IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 28, 2018, accepted May 3, 2018, date of publication May 16, 2018, date of current version June 19, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2837108

Co-EEORS: Cooperative Energy Efficient Optimal Relay Selection Protocol for Underwater Wireless Sensor Networks

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This work is supported in part by the Faculty of Computer Science and Information Technology, University of Malaya, under a special allocation of the Post Graduate Fund for RP036-15AET Project. This work is also supported by the Deanship of Scientific Research at King Saud University for funding this research through Research Group Project NO. (RG#1435-051).

ABSTRACT Cooperative routing mitigates the adverse channel effects in the harsh underwater environment and ensures reliable delivery of packets from the bottom to the surface of water. Cooperative routing is analogous to sparse recovery in that faded copies of data packets are processed by the destination node to extract the desired information. However, it usually requires information about the two or three position coordinates of the nodes. It also requires the synchronization of the source, relay, and destination nodes. These features make the cooperative routing a challenging task as sensor nodes move with water currents. Moreover, the data packets are simply discarded if the acceptable threshold is not met at the destination. This threatens the reliable delivery of data to the final destination. To cope with these challenges, this paper proposes a cooperative energy-efficient optimal relay selection protocol for underwater wireless sensor networks. Unlike the existing routing protocols involving cooperation, the proposed scheme combines location and depth of the sensor nodes to select the destination nodes. Combination of these two parameters does not involve knowing the position coordinates of the nodes and results in selection of the destination nodes closest to the water surface. As a result, data packets are less affected by the channel properties. In addition, a source node chooses a relay node and a destination node. Data packets are sent to the destination node by the relay node as soon as the relay node receives them. This eliminates the need for synchronization among the source, relay, and destination nodes. Moreover, the destination node acknowledges the source node about the successful reception or retransmission of the data packets. This overcomes the packets drop. Based on simulation results, the proposed scheme is superior in delivering packets to the final destination than some existing techniques.

INDEX TERMS Underwater wireless sensor network, energy efficiency, cooperative routing, relay selection.

I. INTRODUCTION

Underwater wireless sensor networks is an emerging era to explore the underwater assets and use this medium for a number of applications [1]. However, it is a harsh environment that makes the delivery of packets from the bottom to the surface of water a challenging task. Cooperative routing is considered as one of the best solutions to reliably delivery packets to the water surface [2]. It is similar to the concept of sparse recovery in that a destination node combines two noisy copies of the same data packets, one from the source and one from the relay node. These data packets are then processed to extract the desired information.

The underwater medium is associated with a number of challenges [3]. The radio waves are absorbed in water to an appreciable extent. As a result, the underwater communications make use of the acoustic waves. However, the acoustic waves travel with a speed that is almost five times slower than the speed of radio waves. This inherently results in long propagation delay in underwater communications. In addition, the acoustic spectrum is limited that, in consequence, allows limited frequencies for communications among the sensor nodes. Also, every node has a finite battery power and battery replacement is not generally feasible. Moreover, the underwater medium is associated with the presence of marine animals and shadow zones. These factors block the communication between a source and a destination that, in turn, hinders the reliable delivery of data packets to the sink node placed usually at the water surface as a final destination.

The speed of an acoustic wave changes with pressure, temperature and salinity of water. This makes the acoustic waves to travel on curved paths that, in turn, makes the sensor nodes inaudible [4]. In essence, packets delivery to the final destination is interrupted. Moreover, the sensor nodes move with water currents that challenges the availability of forwarder nodes for a source node in forwarder selection during data forwarding. All these challenges threaten the reliable delivery of packets to the final destination. Cooperative routing is one of the effective strategies in ensuring reliable packets delivery.

The concept of cooperative routing traces back to the fundamental and pioneering work of Van der Meulen [5]. Cooperative routing for UWSNs has been the subject of recent research to combat with the harsh underwater environment and ensure reliable data delivery to the final destination [6]. In this type of routing, packets forwarding from source to destination is accomplished using one or more relay nodes between them. In general, a destination node receives two or more copies of the same data packets, one directly from the source and one or more copies from the relay node(s). The destination combines the received packets and processes them according to a certain algorithm to extract the desired information. This strategy ensures that if data packets are severely affected by the adverse channel conditions along one or more routes, alternative paths may have less affected data packets. Consequently, the reliable delivery of data packets to the final destination is achieved. Cooperative routing finds its applications in underwater navigation, military surveillance, disaster prevention, environment monitoring, leak and seismic detection and general purpose underwater exploration [7], [8].

The uniqueness of cooperative routing lies in its ability to mitigate the adverse channel effects during packets forwarding. Since a destination node combines two or more copies of the same data packets, there is a certain probability for the destination to receive packets from the routes less affected by channel properties. This increases the chance of reliable packets delivery to the destination that, in consequence, enhances the reliability of the network. Such a reliability is particularly desired in data-critical applications such as military surveillance, underwater seismic monitoring and rescue operations [8].

The conventional routing protocols for UWSNs [9]–[13] do not take into account cooperative routing in packets forwarding from a source to a destination. As a result, they do not guarantee the reliable delivery of data packets. In these protocols, a source node forwards data packets to a forwarder (or relay) node that further forwards the packets towards the water surface. There is no check on whether the received data packets have a bit-error rate (BER) or a signal-to-noise ratio (SNR) within a certain threshold. When the BER or SNR is not within an acceptable threshold, information extraction from the received packets becomes difficult. In addition, there is no check on whether the transmitted packets will reach the destination reliably since the channel conditions are not taken into account. Even if channel conditions are considered [14], forwarding packets along a single link from a source to a relay or from a relay to a destination may not always guarantee reliable delivery of data packets. It is because underwater communications suffer from high propagation delay as they use acoustic waves and the channel is highly unpredictable. Computation of the channel state information and then forwarding the packets along the computed link may take longer and the channel conditions may change prior to data forwarding. As a result, reliable delivery of packets is compromised.

There are a number of cooperative routing techniques for UWSNs in literature [15]–[17]. However, they require either the knowledge of the geographical position of the sensor nodes, time synchronization among the nodes participating in the cooperative routing or the relay nodes are not identified to the source and destination nodes. The calculation of geographical information of sensor nodes in underwater is challenging as nodes may frequently change their positions with water currents. Achieving time synchronizing among the nodes is also challenging due to the harsh nature of the underwater channel. When the relay nodes are not identified in packets transmission from source to destination, redundant packets transmission increases as every node starts to forward packets to the destination. This, as a result, consumes energy of the nodes in unnecessary manner and causes interference. Moreover, there is no acknowledgement of the destination node to the source node regarding the successful reception of data packets or the retransmission of the data packets if the SNR or BER is not within a certain threshold. As a result, reliable delivery of data packets to the final destination is not guarnteed.

