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Research Article

Energy and Path-Aware-Reliable Routing in Underwater Acoustic Wireless Sensor Networks

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In underwater acoustic sensor networks (UASNs), energy awareness, best path selection, reliability, and scalability are among the key factors that decide information delivery to the sea surface. Existing protocols usually do not combine such performance-affecting factors in information routing. As a result, the performance of such protocols usually deteriorates if multiple performance factors are taken into account. To cope with such performance deterioration, this article proposes two routing protocols for UASNs: energy and path-aware reliable routing (EPRR) and cooperative EPRR (Co-EPRR). Compared with the counterpart systems, the proposed protocols have been designed to deal with the problem of long propagation delays and achieve network reliability. The EPRR scheme uses nodes' physical distance from the surface with its depth, which minimized the delay of packet transmission. The channel interaction time has been reduced, therefore, reducing unwanted channel effects on the data. Furthermore, the density of the nodes in the upper part of the network prevents data loss and limits the rapid death of the nodes. The second proposed scheme, Co-EPRR, uses the concept of routing information from the source to the destination on multiple paths. In Co-EPRR routing, the destination node can receive more than one copy of the data packet. This reduces unfavorable channel effects during data delivery. Both the schemes show good performance in terms of packet delivery ratio, received packet analysis, and end-to-end delay.

1. Introduction

Energy awareness, best route selection, reliability, and scalability are among the principal factors that determine the performance of underwater acoustic sensor networks (UASNs) [1] in information routing to the desired target, as these factors are directly linked with performance evaluation. In addition, these performance factors play a key role in undersea applications such as underwater exploration, monitoring, submarine tracking, and navigation and are used for military purposes [2–5]. Unfortunately, existing schemes usually do not consider these factors altogether in information routing, which leads to compromised network performance since one or the other performance parameter can get compromised.

Channel noise and bit error rate can be looked into channel conditions during data routing in order to minimize to a certain extent [6, 7] that the channel impairments affecting data delivery. As described in [6], cooperative communication is one of the techniques that could be exploited to deal with channel properties. This technique is based on multiple paths and on the combination of data at the destination; this approach has been used to increase the reliability of data delivery. In cooperative communication, a relay forwards data to the destination by amplifying or decoding the received signal. The first is known as amplify and forward (AF), and the second is known as decode and forward (DF) [8]. The AF scheme is simpler and forwards data with a lower latency than DF, as DF completely decodes the signal before forwarding [9]. In general, two cooperative methods, called fixed and incremental cooperative relay schemes, are used [10, 11]. In fixed cooperation, the relay always cooperates. While in incremental relaying, the cooperation is done when a destination needs to send the desired signal. In incremental relaying, instantaneous information from the channel reduces data forwarding by limiting the feedback packets to a few bits. In fixed relaying, data are transmitted to the destination regardless of the channel condition [12]. In cooperative communication, The receiver can get more than one copy of the same data packets. All these data packets are then combined using one of the combining techniques to improve the correct reception of the data [13].

Using multiple antennas at a sensor node provides data reliability. However, in the case of UASNs, adding antennas is difficult and expensive. Therefore, to improve reliability, cooperative communication is usually used instead of multiple antennas. In such a case, overhearing of the data by neighboring nodes can lead to high data reliability [14] even when a single antenna node is used. Anyway, in cooperative communication, data retransmission by a relay is used to have error-free data. However, multiple data transmission leads to additional energy consumption and increases latency.

Protocols that do not consider channel awareness and noise in data routing generally do not guarantee reliable data delivery, since there is no retransmission of data packets. On the other hand, cooperative routing protocols enhance data reliability, since data are transmitted by sender and relay nodes as well. Many cooperative [15, 16], noncooperative [17], and different other types of routing protocols are proposed for UASNs [18, 19]. These routing algorithms achieve high reliability at the cost of high latency and excessive energy consumption.

The selection of the best and shortest path during data routing takes into account the overall time to transmit the packet from the source to the desired target. This not only shortens the time of data delivery, which is necessary in emergency and military applications, but also makes the data affected by the channel properties for a short period of time. As a result, reliability is also increased. Scalability ensures that new nodes can be added to the network so that the network can be easily extended when desired.

The existing schemes that route data in UASNs do not consider energy awareness, shortest path selection, reliability, and scalability together [15, 16]. Instead, the proposed methods generally exploit a single parameter or indicator in the routing of information [20–22]. Even when more than one parameter is considered, if the computation of the Euclidean distance for route determination is needed, the network scalability is affected [23, 24]; the calculation of Euclidean distance is, in fact, cumbersome in UASNs, as it involves the computation of nodes' position coordinates and nodes constantly change their positions. As a result, one or more performance indicators are not always optimal when the network operates.

This work proposes two approaches (EPRR and Co-EPRR) to cope with these limitations. In EPRR, data are reached to the sink along the shortest links, so less time is taken by the data. This minimizes the propagation delay and shortens the time it takes for the channel properties to affect the data. As a result, the data transfer reliability is improved. Moreover, consideration of energy and noise parameters further improves routing strategies and data forwarding. The Co-EPRR also adds cooperative routing to EPRR to make data communication even more reliable. In Co-EPRR, data overhearing of the node is exploited and the relay cooperates with the destination. If the destination fails to receive the correct data, then, a relay retransmits the data on request of the destination. The Co-EPRR utilizes amplify and forward incremental cooperation; data retransmission is controlled by using the bit error rate (BER) threshold. Cooperation of the nodes provides data reliability and increases the chances of a successful reception of the data.

Both the proposed schemes have promising performance in data delivery to the desired target and do not affect the scalability of the network as they do not require the Euclidean distance computation in route computation. Instead, nodes' physical distance is involved, which is computationally less complex.

To summarize, the contributions of the proposed work are as follows:

(i) The nodes are deployed in the network in such a way as to avoid early death of the nodes and improve performance. Specifically, the density of nodes in the upper area of the network is greater than other lower part of the network

(ii) The proposed EPRR scheme considers the shortest and best routes, which are the paths that provide the least time from a source to the desired target. The choice of the shortest path is based on the distance amongst nodes and sinks. Channel noise, residual energy, and depth are considered as well for further improving successful delivery

(iii) In the proposed Co-EPRR scheme, to ensure reliable delivery of data packets, cooperative routing is added to the EPRR protocol. Desired information amongst the nodes is shared to advance throughput and reliable data exchange. The relay cooperates with the destination node if the data have an error greater than a given threshold. The relay node retransmits the same data again on request of the destination. Data are processed using maximum ratio combining (MRC) to obtain the required data at the destination

(iv) Both EPRR and Co-EPRR use timer-based operations to compute the distance rather than the computationally complex Euclidean distance. This reduces the complexity of computation and avoids the loss of scalability. As a result, network performance is improved without compromising scalability, as is the usual case with existing schemes

2. Related Work

A routing algorithm presented in [17] uses depth information for data delivery and is a receiver-based approach. The data is exchanged with the nodes having low depth. The lowest depth node accepts data for further transmission to the next step. The node having the lowest depth then informs all other neighbors by transmitting the same packet with the highest preference. When the neighbors receive the same packet, they discard the old one and consider successful delivery of the packet. This algorithm performs very well. However, high traffic on the upper nodes creates data overhead and leads to early death of nodes.

A recent approach [25] that improves the most popular existing algorithm [17] is presented. The fuzzy logic and the bloom filter are utilized to improve the existing routing strategy. The fuzzy logic is used for the uncertainty of energy estimation and hop count. Moreover, for the memory improvement of the DBR, a bloom filter is utilized. This algorithm performs best in terms of many performance metrics, such as energy, data delivery, and node lifetime.

The algorithm in [26] utilized an opportunistic technique for data routing and titled as "confined energy depletion (CED) opportunistic routing (OR) mechanism". The data is routed in steps in order to achieve better performance such as energy utilization and packet reception. Firstly, the data advanced towards the next nodes. Then, the best forwarder is selected to advance the data. Next, the signal-to-noise ratio (SNR) and link quality are determined for the next step to advance the data.

