.

Energy metrics is one of the best criteria that have direct impact on the performance of minimizing energy consumption, maximizing delivery ratio and throughput. The metrics updates the routing protocol on which forwarder node has an impact its battery life. The transmission and reception energy for a packet may always be same for all nodes in the network but the impact of this energy consumption on life or residual energy of each node and life of network will not always be same. For example, suppose that the residual energy of two nodes \(N_1\) and \(N_2\) is six units and three units, respectively. In addition, the depth of the next hope from \(N_1\) is greater than that of \(N_2\). A single unit of
energy consumption cost 50% of residual energy for \( N_1 \) and for \( N_2 \) it is 20%. In this scenario, the node \( N_1 \) will die only after two transmissions. In order to identify these types of impacts on the lifetime on the network, energy scarceness metrics is performed.

To calculate energy scarceness, the concept of residual energy of each node is used. The scarceness \( SC_{Ni} \) on residual energy \( RE_{Ni} \) of a sensor node \( Ni \) calculated over energy consumption \( EC \):

\[
SC_{Ni} = \frac{EC}{RE_{Ni}}
\]  

(1)

\( SC_{Ni} \) prevents the depletion of the whole energy of a node. For example, given earlier suppose a source node (S) broadcast the packet to \( N_1 \) and \( N_2 \) (neighbours of S). After receiving the packet, \( SC_{Ni} \) for transmission is computed. According to the above example \( SC_{Ni} \) cost of transmission for both \( N_1 \) and \( N_2 \) are 0.3008 and 0.88 respectively. Even though the depth of node \( N_1 \) is lower, but \( SC_{N1} \) is less than that of \( SC_{N2} \), it will become the forwarder, and forward the packet first. If we choose \( N_2 \) as a forwarder because of depth it will drains out of its energy sooner, decreasing the network lifetime.

To compute \( SC_{Ni} \) for all energy consumption in a node and the network, Energy Depletion (ED) metrics has been formulated. ED metric contains the following components:

- \( SC_{Ni} \) cost of transmitting data
- \( SC_{Ni} \) cost of receiving data
- The estimated \( SC_{Ni} \) cost of retransmission
- \( SC_{Ni} \) cost of acknowledgement
- \( SC_{Ni} \) cost of idle.

The ED for each node \( Ni \) is computed using the following equation:

\[
ED_{Ni} = \frac{E_{txNi} + E_{rxNi} + E_{transNi} + E_{ackNi} + E_{idleNi}}{RE_{Ni}}
\]  

(2)

Each term in this equation is given in detail as below:

- \( E_{txNi} \) : SC cost of the node \( Ni \) used in broadcasting the \( k \)-bit data packet from \( Ni \) to its’ forwarders using transmission power,

\[
E_{Trans} (n,1) = \begin{cases} n.E_{R.\text{elec}} + n.E_{R.f\cdot t^2} & \text{if } l < l_0 \\ n.E_{R.\text{elec}} + n.E_{R.\text{amp}} & \text{if } l \geq l_0 \end{cases}
\]  

(3)

and is given by the following formula:

\[
E_{txNi} = \frac{E_{Trans}}{RE_{Ni}}
\]  

(4)

- \( E_{rxNi} \) is the SC cost of the node \( Ni \) used in receiving a \( k \)-bit data packet from source or other nodes receiving power,

\[
E_{Receive} (n) = n.E_{\text{elec}}
\]  

(5)

and is given by the following formula:

\[
E_{rxNi} = \frac{E_{Receive}}{RE_{Ni}}
\]  

(6)
$E_{\text{re\_tx\_Ni}}$: is the SC cost of retransmitting a packet to its forwarders using transmission power $E_{\text{Trans}}$ and receiving power $E_{\text{Receive}}$. This transmission and receiving cost has been combined into a single energy cost denoted as,

$$E_{\text{Forward}}(n,1) = E_{\text{Trans}}(n,1) + E_{\text{Receive}}(n)$$

$$= \begin{cases} 
2nE_{R\_elect} + nE_{R\_f,s}l^4 & \text{if } l < l_0 \\
2nE_{R\_elect} + nE_{R\_amp}l^4 & \text{if } l \geq l_0 
\end{cases}$$