In this paper, the Co-EEORS routing protocol for UWSNs is proposed. This paper extends the idea presented in [18] where an energy efficient optimal relay selection (EEORS) protocol is proposed. The extension adds cooperative routing to the EEORS protocol. In addition, the Co-EEORS protocol defines the location value of a node as a measure of its distance from the sink node. This helps in selecting nodes closer to the sink that, in effect, makes the data closer to destination after each transmission. Cooperative routing in CO-EEORS avoids the unfavorable link conditions and ensures reliable delivery of data packets to the water surface. Selection of a destination node by a source node among its neighbors is accomplished on the bases of the lowest depth and the lowest location. The sink node regularly sends beacon signals that help each sensor node to identify its location. The depth of each sensor node is measured using a pressure sensor.

The proposed protocol is unique in its contributions, as compared to the conventional cooperative and non-cooperative routing protocols described above. The proposed scheme does not need the knowledge of the position coordinates of the sensor nodes. The calculation of the distance between two nodes usually require the position coordinates of the nodes (the two or three dimensional position coordinates information). The position of a node may change and its neighbor nodes may know it later as underwater communications have long propagation delay. This leads to false position estimation that, in effect, challenges the data delivery to the destination during packets forwarding. The proposed protocol calculates the distances among the nodes by using the location values of the nodes rather than their geographical information.

Unlike the conventional routing protocols; described above that consider only the depth, the proposed protocol considers the location value in addition to the depth to select a destination node during cooperative routing. A node closest to the sink node has the lowest location value. A destination node is the one that has the lowest depth and the lowest location value. This ensures that data packets get closer to the surface sink after each transmission. It is because two or more nodes may have the same depth but different physical distances from the sink node. In addition; as compared to the conventional cooperative routing, the destination node in the proposed cooperative routing sends an acknowledgement signal to the source node. This acknowledgement either tells the source node that packets are successfully received or requests the source node for retransmission of the data packets. This further enhances the reliable delivery of data packets to the final destination. Moreover, the relay node is the nearest to the destination node so that it forwards data packets to destination with minimal delay during cooperative routing. Finally, the source node identifies the relay and destination nodes to avoid other neighbor nodes from data forwarding during the cooperation phase. This synchronizes the nodes and avoids redundant packets transmission that, in effect, reduces interference during packets forwarding. The performance of the proposed protocol is limited in sparse conditions when nodes are far apart and sender nodes do not find relay nodes for cooperation.

II. RELATED WORK

This section provides a review of some novel cooperating routing protocols for UWSNs. Nasir *et al.* [19] propose a cooperative routing protocol in which a source node selects two relay nodes and a destination node. The destination node combines three copies of data; from the source node and from each of the relay nodes. These data copies are accepted by the destination node if the estimated BER is within a certain threshold using the maximum-ratio-combining (MRC) technique. Otherwise, the data copies are dropped and not retransmitted by the source node. Every relay node amplifies the data before sending it to the destination. The lowest depth criterion is used to choose the relay nodes. The protocol achieves low packet drop at the expense of early death of the sensor nodes, partial energy efficiency and high end-to-end delay. In addition, since the source does not retransmit packets to the destination, packets reliability is not guaranteed for severe link conditions.

A depth and energy aware cooperative (DEAC) routing protocol is proposed in [20]. A source node checks its number of alive neighbors and then chooses a depth threshold. Within the depth threshold, a relay node is chosen on the bases of its residual energy, number of neighbors and the link condition. The source node chooses the destination node outside the depth threshold. The protocol improves packet delivery ratio and energy consumption. However, the use of depth threshold in relay selection increases the end-to-end delay. Moreover, signal amplification by the relay node is not accomplished before sending data packets to the destination node. This leads to data loss in unfavorable link state conditions.

A technique using sink mobility with incremental cooperative routing is proposed in [21]. The residual energy, depth and the path condition are taken into account by a source node to choose a relay node. Mobile sink nodes gather data from the in-range destination nodes. The protocol shows promising results in terms of energy consumption, packets delivery to the sink and network lifetime. However, the sink nodes consume energy due to movements in the network and cause high end-to-end delay when the nodes are far apart in the network.

Umar *et al.* [16] propose two cooperative routing protocols. The first protocol selects a relay node based on its depth in the depth threshold and residual energy. The second protocol combines the link quality of the relay to destination link with the two parameters of the first protocol. The mobile sinks follow pre-established routes and the nodes forward their data to the sink nodes within a certain communication radius. The protocol stabilizes the network operational time and has high number of packets reception at the destination. However, the use of the depth threshold introduces delay in packets forwarding. Furthermore, the source does not retransmit the packets to the destination incase the later does not receive them successfully. This challenges the performance of the proposed protocols in severe link conditions. Also, the paths over which the sink nodes move are predefined. This introduces unnecessary delay as the sinks do not prioritize the paths where destination nodes have data ready for transmission.

An improved adaptive cooperative routing (IACR) protocol is proposed in [17] that defines a depth threshold for the source node. A master node that has the lowest depth and the highest residual energy and lies outside the depth threshold of the source node is selected as a destination node. The depth threshold of the destination node is also defined. Nodes that have the lowest depth and the highest residual energy but lie in-between the depth thresholds of the source and the destination nodes are the cooperative nodes. Two cooperative nodes are selected as relay nodes. However, there is no mechanism defined by which the source, destination and cooperative nodes know about the two selected relay nodes. This increases the redundant packets transmission, especially when there are more than two cooperative nodes available in the cooperation region. The redundant packets cause energy consumption and interference. In addition, when the BER is higher than the specified threshold at the destination, data is sent to the same destination by an alternate source node. This process leads to packets loss when an alternate source node is not available in the same region.

Rehman *et al.* [22] propose an energy efficient cooperative opportunistic routing (EECOR) protocol. A set of forwarding nodes is first selected by the source node and then a single relay node is selected from the set based on fuzzy logic to forward packets to the destination. The protocol is efficient in reducing energy consumption, packets delivery and end-to-end delay. However, it has poor performance in sparse conditions when nodes are far apart and selection of a set of relay nodes becomes cumbersome. In addition, the forwarding set of nodes has to be constantly monitored that introduces extra delay in packets forwarding. It is due to the reason that selection of a forwarder set requires communications among the sensor nodes. This becomes challenging with extra delay when the sensor nodes change their positions with water drift. Nodes have not only to know the recent position of one another but have to identify the changes in their positions as well.