The author suggested a clustered routing method, the location, and energy-aware k-means clustered routing (LE-KCR) algorithm, in [27]. K-means technology is used to determine the location of each node and the remaining energy of each node. Cluster-head selection considers both the situated site and the remaining energy of a prospective cluster-head, as well as the distance between it and its sink node. Compared with the traditional low-energy adaptive clustering hierarchy (LEACH) protocol and the enhanced LEACH protocol based on K-means clustering technology, the LE-KCR scheme consumes less energy and has fewer dead nodes.

To enable time-saving and reliable routing for UWSN, [28] offers the energy-efficient guiding-network-based routing (EEGNBR) protocol. It considers the beneficial distance-vector technique and creates a guiding network to give underwater sensor nodes the shortest route (least hop counts) toward the sinks in order to reduce network latency. Furthermore, it combined classic opportunistic routing with a revolutionary data forwarding technique known as a concurrent working mechanism, which also significantly minimizes forwarding delay while ensuring reliable routing. In terms of network latency, the protocol outperforms certain related traditional protocols while maintaining an equivalent or even superior energy usage and packet delivery ratio.

An energy-aware multilevel clustering scheme is suggested in [29], to increase the lifetime of the underwater wireless sensor network. The undersea network area is composed of 3D concentric cylinders with many layers, and each level is separated into several blocks, each of which represents a cluster. The proposed algorithm employs a vertical communication route from the sea floor to the surface region. Simulations are used to demonstrate the efficacy of the proposed approach, which performs well in terms of network lifespan and residual energy.

A delay-tolerant algorithm with sink mobility is presented in [30]. In order to minimize duplicate data and energy cost, this scheme uses different variations of the depth threshold. For further improvements, the algorithm uses mobile sinks. The deployment of mobile sinks reduces the path length between two nodes. Reducing path length tends to minimize latency and improve successful data exchange. However, the path trajectories for sinks are difficult and costly underwater. Moreover, the depth threshold increases the computational complexity of the algorithm.

The algorithm in [31] tries to maximize the network throughput and data reception by using the novel incremental cooperation. In this case, the retransmission of data by the relay occurs when the receiver fails to retrieve the correct data. Moreover, the algorithm implements a multilayer network structure and uses courier nodes. The courier nodes move in each layer for the collection of data, which maximizes the network throughput and latency. However, the courier nodes increase the cost of network deployment. Due to the cooperation, the energy cost is also high.

A delay-sensitive-energy efficient scheme for UWSNs called FVBF is proposed in [23]. The FVBF enhances the performance of the VBF [24] by using the fuzzy logic technique, where the best forward node is selected by considering the position of the node and the energy information in the cylinder. In FVBF, consideration of the residual energy ratio (RER) and fuzzy logic interference system reduces energy consumption and interference. The lowest distance and highest remaining energy are considered for selection of the destination to forward the information to the desired sink node through the multihop path. The fuzzy logic interference system reduces the contribution of the other nodes during the routing and follows the shortest path to reach the sink node. FVBF minimizes delay during the information forwarding and reduces energy consumption. However, the nodes have a large data burden on the cylinder.

To reduce latency and improve network energy, Ali et al. introduced DVRP [20]. DVRP forwards the information in the network in a diagonal or vertical manner to reduce the path length and decreases the latency. Moreover, the horizontal flow of information in the existing schemes increases the routing path, which increases the energy cost and latency. The best forwarder selection is made on energy and flood angle. Data to the next node are delivered in the same manner. The information is forwarded only in the flooding zones vertically or diagonally to decrease the path

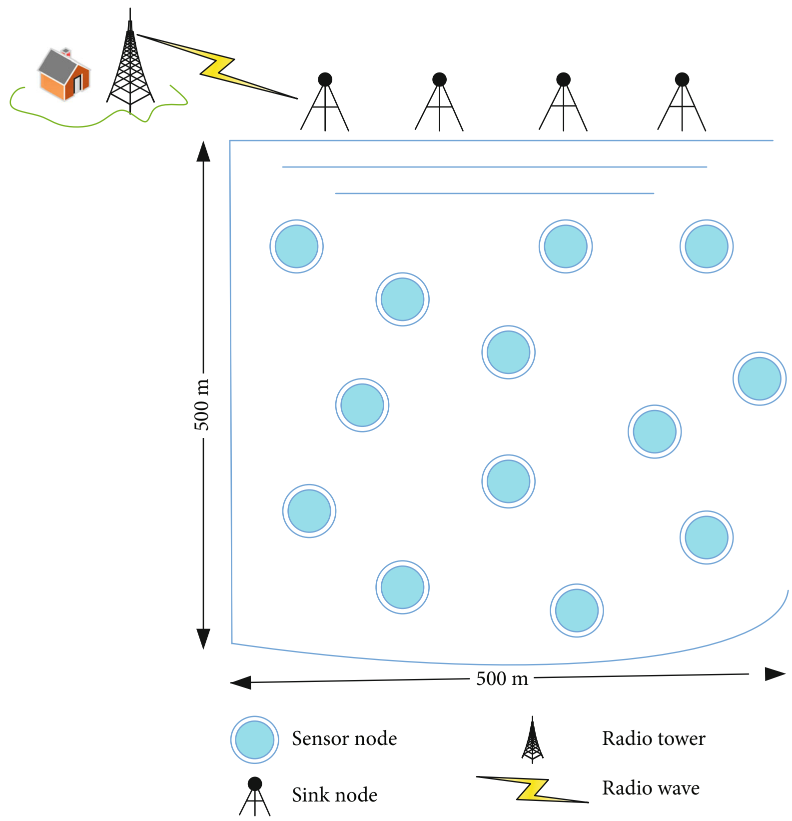

Figure 1: Network model.

Initialization;
S_{source}: Source node;
D_i: Depth possesses by sensor node i;
S_{source} broadcast a hello packet;
Calculate response time t;
$d_{s,n}$: distance between sender and neighbor node;
$d_{s,n} = (v \times t)/2$;
$d_{n,sink}$: distance between sink and neighbor node;
$d_{s,sink} = ds, n_1 + . \cdots dn_1, n_i + dn_i, sink$;
Neighbor nodes reply;
for *round=1:end* **do**
  if S_{source} *receives reply* **then**
    compute $d_{s,n}$ and $d_{n,sink}$;
    compute weight function $W_s(n)$;
    $W_s(n) = R/d_{s,n} + d_{n,sink} + D_n + N$
  end
end
Find maximum value of the $W_s(n)$ to choose relay node;
The Best relay having the highest value of the weight function

Algorithm 1: Network initialization and destination selection.

length and allow the node to forward the information to the upper sink node with a small delay. DVRP reduces the network energy consumption and minimizes the latency during packet forwarding. However, the flooding angle updating is required for data forwarding.

In [21], an efficient energy and delay minimization algorithm named PBR for underwater UWSNs is presented. The information flows in two different ways, one is a regular information packet and the other is an emergency information packet, and it is transmitted by the path which leads to