(7)

This cost is given by the following formula:

$$E_{\text{re\_tx\_Ni}} = \frac{E_{\text{Forward}}}{RE_{\text{Ni}}}$$

(8)

- $E_{\text{ack\_Ni}}$: is the SC cost of the node $N_i$ in broadcasting the k-bit acknowledgement packet from $N_i$ using transmission power $E_{\text{Trans}}$ and is given by the following formula:

$$E_{\text{ack\_Ni}} = \frac{E_{\text{Trans}}}{RE_{\text{Ni}}}$$

(9)

- $E_{\text{idle\_Ni}}$: is the SC cost of the node $N_i$ in idle mode using idle energy consumption

$$E_{\text{idle}} = P_{idle} \cdot t_{idle}$$

(10)

and is given by the following formula:

$$E_{\text{idle\_Ni}} = \frac{E_{\text{idle}}}{RE_{\text{Ni}}}$$

(11)

Other forwarder nodes in the forwarder list of source node will follow similar process. The forwarder with the minimum value of ED will be the candidate who forwards the data packet first and rest of all nodes in forwarder list will wait for acknowledgement from this node.

In the information acquisition phase, each node broadcast a hello packet periodically to its one hop neighbours after a specific time. This hello packet includes node ID, depth and residual energy as shown in Figure 1. After receiving the hello packets, each node extracts the depth information that embedded in the hello packet and compares it with its depth. It saves the information in its neighbour table (NT), if the depth that is 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 neighbours and save it in its NT. Once the node finish updating its NT, each node will call the ED to calculate the energy metrics for each neighbour in hello packets is less than receiver depth. Otherwise, it directly discards the hello packet. Finally, the energy metrics for each node have been inserted in NT and the information is sorted based on the lowest ED will rank highest. At the end of this phase, each sensor nodes become aware of their neighbours’ information such as depth, residual energy and energy metrics.

| Sender ID | Depth | Residual Energy |
|-----------|-------|-----------------|
| **Figure 1.** Hello packets |

In the data-forwarding phase, data packets are forwarded from source node to the destination/sink. The next forwarding node should be closer to the sink, with best ED value. All of the nodes that closer to the sink are eligible to forward data packets. The data packets’ forwarding process is as follows. The sender node, $N$, firstly retrieve all neighbour’s information from the neighbour table (i.e., node 1, 2 and
3). The sender node then selects the nodes that have minimum ED. Given that node 2 has the minimum
ED, node 2 is the best candidate node and will be 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 neighbours. Upon
receiving the packet, the receiving nodes compare 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, whereas it discarded by all remaining nodes. This process is continuously repeated until data packets reach one of the sink nodes. In the event that nodes that have the same ED value, the node with a lower depth will get priority forward the data.

3. Results and Analysis
In order to evaluate the performance of our proposed protocol, we use three metrics that have been used
for most of well-known routing protocols in USNs. These metrics have been described below:

- Energy Consumption: the total amount of energy that consumed by sensor node for the data
packets that transmitted successfully.
- 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.
- Total Number of Forwarded Data Packet: the total number of forwarded data packet shows the
efficiency of ranking algorithm and overhear and suppression algorithm. The total number of
forwarded data packet is defined as Equation 12, where N is the number of underwater nodes and
$N_d_{Tx_i}$ represents the number of forwarded data packet by the $i$-th node

$$\text{numFwdDataPkt} = \sum_{i=1}^{N} N_d_{Tx_i}$$  \hspace{1cm} (12)

To evaluate and validate the performance of introduced routing algorithms, the proposed routing
algorithms, EE-OR and benchmark algorithms (i.e., DBR) are developed using C++ language as a
routing protocol in network layer of AquaSim (ns2) with the same simulation setup. Then, different
scenarios are developed by TCL language and run. Then, AWK language is used to extract different
results from trace files of different scenarios and save these results in some text files. Finally, the result
is extracted from relative text files using MATLAB. That is noteworthy that to increase the accuracy of
simulation results, each experiment is run 50 times and the average of these 50 results is considered as
the result [9]. The simulation time also is set to 1200 seconds.