In [23], the division of the total depth of the network is accomplished into three regions of varying depth. Each region is subdivided into three regions according to the selection of the source, relay and destination nodes. A best relay node is selected from the relay region in each of the three sections of the network. The destination nodes then forward the data either to the surface through multi-hoping or the mobile sinks gather data from the destination nodes. The protocol performs better than some existing techniques in enhancing network lifetime, throughput and reducing the energy consumption. However, it suffers from redundant packets transmission. It is because, the nodes between the source and destination nodes do not know exactly about the identified relay nodes. In addition, without the identification of the selection of the relay nodes to other neighbor nodes, the protocol does not specify the time for which a relay node has to hold a packet or forward it to the destination.

Ghoreyshi *et al.* [24] propose a cooperative and opportunistic routing protocol. The surface sink and all the nodes communicate with one another through the regular exchange of beacon signals. A beacon signals contains the ID, depth, hop count and neighbors' information of the broadcasting node. This process is done by every node so as no node in the network is left without any neighbor. This controls the data loss due to absence of the neighbor nodes. The set of forwarding nodes for opportunistic routing is selected on the bases of the packet delivery probability and packet advancement that the nodes also share with one another. A trade-off is established between energy consumption and the participant forwarding nodes by using packet holding time. Energy consumption, throughput and latency are improved by the protocol. However, its performance is compromised in sparse condition where the beacon signals do not work efficiently and effectively.

III. CHANNEL MODEL

A. CHANNEL NOISE

The noise associated with the underwater medium corrupts data packets. This makes the extraction of information difficult from the corrupted packets. The generation of noise in underwater medium is due to shipping activities, waves generated by wind at the surface of water, turbulence and temperature of the sea. The following relations define the power spectral density (PSD) of each noise component in $dB\, re\, \mu\, Pa$ [25]

$$\begin{aligned} 10\log N_{sh} &= 40 + 20(s-0.5) + 26\log f \\ &\quad - 60\log(f+0.03). \end{aligned} \tag{1}$$

$$10\log N_{wv} = 50 + 7.5w^{0.5} + 20\log f - 40\log(f+0.4). \tag{2}$$

$$10\log N_{tb} = 27 - 30\log f. \tag{3}$$

$$10\log N_{th} = -25 + 20\log f, \tag{4}$$

where N_{sh}, N_{wv}, N_{tb} and N_{th} are the power spectral densities of the shipping, wave, turbulence and thermal noise, respectively. The parameter s takes values in the interval $[0, 1]$ and defines the extent of shipping activities in water. The parameters w and f are wind speed at the surface of water in m/s and frequency of the acoustic wave in kHz, respectively. If the PSD of the total underwater ambient noise is N, then it is modeled by

$$N = N_{sh} + N_{wv} + N_{th} + N_{tb}. \tag{5}$$

The shipping noise exists in the spectrum 20 - 200 Hz. The range of 200 Hz - 200 kHz is dominated by the wave noise. Thermal noise affects the frequencies higher than 200 kHz while turbulence noise corrupts the frequencies below 20 Hz.

B. THE ATTENUATION MODEL

In underwater communications, the attenuation of an acoustic wave of frequency f in kHz that is away from the source by a distance d in km is denoted by $A(d, f)$ and measured in $dB\, re\, \mu\, Pa$. This attenuation is modeled by the Thorp's formula [26] as

$$10\log A(d,f) = k\ 10\ \log(d) + d\ 10\ \log(\alpha(f)). \tag{6}$$

The above equation shows that underwater attenuation is the sum of the spreading loss and the absorption loss. The parameter $\alpha(f)$ is called absorption co-efficient. The spreading loss measures the reduction in power of an acoustic wave as it travels away from the source. The parameter k is a geometric parameter and specifies the geometry of the spreading. For cylindrical spreading, $k = 1$ while $k = 2$ for spherical spreading. In practice, $k = 1.5$ in underwater communications that the proposed protocol also takes into account. The computation of the absorption coefficient in dB/km follows the following empirical relationship [26]

$$10 \log \alpha(f) = \begin{cases} \frac{0.11 f^2}{1+f^2} + \frac{44 f^2}{4100+f} + 2.75 \times 104 f^2 & f \geq 0.4 \\ 0.002 + 0.11 \frac{f}{1+f} + 0.011 f. & f < 0.4 \end{cases} \tag{7}$$

The attenuation described above models the transmission and absorption losses of the acoustic waves in water. These are the major losses associated with underwater communications. The acoustic energy is also lost when the acoustic waves are reflected from the surface of water and sea bottom. The acoustic energy loss due to reflection from the surface of sea at an incidence angle of θ to the horizontal is denoted by RL_s; where the subscript s stands for surface, and is empirically modeled by the Beckmann-Spizzichino formula [27] as

$$RL_s = 10 \log \left[\frac{1 + (f/f_1^2)}{1 + (f/f_2^2)} \right] - \left(1 + (90 - w)/60 \right) (\theta/30)^2, \tag{8}$$

where $f_1 = \sqrt{10} f_2$ and $f_2 = 378/w^2$. The reflection loss due to bouncing of the acoustic waves from the bottom of the ocean is denoted by RF_b; where the subscript b stands for bottom, and is modeled by [25]

$$RL_b = 10 \log \left[\frac{(m \sin \theta_1 - (n^2 - \cos^2 \theta_1)^{1/2})}{(m \sin \theta_1 - (n^2 - \cos^2 \theta_1)^{1/2})} \right]^2. \tag{9}$$

In reflection loss from the bottom of the sea, an acoustic wave travels from water with density ρ_1 and speed c_1 and bounces from the bottom of the ocean with water containing sediment that has density ρ_2 and in which the acoustic wave travels with speed c_2. The other parameters are related by $m = \frac{\rho_1}{\rho_2}$, $n = \frac{c_1}{c_2}$ and θ_1 is the grazing angle. The depth of the proposed network is 500 m, significantly less than the usual several hundred kilometers depth of sea. Therefore, the reflection loss due to bouncing of an acoustic wave from the sea bottom is not taken into account in the calculation.