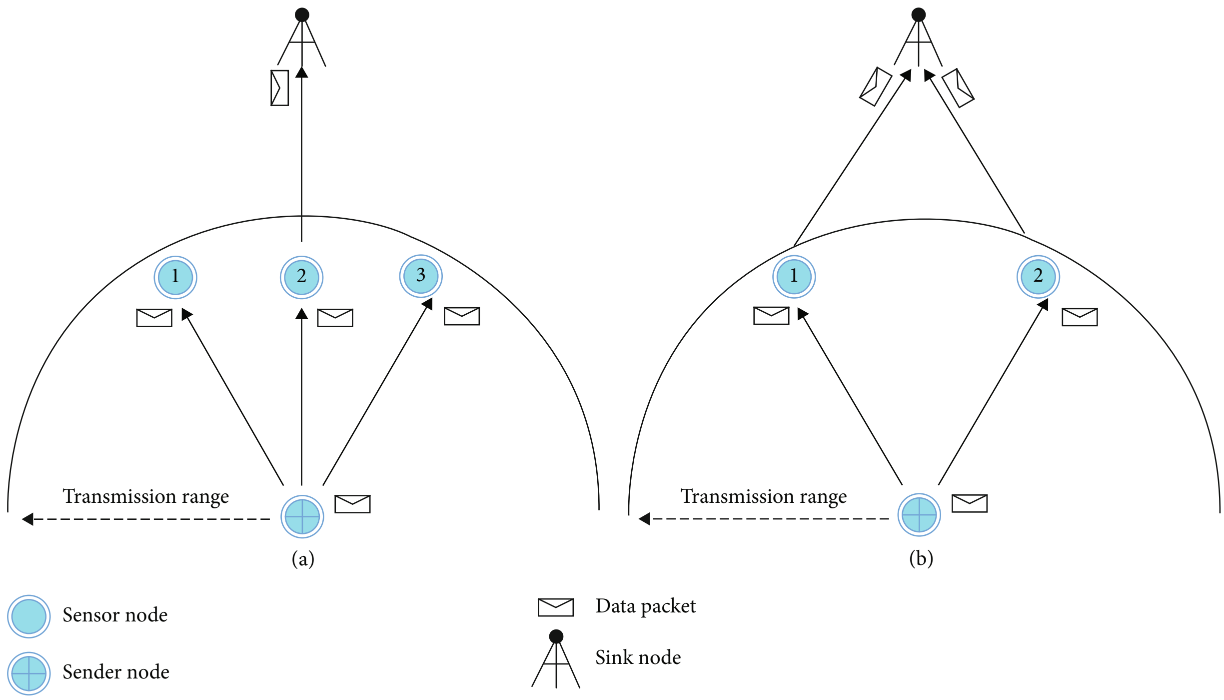

Figure 2: Data forwarding in EPRR.

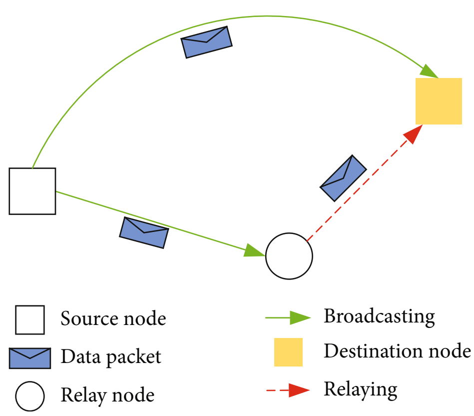

Figure 3: Data forwarding technique.

deliver data through the shortest path. The picking of the best forwarder node is based on the desired attributes such as the remaining energy, delay, and number of hops. The node having a minimum number of hops, delay, and high residual energy which lies within the communication range is considered the best forwarder node which forwards the information further to the sink node. By taking the desired parameters, it reduces the path length and increases the information that reached the sink node with low cost of energy and taking less time as compared to the counterpart schemes. However, the regular information is received with a high latency compared to the emergency packet. An efficient mechanism for the video and image transmission using acoustic waves is discussed in [32].

The UMDR [22] algorithm forwards the information with a small latency and uses a directional antenna. Instead of the broadcast nature of the data transmission, the nodes use a directional antenna to deliver data in less time. In addition, it reduces the energy cost and the overhead of the control message due to the directional antenna. However, the computational complexity due to the directional antenna is high.

The idea is introduced in [33] to obtain an efficient algorithm in energy consumption and reliability of the network by considering nodes' depth and minimum number of neighbors. The selection of the best forwarder node is established on the function parameter; minimum depth, and number of neighbors to reduce the interference between the nodes. In this algorithm, the source node first broadcasts a hello packet to collect the information of all the nodes. The node close to the sink node having the least number of neighbors is selected as the destination node. Selecting the node which has the minimum number of neighbors as a forwarder reduces the interference and collision of the data packets. The algorithm sounds superior in energy consumption, remaining energy, packets received at the sink node, packets dropped, PDR, and delay. However, the data load at the lowest depth is greater in the network and tends to die soon.

A cooperative depth-based routing (CoDBR) is presented in [15]. Data are forwarded to the destination using the fixed relaying cooperative technique. Three copies of the data are received by the destination, one is transferred directly to the destination by the sender, and the other two copies of the data are transmitted by the relay nodes. The data are then combined utilizing the MRC technique. The relay and destination selection is based on the depth information. The node that has the lowest depth is selected as a destination. The CoDBR improves the network throughput and reliability with high latency and high energy

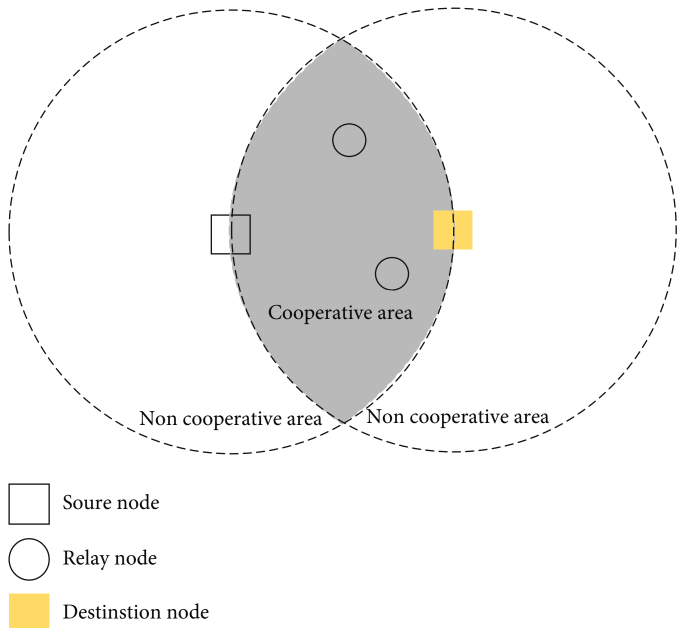

FIGURE 4: Relay selection.

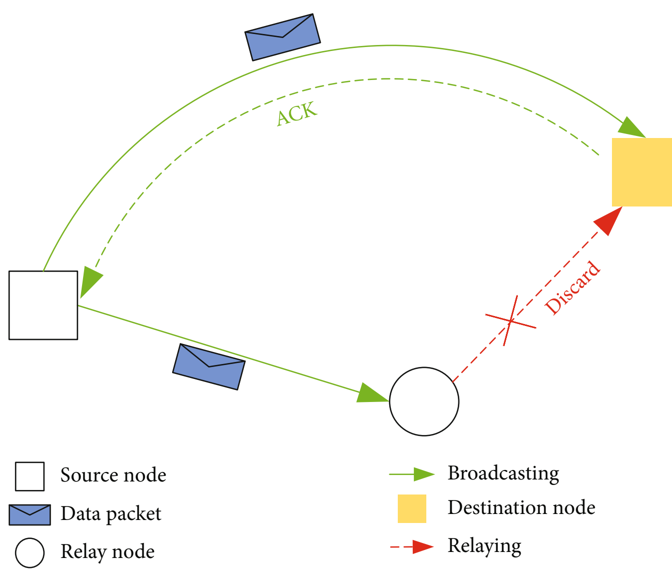

FIGURE 5: Data transmission (ACK).

consumption. Lee and his colleagues propose an automatic repeat request (ARQ) cooperative algorithm in [16]. All relay nodes transmit the data one by one on the destination request for correct data reception to achieve high throughput. However, the request of the destination to all the relay nodes one by one for retransmission consumes excessive energy and increases latency.

A cooperative void avoiding routing that requires the location information of the nodes for data forwarding is presented in [34]. For data forwarding, the sender considers an imaginary pipeline to the sink node to avoid data flooding. Nodes within the cylinder are eligible for data forwarding. The redundant packet forwarding is restricted using data holding mechanism. The protocol achieves a better packet delivery ratio by utilizing a minimum amount of energy. However, this routing algorithm requires the location of the sensor nodes for information exchange.

In the region-based cooperative routing protocol (RBCRP) [35], the whole network is divided into four regions. In each region, a mobile sink moves horizontally in the network and collects data from the nodes in its own region. The source transmits data directly or through a relay node to the MS. Direct transmission is done when the source node finds MS in its transmission range. Otherwise, the data are transmitted through a relay node to the MS. The RBCRP is an energy-efficient and reliable algorithm in terms of PDR.