The average end-to-end delay of both the protocols is shown in Figure 2. For DBR each sensor node
will hold the packet for a certain time proportional to the depth of the sensor node, therefore, the average
end-to-end delay of DBR is higher. In contrast, our proposed protocol, EE-OR the node in transmits a
packet based on the fair ranking scheme of its forwarding list, therefore delay is reduced as the number
of nodes increases.
Figure 2. Comparison of average end-to-end delay between DBR and EE-OR protocols

Figure 3 shows the energy consumption of both the protocols. The energy consumption of DBR is higher than that of the proposed EE-OR protocol. The reasons for this phenomenon are the increased number of nodes involved in the forwarding of data packet and the redundant packet transmissions in DBR. In addition, DBR does not utilise any energy metrics during the data-forwarding phase. Packets are transmitted to the next forwarding node based on depth Information only. The total energy consumption of EE-OR reduces in comparison with DBR because with increasing the number of nodes, the total number of forwarded data packet in EE-OR further reduced compared to DBR. EE-OR consumes less energy consumption than DBR. This is because EE-OR utilise energy metrics along with depth Information for choosing the next forwarding nodes. Moreover, EE-OR reduces the number of packet transmission and balance the energy consumption between nodes.

Figure 3. Comparison of energy consumption between DBR and EE-OR protocols

The results, shown in Figure 4, reveal the superiority of EEPR to the DBR in terms of packet delivery. In DBR, the packet delivery ratio comes at the expense of excessive energy consumption and increased end-to-end delay. Unlike DBR, EE-OR obtains a higher delivery ratio with increasing node while still maintaining low energy consumption. The obtained results indicate that with an increase in the number
of nodes, the average packet delivery ratio only increases slightly in both DBR and EE-OR. This is because, the fair multi-criteria forwarding set ranking algorithm in EE-OR fairly ranked the eligible forwarder nodes based on energy metrics and it assigns the highest importance to depth criterion in order to decrease the number of hops and increase the likelihood of successful packet delivery.

Figure 4. Comparison of packet delivery ratio between DBR and EE-OR protocols

Figure 5 shows that with increase in the number of nodes, the total number of forwarded data packet increase in all protocols. However, EE-OR outperforms DBR. EE-OR fairly ranks the nodes in forwarding set based on energy metrics, therefore the performance of the ranking algorithm enhances when the number on eligible nodes for ranking increase. Another factor for the higher throughput is EE-OR computes the holding time of these nodes based on their position in the ranking list, therefore, the possibility of forwarding the same data packet by lower rank node due to close holding time is decreased.

Figure 5. Comparison of throughput between DBR and EE-OR protocols

4. Discussion and Conclusion
Existing opportunistic pressure-based routing algorithms suffer from lack of an appropriate ranking algorithm to rank fairly nodes during the data-forwarding phase. This in result in higher energy consumption and, at the same time, these protocols are unable to provide satisfactory packet delivery
ratio. To deal with this issue, an energy-efficient opportunistic routing protocol, EE-OR, is introduced to fairly rank the neighbouring nodes of each forwarder node locally based on energy metrics and depth information. EE-OR is composed of two phases; neighbour information acquisition phase and data packet forwarding phase. In the first phase, each node collects information about its neighbours to rank its neighbouring nodes. In the second phase, each forwarder node forwards the data packet via its neighbouring nodes based on an opportunistic routing approach. Results show that the performance of EE-OR outperforms the existing energy efficient pressure-based routing algorithms, DBR in terms of end-to-end delay, total energy consumption and packet delivery ratio. However, EE-OR has its limitations. EE-OR does not solve to the communication void problem. Communication void is one of the critical issues in opportunistic routing especially in networks with low density and high dynamic topology. A void avoidance scheme is essential to increase the packet delivery ratio while identifying and avoiding void nodes in the packet forwarding process. Priority should be given to these issues in future works within this field of study.

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