C. THE ENERGY CONSUMPTION MODEL

A typical acoustic modem is used in underwater communications for packets transmission and reception. To model the power consumption characteristics of such a modem with respect to a specific transmission range, the passive sonar equation is used. This equation models the SNR in $dB\, re\, \mu\, Pa$ of an acoustic wave at a receiver as [25]

$$SNR = SL - TL - NL + DI \geq DT \tag{10}$$

where SL, TL, NL, DI and DT represent the source level of the transmit sound wave, transmission loss, noise level, directivity index (it is zero when the acoustic source is omni-directional) and detection threshold, respectively. The above Equation signifies that in order for a transmitted acoustic wave to be detected by an acoustic modem at a receiver, its SNR at the receiver should be greater than or equal to the detection threshold of the modem. The source level represents the intensity of the acoustic wave at the source. When this wave travels away from the source, the transmission loss and noise level tend to weaken the intensity of the sound wave. As a result, these terms are subtracted from the source level. The directivity index directs the acoustic wave from source to destination. This tends to reduce the lossy effects of the medium. As a result, the directivity index is added to the source level. The value of 1 μPa is used as a standard reference in underwater communications and it is equal to $0.67 \times 10^{-18}\, Watts/m^2$. The proposed protocol considers a directivity index of 3 $dB\, re\, \mu\, Pa$ and an SNR of 20 $dB\, re\, \mu\, Pa$ [29].

The source level SL can be related with the transmitted signal intensity I_T at 1 m distance away from the source as

$$SL = 10\, log \frac{I_T}{1 \mu Pa}, \tag{11}$$

where I_T has the unit of $\mu\, Pa$. In terms of $Watts/m^2$, I_T can be written as

$$I_T = 10^{SL/10} \times 0.67 \times 10^{-18}. \tag{12}$$

The intensity I_T at 1 m distance away from the source distance in shallow water requires the power transmitted by the source $P_T(d)$ to be

$$P_T(d) = 2\pi \times 1m \times H \times I_T. \tag{13}$$

The source transmitted power in deep water for the same intensity is given by

$$P_T(d) = 4\pi \times (1m)^2 \times H \times I_T, \tag{14}$$

where d and H are the distances from the source and depth of the sea, both in meters. Finally, transmission of k bit over a distance d away from the source requires the amount of energy $E_{TX}(k, d)$ which is computed by

$$E_{TX}(k, d) = P_T(d) \times T_{TX}, \tag{15}$$

where T_{TX} signifies the transmission time in seconds.

D. THE VARIABLE SPEED OF ACOUSTIC WAVES

The speed of an acoustic wave is affected by the characteristics exhibited by the underwater channel. Specifically, the speed c of an acoustic wave in m/s varies with respect to the sea depth D in meters, salinity S in parts per thousand (ppt) and temperature T in degree Celsius ($0\,^{\circ}C$) of the sea water. These parameters empirically characterize the speed of an acoustic wave as follows [28]

$$\begin{aligned} c = {} & 1449 + 4.591T - 5.304 \times 10^{-2} T^2 \\ & + 2.374 \times 10^{-4} T^3 + 1.34(S - 35) \\ & + 1.63 \times 10^{-2} D + 1.675 \times 10^{-7} D \\ & + 1.025 \times 10^{-2} T(S - 35) - 7.139 \times 10^{-3} T D^3. \end{aligned} \tag{16}$$

On account of the slower speed of acoustic waves than radio waves, the underwater communications inherently suffer from higher propagation delay than the terrestrial radio communications. The calculation of the speed of an acoustic wave using the above equation demands that the temperature be in the 0°C to 30°C range, salinity in the 30 - 40 ppt range and the depth from 0 m to 8000 m. All these conditions are taken into consideration while calculating the speed of an acoustic waves.

IV. THE PROPOSED PROTOCOL

A. NETWORK DESCRIPTION

A three dimensional cube is considered as a network. Nodes are placed in a random manner in the network. The top mid of the network specifies the position of the sink node. To ensure greater network coverage, it is assumed that every node is capable of sensing the desired attribute. Data packets forwarded towards the water surface are collected by the sink node that sends them towards the onshore data center as shown in Fig. 1. The onshore data center further processes the received packets to extract the desired information. Since the transmission range of every node is limited, multi-hopping is used among the nodes to forward data packets to the sink node.

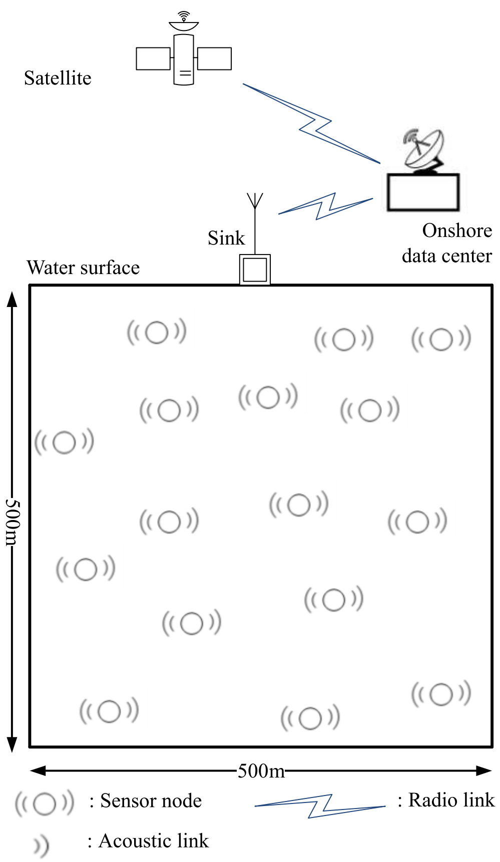

FIGURE 1. The proposed network model.

All the sensor nodes communicate with one another using acoustic waves. The sink node is a hybrid node that uses both the acoustic and radio waves. Communications between the sink and the onshore data center are accomplished using radio waves. The sink communicates with the sensor nodes in water using acoustic waves. Because of the greater speed of radio waves than acoustic waves, it is assumed that data packets that are received at the sink are considered to be successfully delivered to the onshore data center.

B. NETWORK INITIALIZATION

In this phase, the sink node broadcasts a hello packet. The hello packet contains the position information of the sink. Every node that receives the hello packet calculates its physical distance from the sink using the Time of Arrival (ToA)/Time Difference of Arrival (TDoA) [30]. The calculation of the depth of a node involves the use of a pressure sensor with the sensor node. The node then inserts its own ID, depth and physical distance from the sink in the hello packet and rebroadcasts it. This process continues unless all the nodes exchange the hello packets. When a node rebroadcasts a hello packet, it waits to hear from its neighbors in a specific interval of time. This time interval is proportional to the sum of the propagation and processing delays in underwater communications and is denoted by t_o. When the maximum time $t_{o_{max}}$, for which the node waits, expires and the node does not hear in response, it declares itself as a node having no neighbor.