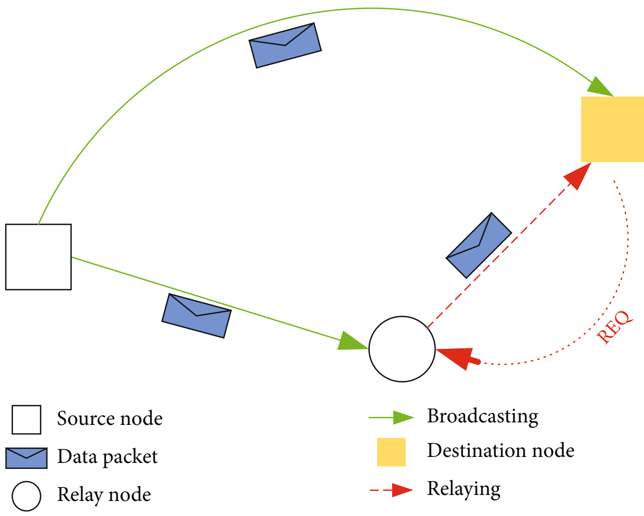

FIGURE 6: Data transmission (REQ).

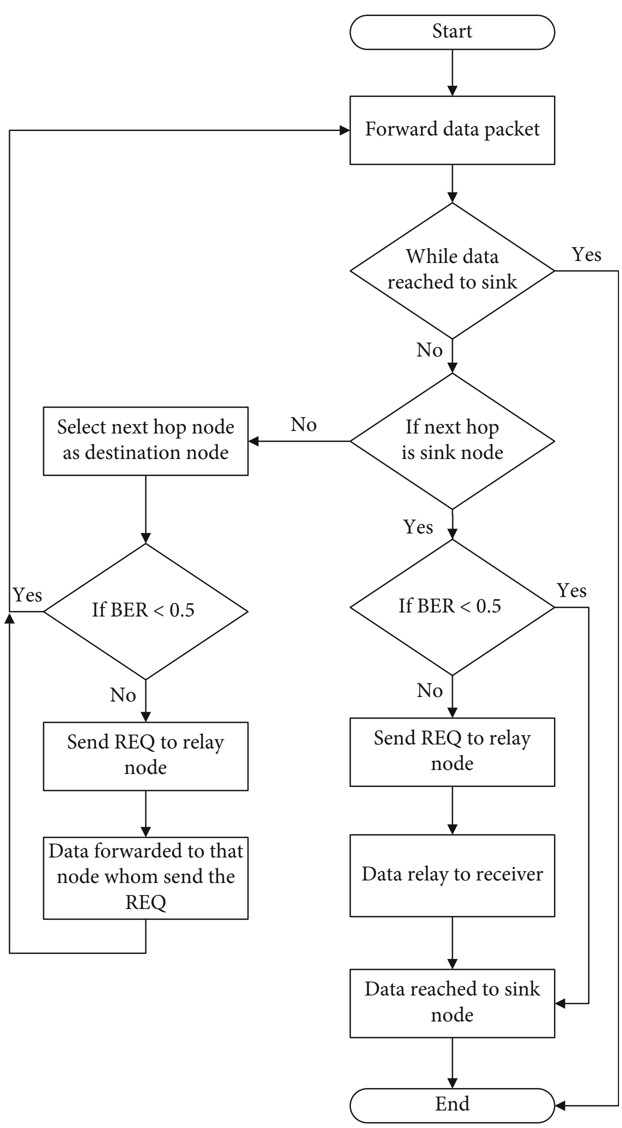

FIGURE 7: Flow chart.

S_{sender}: Sender node;
N_i: Neighbor node i of the sender node;
S_{sender} send a data packet;
for *round=1:end* **do**
  while *data packet not reached to sink node* **do**
    if *Next hop = Sink node* **then**
      if *BER* < 0.5 **then**
        data packet accepted;
        send ACK to sender;
          Data reached to sink node = true
      else
          Select N_1 as relay node;
          Send REQ to N_1 by the sink node;
          Forward data by N_1;
          data packet accepted;
          Data reached to sink node = true;
      end
    else
      Select N_1 as destination;
      if *BER* < 0.5 **then**
        data packet accepted;
        $S_{sender} = N_1$.
      else
        Select N_2 as a relay node;
        send REQ to N_2 by N_1;
        Forward data by N_2
        data packet accepted;
        $S_{sender} = N_1$
      end
    end
  end
end

ALGORITHM 2: Routing mechanism.

TABLE 1: Parameters choice.

Parameters	Size	Unit
Network size	500 × 500 × 500	Meter
Sink nodes	4	
Sensor nodes	225	
Transmission range	100	Meter
Depth threshold	60	Meter
Data packet	50	Bytes
Threshold	0.5	
Frequency	30	kHz

However, the movement of the mobile sink node is difficult underwater in terms of defining its path.

An algorithm in [36] is proposed for cooperative data transmission to the sink with a minimum energy consumption. The fuzzy logic chooses the best relay among the neighboring nodes. The proposed scheme improves the PDR and delay of the network. Packet collision minimization is done using the holding time. However, the remaining energy of the node is used for relay selection which is updated after a short time interval causes communication overhead and high latency.

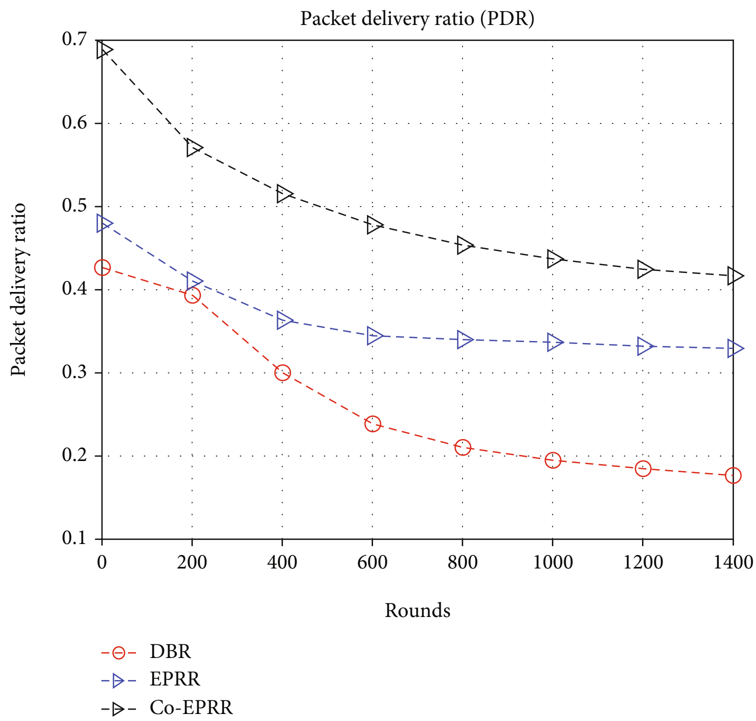

Figure 8: Packet delivery ratio (PDR).

Table 2: Packet delivery ratio (PDR) analysis.

Protocol	PDR at round 1	PDR at round 200	PDR at round 400	PDR at round 600	PDR at round 800	PDR at round 1000	PDR at round 1200	PDR at round 1400
Co-EPRR	0.688	0.571	0.515	0.478	0.453	0.437	0.424	0.416
EPRR	0.480	0.410	0.363	0.344	0.340	0.336	0.332	0.329
DBR	0.426	0.393	0.300	0.238	0.210	0.195	0.184	0.176

The cooperative routing that uses fixed ratio combining (FRC) is proposed in [37]. The selection of the relay is made on the channel noise, the distance of the source to the relay node, and the remaining energy of the node. The protocol achieves better energy consumption, delay, and network lifetime than its counterpart schemes. However, acknowledgment consumes excessive energy. The same routing metrics such as SNR, time of arrival, and distance between are used also in the algorithm presented in [38]. The relay node cooperates with the destination node whenever it does not receive the correct data. PDR and delay are improved. However, using CTS, RTS, and ACK causes communication overhead.