By virtue of the identical structure of the sensor nodes and the fixed size of the hello packet, the processing delay inherently becomes equal for all the nodes. When the node receives a reply, it decodes the reply message of its neighbor node and saves the information about the ID, depth and physical distance of the neighbor node in a routing table. The routing table is then broadcasted after the maximum waiting time $t_{o_{max}}$. This process is accomplished by every node. The completion of the network initialization is characterized by every node knowing the number of its neighbor nodes, their IDs, depth and physical distance values. Since the water currents cause the movements of the sensor nodes and also nodes die when they drain their batteries, the process of network initialization is performed regularly so as to keep the nodes's information updated.

C. SELECTION OF THE DESTINATION AND RELAY NODES

Upon having a data packet ready for transmission, a source node sends the packet directly to the sink if it lies in the communication range of the source node. Otherwise, the source node uses multi-hopping to forward data to the sink node. A neighbor node of the source node that has the lowest depth and the lowest location value is selected as a destination node. The location value of a node is the measure of its physical distance from the sink node. A node closest to the sink node has the lowest location value. The reason for considering the location value along with depth in destination selection is that the depth of a sensor node is not enough to specify nodes close to the sink node. Two or more nodes may have the same depth but they may be at different physical distances from the sink node. For instance, three nodes that lie at the right, mid and left of the network at the same depth of 100 m have different distances from the surface sink. Therefore, considering the depth and location values together for selection of the destination node brings the data packets closer to the sink (water surface) after every transmission.

A neighbor node of the source node closest to the destination node is considered as a relay node. It is because selection of a node nearest to the destination as a relay node ensures that packets reach the destination in minimal time. This is necessary for the cooperation phase to be discussed later. The source node decides the relay and destination nodes on the bases of the information of the neighbor nodes obtained during the network initialization phase.

After identifying the relay and destination nodes, the source node sends a hello packet to its neighbors. This packet contains the IDs of the destination node and the relay node. All the neighbor nodes of the source nodes look for their corresponding IDs in the hello packet. Those nodes that do not find their IDs know that they are not selected to participate in the routing process. On the other hand, the destination node and the relay node, after finding their IDs in the hello packet, know that they are selected for data forwarding. This process avoids unnecessary forwarding of packets by the neighbors of the source node.

D. COOPERATIVE ROUTING

Specification of the relay and destination nodes by the source node follows data transmission from the source node to the destination node. All the neighbor nodes of the source node also overhear the transmission of the data packets from the source to the destination. However, only the selected relay node and the destination node participate in the routing process. The signal received at the destination node from the source node is denoted by y_{sd} and is modeled by [24]

$$y_{sd} = \sqrt{P_s} h_{sd}\, x + n_{sd}, \tag{17}$$

where P_s is the transmit power level at source, x is the symbol transmitted, h_{sd} is the channel gain from source to destination and n_{sd} is the noise associated with the link from source to destination. The signal received at the relay node from the source node is denoted by y_{sr} and is given by [24]

$$y_{sr} = \sqrt{P_s} h_{sr}\, x + n_{sr}, \tag{18}$$

where h_{sr} and n_{sr} represent the channel gain and noise along the source to relay link.

As soon as the relay node receives the signal from the source node, it amplifies the signal and forwards it to the destination node. The corresponding received signal at the destination is y_{rd} and is given [24]

$$y_{rd} = \sqrt{P_r} h_{rd}(\beta y_{sr})\, x + n_{rd}, \tag{19}$$

where P_r is the transmit power level at relay, h_{rd} is the channel gain from the relay to the destination and n_{rd} is the noise over the relay to destination link. The channel gains h_{sd}, h_{sr} and h_{rd} reveal the characteristics of the wireless links from source to destination, source to relay and relay to destination, respectively. They are characterized as complex Gaussian random variables with zero mean and variance denoted by σ^2 and modeled by [31]

$$\sigma^2 = \eta d^{-\alpha}, \tag{20}$$

where d is length of the link in meters along which the noise is measured, α denotes the loss during propagation and the constant η models the scenario in which the signal propagates. The factor by which the relay amplifies the signal before transmission to the destination is β which is mathematically expressed as [31]

$$\beta = \sqrt{\frac{1}{P_s\,|h_{sr}|^2 + \sigma^2}}. \tag{21}$$

The destination node combines the signal it receives directly from the source and the amplified signal from the relay node using MRC. The total SNR γ_{AF} at the output of the MRC is expressed as [31]

$$\gamma_{AF} = \gamma_{sd} + \frac{\gamma_{sr}\gamma_{rd}}{1 + \gamma_{sr} + \gamma_{rd}} \tag{22}$$

where $\gamma_{sd} = \frac{P_s|h_{sd}|^2}{\sigma^2}$, $\gamma_{sr} = \frac{P_s|h_{sr}|^2}{\sigma^2}$ and $\gamma_{rd} = \frac{P_r|h_{rd}|^2}{\sigma^2}$ represent the SNR values along the source to destination, source to relay and relay to destination links, respectively. The subscript AF signifies the amplify and forward cooperation technique. The destination node checks the value of the SNR at the output of the MRC. If this value

is greater than or equal to a certain threshold γ_{th}, the destination node sends an acknowledgment signal to the source node about the successful reception of the data packets. The destination node then checks if the channel is free or not. If the channel is free, it further forwards the data packets towards the sink in the same manner as described above. Otherwise, the destination node waits for some time called the waiting time τ_o. If the channel does not become free till the maximum waiting time $\tau_{o_{max}}$, the data packets are dropped.

When the SNR at the output of the MRC at destination is not within the acceptable threshold, the destination node requests the source node to send the packets again. Data packets are dropped by the destination node when it does not successfully receive the packets from the source or when the total SNR at the output of MRC is below the certain threshold even after multiple transmissions of packets by the source node to the destination node. This process of routing continues unless the data packets either reach to the sink at the water surface or are dropped. Fig. 2 shows the flow chart of the proposed routing scheme. For the sake of convenience, some of the processes described in the above lines are not shown in the flow chart.

The presence of at least one relay node is necessary between the source and the destination in order for the destination to receive the copy of the data from the relay node that the source originally sends to the destination. It is because

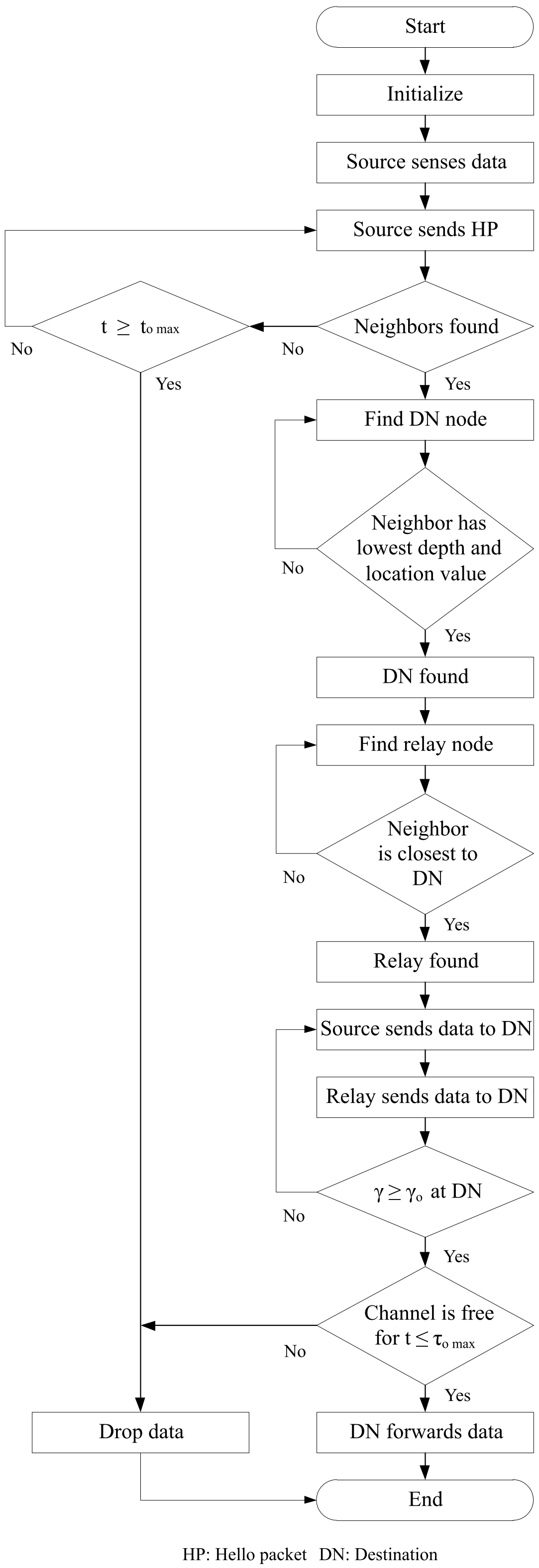

FIGURE 2. **Flow chart of the Co-EEORS scheme.**

the cooperative routing involves the reception of the same data packets at the destination from the source and the relay nodes. If there is no relay node, the destination node only processes the packets it receives from the source node. In this

Algorithm 1 Co-EEORS

$DN \leftarrow$ Destination
$RN \leftarrow$ Relay node
$N_i \leftarrow$ Neighbor set of a source node i
$E_i \leftarrow$ Energy of a source node i
$E_j \leftarrow$ Energy of j-th neighbor of a source node i
$Loc_j \leftarrow$ Location of j-th neighbor of a source node i
$D_j \leftarrow$ Depth of the j-th neighbor of a source node i
$p_j \leftarrow$ Water pressure on a forwarder node j
$R \leftarrow$ communication range of a sensor node
$E \leftarrow$ Energy of a sensor node
for $j = 1 : 1 : N_i$ **do**
  if $E_j > 0 \ \ \& \ \ E_i > 0 \ \ \& \ \ j \in N_i$ **then**
    $DN = argmin_{j \in N_i}(Loc_j, D_j)$
    $RN = argmin_{j \in N_i}(Loc_{DN} - Loc_j)$
    if $\gamma \geq \gamma_{th}$ **then**
      DN forwards packet
    else if $\gamma < \gamma_{th} \ \ \& \ \ t \leq \tau_{o_{max}}$ **then**
      i sends packets to DN
    else
Drop packet
    end if
  else
All the nodes have drained their battery power
  end if
end for

case, the destination node simply checks whether or not the SNR of the received data packets is within the threshold and acknowledges the source node accordingly.

The Co-EEORS algorithm shows the cooperative routing and the selection of the relay and destination nodes by a source node i. As is shown, a neighbor node of the source node that has the minimum (lowest) depth and location values is considered as a destination node. It is to make the packets closer to the water surface after each transmission. The relay node is the neighbor node of the source node other than the destination node. This relay node is selected to be the node that is closest to the destination node. The closeness of the relay node with the destination node is measured by the difference of the location values of the destination node and the relay node. Since the location value is the measure of the physical distance from the sink node, two nodes that are closest to one another will have the smallest difference of the location values.

V. SIMULATION RESULTS AND DISCUSSION

The simulation is accomplished using MATLAB by considering an underwater cube with 500 m length of one side as considered in the EEDBR protocol [32]. Within the network, 250 sensor nodes are randomly deployed. Every node communicates with other nodes using the LinkQuest UWM2000 modem [33]. The specifications of this modem include a date rate of 10 kpbs, power consumption of 2 W, 0.8 W and 8 mW in transmission, reception and in idle mode, respectively. The maximum working depth of this modem is 2000 m or 4000 m which makes it a suitable candidate to work in the proposed depth (500 m). The transmission range of every node is fixed and is 200 m in all directions (omni-directional). This transmission range is within the allowable limit of the selected modem. The omnidirectional beam width of the modem is 210^0 that is enough for a source node to select a forward node in its full transmission range towards the water surface. A single data packet has a size of 50 bytes.

For the MAC layer, the 802.11-DYNAV protocol is considered [34]. This MAC protocol defines a specific interval of time for the channel to become free so as to transmit the packets. Packets are dropped if the channel does not become free within the specified time interval. The water currents move the sensor nodes from one position to another. Such movements are modeled by the random-walk mobility model [35] as it does not need the position coordinates of the sensor nodes to be known. This model implies that a node moves in a random direction from one position to another with a speed that varies from 1 m/s to 5 m/s. Table. 1 shows the simulation parameters. The proposed protocol is compared with EEDBR and its previous version (EEORS). The reason is that like EEDBR, a sender node also selects the relay node in Co-EEORS and in EEORS. In addition; just like EEDBR, both EEORS and Co-EEORS also consider the depth (in addition to the location information) of a relay node in packets forwarding. The Co-EEORS routes data packets using cooperative routing. The cooperative routing increases data reliability by accepting data packets from the paths within some threshold of channel adverse effects. The obtained data plots are the result of extensive simulations averaged over 50 runs.