A cooperative communication is presented in [39], in which the relay regenerates the data followed by its transfer further to destination. The best relay node is selected using the SNR, time of arrival (TOA), and hop count information. In this approach, a better packet delivery ratio is achieved with minimal energy usage and delay. The sink node broadcasts an advertising packet to obtain the hop count information. However, this needs to be updated after specific intervals of time that cause delay.

In [40], a cooperative algorithm is proposed. The relay and destination nodes are chosen using three parameters: link quality, time of arrival, and hop count information. The data are retransmitted by the sender when it receives a request from the destination. If the sender does not receive a request from the receiver, then after some time intervals the sender forwards the same packet to the receiver. This scheme achieves better PDR with minimum energy consumption and latency. However, information updating is required for relay and destination node selection and location information is needed for data routing. A most recent approach that used both acoustic and optical waves is presented in [41]. The acoustic waves are used for the control signal transmission, while data is exchanged using optical waves.

3. Proposed EPRR Algorithm

3.1. Network Architecture. Below the water surface, a sensor network setup is installed as shown in Figure 1. The deployment of the nodes affects the performance of the network, especially underwater. In particular, nodes are deployed to have a bigger number in the upper part of the network than in the other part of the area to be monitored. The nodes are capable of detecting attributes such as temperature, pressure, and light. These sensor nodes are powered by a limited battery. The communications among sensor nodes are done

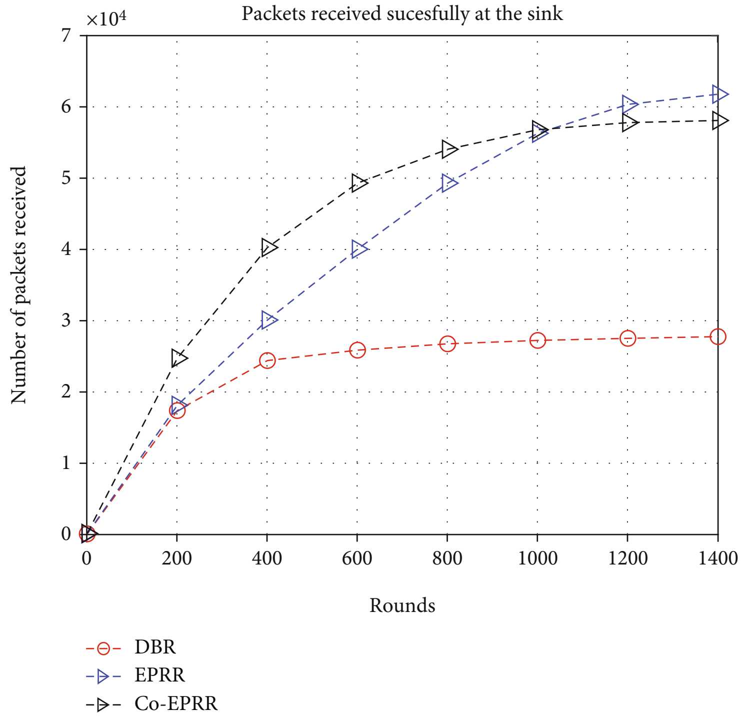

Figure 9: Received packet analysis.

Table 3: Successful packet reception analysis.

Protocol	Received data at round 1	Received data at round 200	Received data at round 400	Received data at round 600	Received data at round 800	Received data at round 1000	Received data at round 1200	Received data at round 1400
Co-EPRR	155	24632	40199	49275	54039	56783	57789	58091
EPRR	108	18039	30047	40000	49259	56280	60344	61778
DBR	96	17300	24351	25865	26753	27235	27522	27766

using acoustic waves. Each sensor node acts as a relay or source node. On the other hand, on the sea surface, sinks are placed at a fixed position. The sink nodes are different from the sensor nodes and communicate with each other through radio waves, while still using acoustic waves to communicate with the sink nodes. The acoustic modem is installed to communicate between sensor nodes at each sensor node. The sink nodes gather information from the sensor nodes; for further processing, the data is then delivered to the base station.

3.2. Network Initialization and Forwarder Selection. After network setup, the depth information of every sensor node is obtained by a pressure sensor attached to it. The depth value of the node i is denoted by D_i. Each node finds the distance from their neighbor nodes sending a specific "hello" packet. When a node receives the broadcasted hello packet from a sender, it sends a response. The sender, once it receives a response from a neighbor node, can calculate the roundtrip time taken t and then calculate the distance. The neighbors also share their depth with the sender in the hello packet. The sender s finds that its distance from every neighbor node n is represented by $d_{s,n} = (v \times t)/2$, where v represents the speed of acoustic waves in water. Then, the next forwarder finds its distance in the same manner from the next nodes and shares that distance value with the sender. At the end of the process, each node knows the distance value from the sink $d_{s,\mathrm{sink}} = ds, n_1 + \cdots + dn_1, n_i + dn_i$, sink, where n_i is the last node which communicates directly with the sink. In other words, the sink lies in the coverage area of the node. Based on the parameters D_n, $d_{s,n}$,$d_{n,\mathrm{sink}}$, noise N, and residual energy R a sender node can also compute a weight function for the neighbor node as follows:

$$W_s(n) = \frac{R}{d_{s,n} + d_{n,\mathrm{sink}} + D_n + N}. \quad (1)$$

The weight function for each neighbor node is determined by equation (1). The source then determines the next forwarder on the basis of the maximum value of the weight function. The best forwarder node is selected as the one with the highest value of the weight function. Algorithm 1 depicts the selection of the forwarder node.

The sender calculates the weight function for every neighbor and selects the node that follows the shortest route

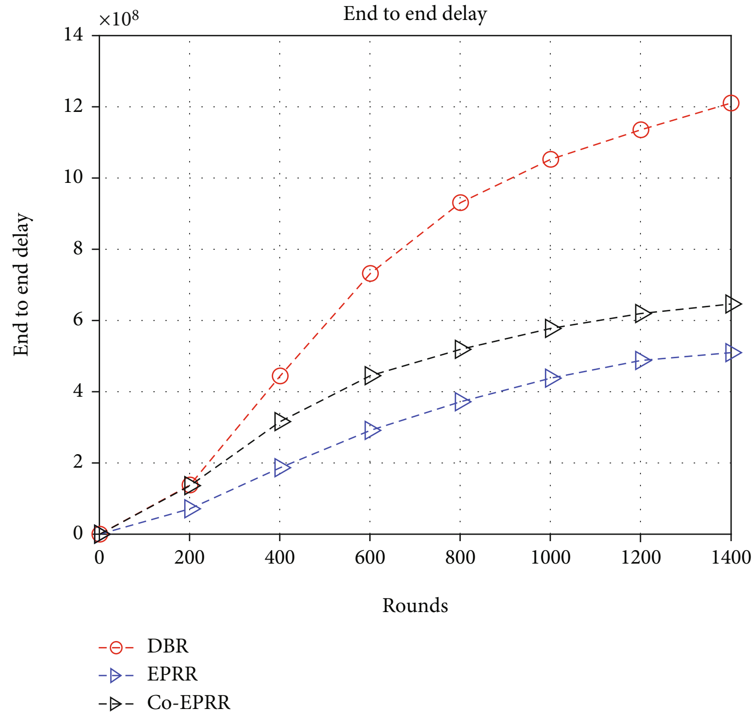

FIGURE 10: Network delay.

TABLE 4: End to end latency analysis.

Protocol	Delay at round 1	Delay at round 200	Delay at round 400	Delay at round 600	Delay at round 800	Delay at round 1000	Delay at round 1200	Delay at round 1400
Co-EPRR	5.62×10^3	1.35×10^8	3.15×10^8	4.44×10^8	5.18×10^8	5.77×10^8	6.19×10^8	6.46×10^8
EPRR	2.43×10^3	7.07×10^7	1.86×10^8	2.91×10^8	3.71×10^8	4.37×10^8	4.87×10^8	5.09×10^8
DBR	2.74×10^3	1.36×10^8	4.42×10^8	7.30×10^8	9.30×10^8	1.05×10^9	1.13×10^9	1.21×10^9

to the sink. Two different scenarios are depicted in Figure 2 in which all neighbors have the same depth. When using only depth information, all neighbors will direct data to the next stage because of having the same depth value. Therefore, the proposed approach chooses the best forwarder using the distance with the depth information of the nodes. In the scenario depicted in part a, node 2 is selected as the next forwarder, because it has the highest value of the weight function than the other neighbors. In other words, it is the shortest route to the sink than the others. In part b, both nodes have the same depth and distance from the source and the sink. So, both hold the same value of the weight function. Therefore, in this case, the sender has an open choice to select any of these nodes. And one of them directs data toward the sink.