TABLE 1. Simulation parameters.

Parameter	Value
Data Rate	10 kbps
Packet size	50 B
Network depth	500 m
Network length	500 m
Network width	500 m
Transmission range	200 m
Idle mode power consumption	8 mW
Receive mode power consumption	0.8 W
Transmit mode power consumption	2 W

The protocols are compared based on the following performance parameters.

Round: The time duration in which one or more sensor nodes send one or more data packets towards the sink. The packet(s) either drops (drop) along the channel or reaches (reach) successfully to the sink.

Dead Node: A node that drains its battery completely.

Alive Node: A node that has not yet drained its battery completely.

Total Energy Consumption: The total energy consumption of all the nodes in the network in one round. It includes energy consumed by nodes during packets processing and when the nodes are idle.

End-to-end Delay: The latency associated with a data packet along its journey from source to destination.

Packet Delivery Ratio: It is the ratio of the total number of data packets successfully transferred to the sink to the total number of transmitted packets.

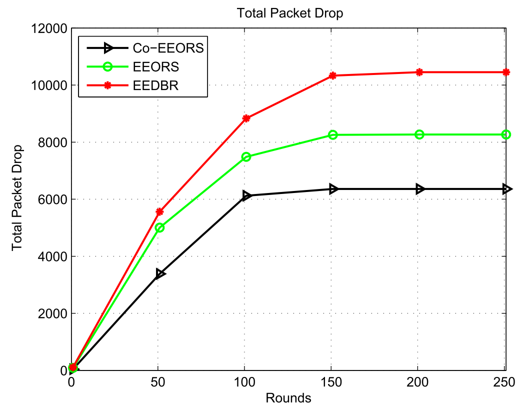

FIGURE 3. Number of packets drop.

Fig. 3 shows the plot of number of dropped packets. The Co-EEORS has the lowest packet drop. It is due to cooperative routing in Co-EEORS that combines signals at the destination from the two links: source to destination and relay to destination. Receiving data packets at the destination from the two links and checking the SNR to be within the acceptable threshold ensure that data packets are less affected by the channel properties. In addition, the destination node acknowledges the source node regarding the successful reception of data packets or retransmission of the packets if the threshold SNR is not met. This, in essence, reduces the packet drop in Co-EEORS. The EEDBR and EEORS do not make use of cooperative routing. Also, there is no mechanism in these protocols to retransmit packets to the destination if the destination node is unable to successfully decode the received data packets. As a result, Co-EEORS has the lowest packet drop.

The EEORS has lower number of dropped packets than EEDBR due to selection of forwarder nodes based on depth and location values. The depth and location values of the forwarder nodes are selected in a manner that nodes close to the surface sink are selected in data forwarding. This ensures that nodes that are away from the sink are not selected. The EEDBR selects forwarder nodes based on depth and residual energy. The inclusion of residual energy results in selection of high energy nodes even if they are away from the surface sink; sidewise to the center of the network. This makes the packets away from the surface sink that increases the probability of packet drop, as the underwater channel is highly unpredictable. In addition, for fair comparison, the proposed scheme considers one sink in all the three protocols rather than four sinks in EEDBR. This further challenges the delivery of packets to the sink in EEDBR when high residual

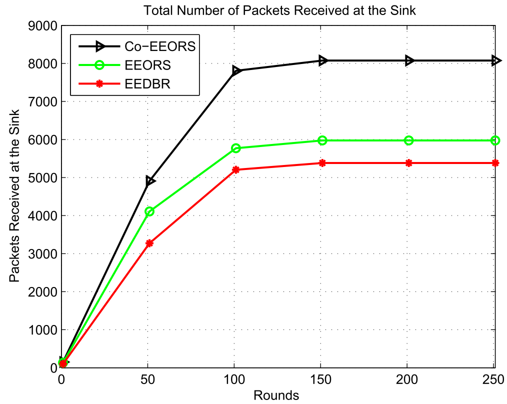

FIGURE 4. Packets received.

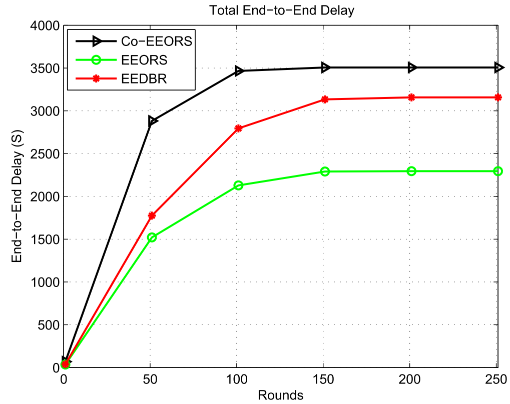

FIGURE 5. End-to-end delay.

energy nodes away from the sink are selected. As a result, EEDBR has higher packet drop than EEORS.

Fig. 4 shows the plot of total number of packets received at the sink. Due to cooperative routing, the number of packets that reach the sink is the greatest for Co-EEORS. The EEDBR and EEORS do not involve cooperative routing. In addition, since there is no mechanism of retransmission of data packets to the destination node is case of unsuccessful packets decoding in EEORS and EEDBR, these protocols have lower number of packets received at destination than Co-EEORS.

The EEORS has lower packet drop than EEDBR due to the reasons explained above. Furthermore, EEORS selects nodes close to water surface than EEDBR as described above. Therefore, packets follow shorter paths and reach to destination with less number of hops in EEORS than EEDBR. The indirect selection of the relatively longer paths for packets forwarding in EEDBR than EEORS, due to inclusion of the residual energy of the forwarder nodes, results in less mitigation of the channel effects on packets in EEORS. This, in turn, severely affects the reliable delivery of data packets to the sink in EEDBR. All these factors collectively result in greater number of packets reception at the sink in EEORS than EEDBR. The longer paths selection in EEDBR than EEORS also results in greater end-to-end delay in the former, as shown in Fig. 5. The highest end-to-end delay in Co-EEORS is due to cooperative routing. The cooperative routing ensures the destination gets the signals from the source and relay and acknowledges back to the source node about the status of the received packets. This increases the end-to-end delay in packets forwarding. As a result, Co-EEORS has the highest end-to-end delay.