3.3. Data Forwarding. When a source needs to exchange a data, it first checks the sink in its proximity. If a sink is available, then, direct exchanging of data with the sink node is performed without any other indirect path. When a sink is not present, the data are routed through other nodes until they reach the sink node. Namely, the source node gives the packet to be sent to its neighbor nodes in case of not finding any sink node in its neighborhood. When the source to destination link fails, the data are dropped. From these neighbor nodes, a destination is selected on the basis of equation (1) which has the maximum value. Then, the sender sends the data with their unique ID and also embed the ID of the destination to the data packet. The same process is followed at every next hop until the data reach the sink node.

4. Proposed Co-EPRR Algorithm

The EPRR does not guarantee reliable data delivery, because if the source to destination link fails, then, the data is lost. The Co-EPRR is proposed, which provides data reliability whenever the source to the destination link is failed and then relays the data to the destination. The cooperation of the relay node and the combining technique is discussed in this section. The network architecture, network initialization, and destination selection are the same in Co-EPRR as in EPRR.

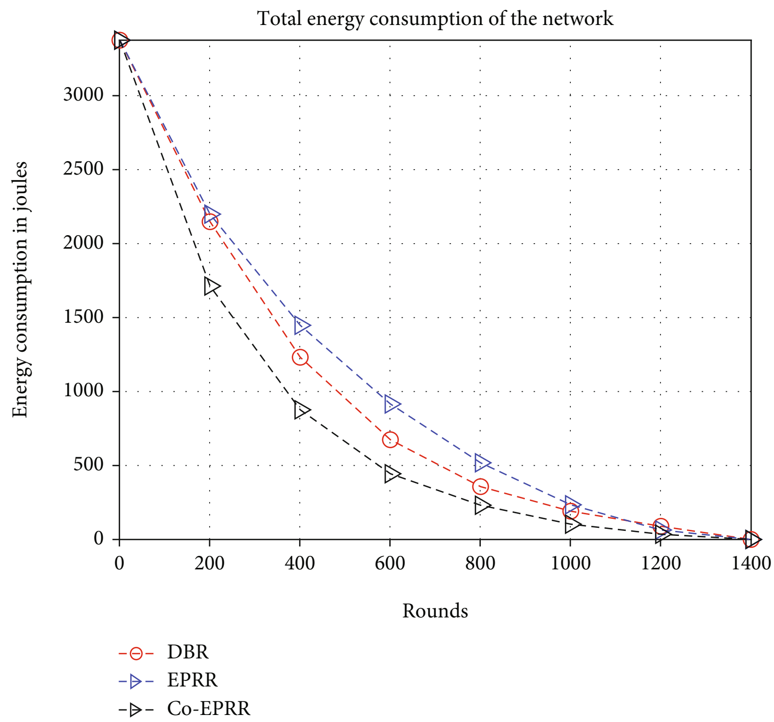

Figure 11: Residual energy analysis.

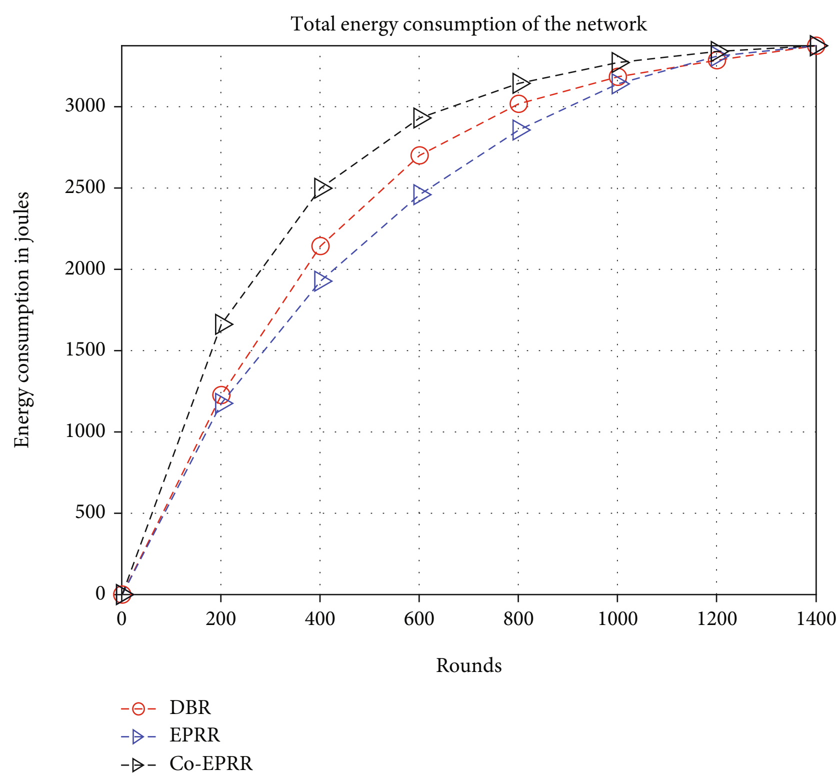

Figure 12: Energy expenditure analysis.

4.1. Relay Selection Using Cooperation. For cooperation, three nodes are considered: the source, the relay, and the destination nodes as depicted in Figure 3. In cooperative schemes, data is received at the destination from the sender as well as by the relay node. The first one is known as broadcasting, and the second is relaying. In the first phase, the

Table 5: Remaining energy analysis.

Protocol	Residual energy at round 1	Residual energy at round 200	Residual energy at round 400	Residual energy at round 600	Residual energy at round 800	Residual energy at round 1000	Residual energy at round 1200	Residual energy at round 1400
Co-EPRR	3.37×10^3	1.71×10^3	880.00	445.84	232.27	103.85	35.49	0
EPRR	3.37×10^3	2.20×10^3	1.45×10^3	918.23	520.10	235.62	64.68	0
DBR	3.37×10^3	2.15×10^3	1.23×10^3	676.52	358.38	191.74	89.66	0

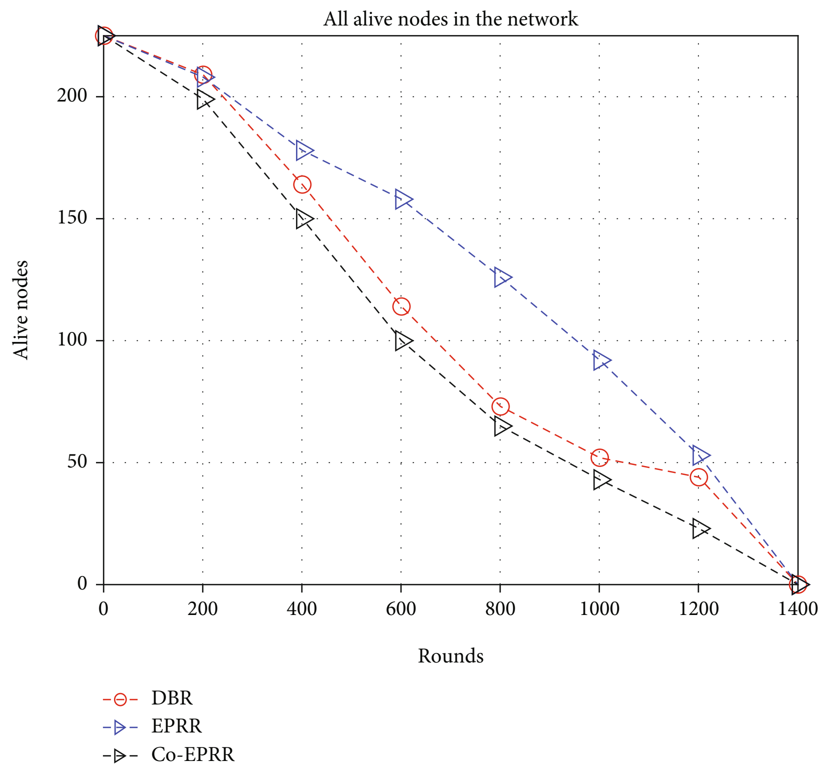

Figure 13: Alive node analysis.

destination and relay nodes receive data directly from the source node. In the second phase, the data received by the relay node is directed toward the destination.