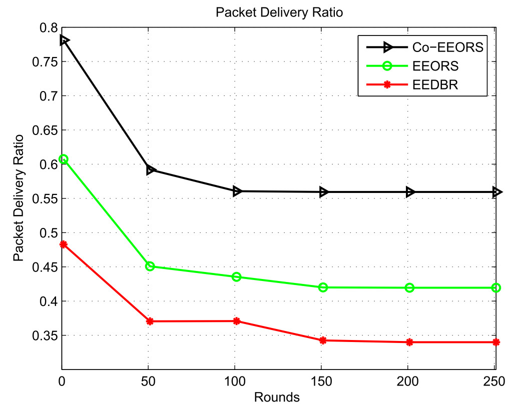

FIGURE 6. Packets delivery ratio.

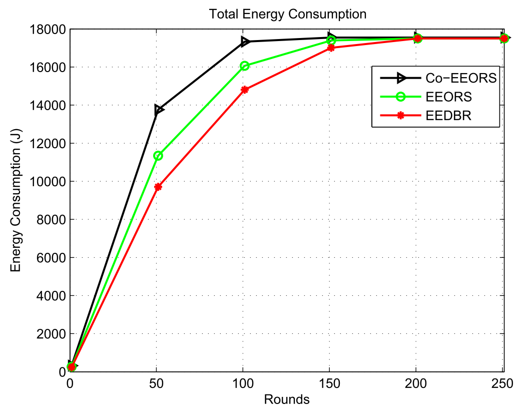

FIGURE 7. Total energy consumption.

The packet delivery ratio is plotted in Fig. 6. Due to the lowest packet drop and the greatest number of packets reception at the sink, Co-EEORS has the highest packet delivery ratio. The lower packet drop and greater number of packets reception at the sink result in greater packet delivery ratio in EEORS than EEDBR. For all the schemes, the packet delivery ratio is the highest initially as all nodes are alive in the network. As the network operates, nodes start to die that reduces the number of packets reaching the sink. As a result, packet delivery ratio decreases for all the three protocols in subsequent rounds.

The plot of energy consumption is shown in Fig. 7. The greatest packet delivery ratio makes energy consumption highest in Co-EEORS. In a similar fashion, the greater packet delivery ratio of EEORS makes its energy consumption higher than EEDBR. It is because successful transmission of data packets to the surface destination requires energy consumption. If more or the greatest number of packets are received at the sink, more or the highest amount of energy will be required. There is always a trade-off between the consumption of energy and the delivery of the packets to the final destination.

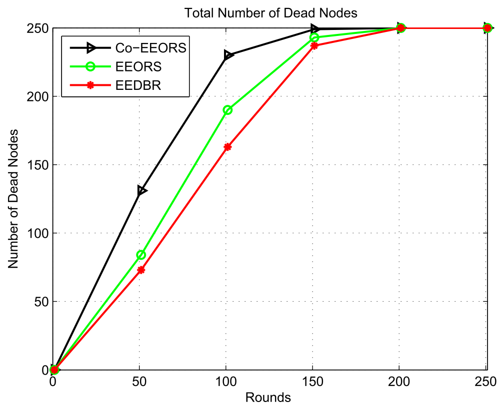

FIGURE 8. Total number of dead nodes.

The plot of dead nodes is shown in Fig. 8. The greatest energy consumption in Co-EEORS causes its nodes to die with the fastest rate. It is because when energy is consumed in the fastest manner, nodes are depleted of energy in the proportional manner. As a result, the energy of nodes is consumed in the proportional way until they lost all the energy and become dead. Greater energy consumption of EEORS than EEDBR results in more rapid death of nodes in the former.

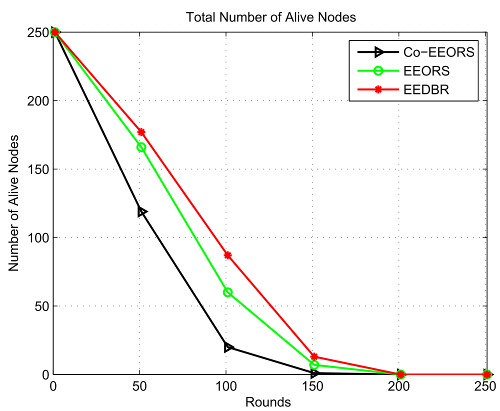

FIGURE 9. Total number of alive nodes.

Finally, Fig. 9 shows the plot of alive nodes. It is reciprocal to the plot of dead nodes. The fastest death of nodes in Co-EEORS leaves the least number of nodes to remain alive in the network. In the same way, more nodes are alive in EEDBR than EEORS as nodes die with a slower rate in the former.

VI. CONCLUSION AND FUTURE WORK

To mitigate the harsh underwater environment and ensure reliable delivery of packets, a cooperative energy efficient optimal relay selection (Co-EEORS) protocol is proposed for UWSNs. The protocol uses cooperative routing to counteract the unfavorable channel conditions. A source node selects a destination node on the bases of the lowest depth and the lowest location value. The location value measures how far a node lies from the sink node. Nodes closer to the sink have smaller location values. A node closest to the destination node is selected as a relay node. The destination node combines the same data packets from the source and relay nodes and processes it to ensure if they are within a certain SNR threshold. As compared to the conventional cooperative and non-cooperative routing protocols, the proposed protocol needs no knowledge of the position coordinates of the sensor nodes in specifying the routing trajectories. The knowledge of position information is challenging as nodes move with water currents and change positions. In addition, a destination node sends an acknowledgement signal to the source node for the successful reception of the packets or for retransmission of the packets if the packets are not correctly decoded. Simulation results reveal that the proposed protocol has higher delivery of packets to the final destination than some existing routing protocols. The performance of the proposed protocol is limited in sparse conditions when nodes are far apart and sender nodes do not find relay nodes for cooperation.

To avoid the data load on the relay and destination nodes, opportunistic routing can be combined with cooperative routing in future investigation. Such type of routing selects a certain set of nodes that forwards data packets to the final destination rather than selecting a single node. This relaxes the data load on individual nodes and avoids their early death that hinders the network operation.

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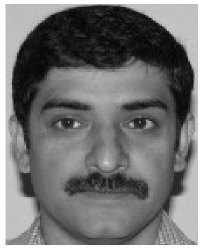

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