The data forwarding from source S to relay R and destination D is formulated as

$$\begin{aligned} y_{sd}(t) &= h_{sd}X_s(t) + N_{sd}(t), \\ y_{sr}(t) &= h_{sr}X_s(t) + N_{sr}(t), \end{aligned} \quad (2)$$

where h_{sd} and h_{sr} are the channel gains between $S-D$ and $S-R$, respectively. The signal that S transmits at time t is X_s. The y_{sd} and y_{sr} are signals from $S-D$ and $S-R$, respectively. The N_{sd} and N_{sr} are the channel noise added to the desired signal from the $S-D$ and $S-R$ links, respectively.

Data communications from R to D are formulated as follows:

$$y_{rd}(t) = h_{rd}f(y_{sr}(t)) + N_{rd}(t), \quad (3)$$

where h_{rd} is the channel gain from $R-D$. The N_{rd} is the channel noise along the $R-D$ link. R processes the signal received from S represented by a function $f(y_{sr})$. In this paper, the AF technique (amplify and forward) is used. R amplifies the desired signal by a factor of β before sending it to D and receives the signal as follows:

$$y_{rd}(t) = h_{rd}\beta(h_{sr}X_s(t) + N_{sr}(t)) + N_{rd}(t). \quad (4)$$

The channel is modeled as Rayleigh fading and AWGN is used to simulate the channel noise. The sequence of bit generated by a sender using binary phase shift keying (BPSK) is sent over the AWGN channel directly to a destination. Then the destination checks the bit error rate (BER) and is given as [42]

$$\text{BER} = \frac{1}{2}\left(1 - \sqrt{\frac{\bar{\text{SNR}}}{1 + \bar{\text{SNR}}}}\right), \quad (5)$$

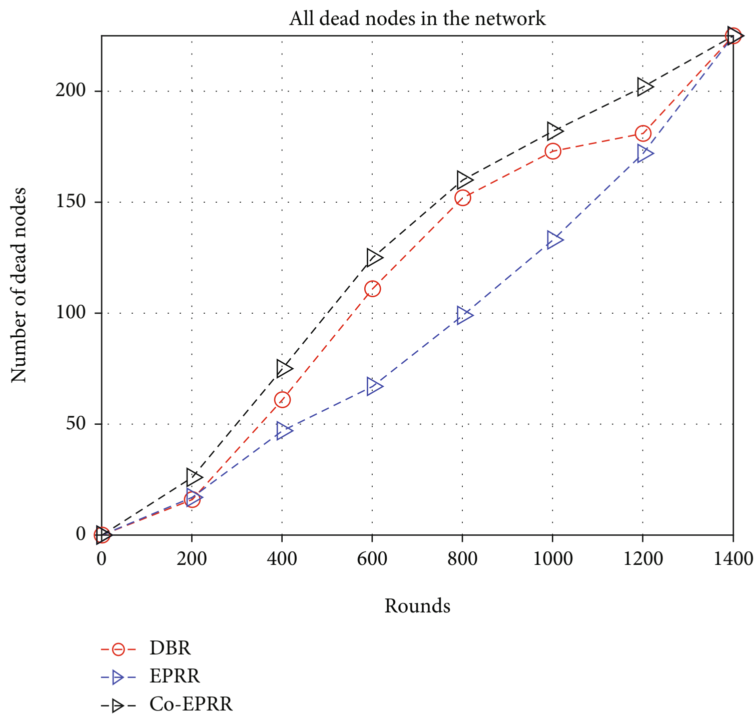

Figure 14: Dead node analysis.

Table 6: Analysis of the number of alive nodes in the network.

Protocol	Alive nodes at round 1	Alive nodes at round 200	Alive nodes at round 400	Alive nodes at round 600	Alive nodes at round 800	Alive nodes at round 1000	Alive nodes at round 1200	Alive nodes at round 1400
Co-EPRR	225	199	150	100	66	43	23	0
EPRR	225	209	178	158	127	92	53	0
DBR	225	209	165	114	73	52	44	0

where

$$\bar{\text{SNR}} = 10^{\text{SNR}/10},$$
$$\text{SNR} = \frac{P_t}{A(d,f)N(f)}, \quad (6)$$

where P_t represents the transmitted power of the source. The $A(d,f)$ and $N(f)$ represent the attenuation and noise associated with the underwater channel.

The relay is selected from the nodes which lie in the common transmission range (cooperative area) of both S and D as shown in Figure 4. The relay and destination selection criterion is the same as for the destination selection in the EPRR. Based on the weight function, two nodes are selected: one serves as a relay and the other as a destination (equation (1)). The destination is selected which has the highest value of the weight function, and the second node is selected as a relay which holds the highest value of the weight function. The relay forwards data only once to the destination to reduce the data collision and delay time.

When a data is received by the destination, it analyzes the BER. If the BER is less than 0.5, then, the destination responds to the sender and sends an acknowledgment (ACK) as shown in Figure 5. When the data packet BER is greater than 0.5, then, D requests R for retransmission as shown in Figure 6. The sender node embeds relay ID information when transmitting the hello packet. Whenever the destination needs for retransmission of the data, then, the destination requests to relay which is close to it. The relay node amplifies and forwards (AF) the desired data packet and sends it to the destination.

4.2. Combining Technique. When a destination has multiple replica of the same data packet, all these data packets are combined using one of the diversity combining techniques. In this paper, the MRC technique is used. At the destination, the received signal y_d is the combination of all relaying and directly transmitted signals, which is combined by using the MRC technique and is given as [43]

$$y_d(t) = \sum_{k=1}^{L} h_{kd}^{*} \times y_{kd}(t), \quad (7)$$

where y_{kd} is the received signal through multiple paths and h_{kd}^{*} represents the conjugate of the channel gain. In this case,

D combines two signals: one from S and one from R; therefore, $L = 2$ and is expressed as follows:

$$y_d(t) = h_{rd}^* \times y_{rd}(t) + h_{sd}^* \times y_{sd}(t). \quad (8)$$

The flow chart in Figure 7 shows the detail of the data transmission of the proposed algorithm. Algorithm 2 also explains the whole process of the proposed scheme.

5. Simulation Results and Discussion

MATLAB is used for simulation purposes to authenticate the results of the EPRR and Co-EPRR. The EPRR and Co-EPRR schemes are compared with DBR, because the DBR considers the depth of the node for data routing. For fair comparison, the mobility model and the MAC scheme considered in DBR are also taken into consideration by the proposed schemes. A network having a size of 500 m × 500 m × 500 m is considered which distributes nodes randomly. The density in the upper area of the network is kept higher than that of the rest of the network. It is due to the high traffic load on the upper nodes, in which the death ratio is greater than the highest depth nodes. Among 225 nodes, 100 of them are deployed in the upper 100 m^3. The sinks are placed at the top of the networks. The sink node has an infinite energy source, because it can be easily powered on the sea surface. The sensor node consumes 2 W, 0.8 W, and 8 mW power in transmission, reception, and idle mode, respectively. A hello packet contains 48 bits and is broadcasted to establish a connection. The transmission range and depth threshold of the sensor nodes are 100 m and 60 m, respectively. Table 1 shows metrics under consideration.

In Co-EPRR, the packet delivery ratio is the highest than EPRR and DBR. Because when data are received by a destination, it is checked. When the BER is less than the threshold value, it is accepted. However, if BER exceeds the limits, then, the destination requests are relayed for retransmission, which enhances the packet delivery ratio. The cooperation is helpful in advancing packets to the surface that raises PDR. Moreover, the greater number of nodes in the upper area of the network provides a path for the data. The path providing by the upper nodes leads to enhance the packet reception probability. Also, the selection of the shortest path is another reason for the highest PDR. The effects of the channel are less due to the shortest path. Due to all these reasons, the PDR of the Co-EPRR is the highest than that of the rest of the algorithms. The results of PDR are shown in Figure 8.

The PDR of the proposed EPRR is better than the DBR. Because in the former, the shortest path is followed toward the sink node in which the probability of packet loss is less. Also, the packet is less affected by the channel noise and attenuation which is received correctly at the destination and the packet drop probability is less than DBR. Another reason for better PDR is the density of the network. In the upper area of the network, the number of nodes is kept greater in order to increase the packet delivery probability. So, the proposed algorithms get good performance with respect to PDR.

The DBR has the lowest PDR. It is due to the high traffic on the upper nodes that the death ratio is high. The death of the nodes leads to break the communication between sinks and the lower nodes. Moreover, DBR considers the depth for path selection which does not guarantee the shortest path and the data may be corrupted by noise and tend to reduce the PDR. The PDR performance analysis is also shown in Table 2.

The received packet analysis is shown in Figure 9. The number of packets received in Co-EPRR is higher than that in EPRR and DBR. Due to the cooperation of the nodes, it maximizes the number of received packets. The proposed cooperative scheme requests to relay for retransmission of the data. Retransmission of data increases the chances of successful reception. Another reason for the highest data reception is the best possible route for the data exchange. Moreover, the network topology also contributes. The greater number of nodes provides multiple paths to the surface which enhances the reception of the data. At round 1000, the reception of the packets performance goes down than the EPRR. It is due to the death of the node. The death of the nodes reduces the chances of cooperation. Reduction in the cooperation process leads to fewer packet reception.

The EPRR has a higher packet reception than DBR. Due to the distribution of nodes in the network, multiple paths are available for data exchange, which increases the reception of the packets. Also, the shortest path selection leads to reduce channel effects on the data. The less channel effects on the data tend to the correct data reception and increase them. At the start up to 200 rounds, the packet reception in both EPRR and DBR is the same. It is due to the flooding of the data in DBR. After that, the nodes die, leading to reduction of packet reception. The analysis is also shown in Table 3.

The EPRR delay is the lowest than the others as shown in Figure 10, because it follows the shortest path to the sink node which deliver data with small latency, while the Co-EPRR has a greater delay than the proposed EPRR scheme. The reason is that the destination takes time to check the received data through multiple paths and to combine these data packets. The cooperation at every next hop node takes time, which results in delay. Therefore, in the Co-EPRR, the data is received at the sink node with high latency.

In the counterpart DBR scheme, redundant packets are transmitted, which increases packet collision, energy consumption, and latency. Also, the selection parameter only considers the nodes' depth for data routing, which does not guarantee the shortest route to the destination. In the proposed EPRR and Co-EPRR schemes, the shortest route is used for data transmission by considering the distance with the depth value of the node. The decision for the forwarder selection is made by the sender which selects only one forwarder which leads to reducing the packet collision probability and redundant transmission. The delay performance is further elaborated in Table 4.

In Figures 11 and 12, the residual energy and energy consumption results are shown. The Co-EPRR residual energy is the lowest than the counterpart schemes as it checks the BER prior to packet advancing. If BER is greater than 0.5, then, the destination requests to relay for retransmission. In short, two sensor nodes are used to transmit the same data packet and both sensor nodes consume energy. The cooperation is done at every next hop node, which consumes excessive energy. So, in Co-EPRR, the energy consumption is greater than that of the proposed EPRR and the counterpart scheme. Conversely, the residual energy is minimum than the counterpart schemes.

The EPRR has a higher residual energy than the counterpart scheme. The shortest path is followed to the sink node, which reduces energy consumption as few nodes are involved in data forwarding. Also, multipath transmission is avoided which consumes less energy and its residual energy is higher than the counterpart schemes. While in the competitor DBR algorithm, redundant data transmission tends the more energy consumption and reduces the network lifetime. Table 5 shows more detail about the energy of the network.

In Co-EPRR, nodes die soon as cooperation makes them use of their energy rapidly. Therefore, cooperative schemes have the lowest alive nodes and the highest dead nodes compared to DBR and EPRR as shown in Figures 13 and 14, respectively. In EPRR, the nodes do not die soon due to the lower energy usage. In DBR, the higher energy consumption leads to rapid death of the nodes. Therefore, the number of alive nodes in DBR is lower than that of the proposed EPRR. As a result, the number of alive nodes is higher in EPRR than in the counterpart scheme as shown in Figure 13 and also in Table 6.

6. Conclusion and Future Work

Two routing algorithms are proposed for UASNs: EPRR and Co-EPRR. The former used delay-sensitive paths for data routing. This reduced the delay and shortened the time for which data are affected by channel properties, which improved the reliability of data delivery. The latter algorithm added cooperative routing to EPRR to further counteract adverse properties of the channel in the data, which involved sending data over multiple links from a source to a destination. This increased the probability of successful data delivery to the desired target, even if some links failed to deliver the data. Both protocols maintained scalability of the network by computing physical distance rather than the computationally complex Euclidean distance. Network scalability is lost when Euclidean distance is computed, as it involves nodes' coordinate computations, and nodes constantly change their positions. Furthermore, the higher density of the nodes provides stable operation in the proposed schemes. Extensive simulations proved that the proposed schemes performed better in delivering packets to the desired target. The delay of the EPRR scheme was shorter than that of the counterpart scheme. However, the delay of Co-EPRR was greater than that of the counterpart scheme due to the routing data over multiple paths in the former. In the future, energy harvesting techniques will be used to energize the surface nodes to prolong the network lifetime.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] Y. W. Hong, W. J. Huang, F. H. Chiu, and C. C. J. Kuo, "Cooperative communications in resource-constrained wireless networks," *IEEE Signal Processing Magazine*, vol. 24, no. 3, pp. 47–57, 2007.

[2] J. Heidemann, M. Stojanovic, and M. Zorzi, "Underwater sensor networks: applications, advances and challenges," *Philosophical Transactions of the Royal Society A*, vol. 370, no. 1958, pp. 158–175, 2012.

[3] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: research challenges," *Ad Hoc Networks*, vol. 3, no. 3, pp. 257–279, 2005.

[4] I. F. Akyildiz, D. Pompili, and T. Melodia, "State-of-the-Art in Protocol Research for Underwater Acoustic Sensor Networks," *Proceedings of the 1st ACM International Workshop on Underwater Networks*, , pp. 7–16, ACM, 2006.

[5] J. Heidemann, W. Ye, J. Wills, A. Syed, and Y. Li, "Research challenges and applications for underwater sensor networking," in *IEEE Wireless Communications and Networking Conference, 2006. WCNC 2006*, Las Vegas, NV, 2006, April.

[6] A. Agustin and J. Vidal, "Amplify-and-forward cooperation under interference-limited spatial reuse of the relay slot," *IEEE Transactions on Wireless Communications*, vol. 7, no. 5, pp. 1952–1962, 2008.

[7] H. Esmaiel, Z. A. H. Qasem, H. Sun, J. Wang, and N. U. R. Junejo, "Underwater image transmission using spatial modulation unequal error protection for internet of underwater things," *Sensors*, vol. 19, no. 23, p. 5271, 2019.

[8] D. Simmons, D. Halls, and J. P. Coon, "OFDM-based nonlinear fixed-gain amplify-and-forward relay systems: SER optimization and experimental testing," in *Networks and Communications (EuCNC), 2014 European Conference on (pp. 1-5). IEEE*, Bologna, Italy, 2014, June.

[9] M. Fadoul, M. B. Morsin, C. Y. Leow, and A. A. Eteng, "Using amplify-and-forward relay for coverage extension in indoor environments," *Journal of Theoretical and Applied Information Technology*, vol. 91, no. 2, 2016.

[10] Q. Song and M. Garcia, "Cooperative OFDM underwater acoustic communications with limited feedback: part I," *International Journal of Computer Applications*, vol. 54, no. 16, pp. 42–46, 2012.

[11] J. N. Laneman, D. N. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062–3080, 2004.

[12] M. O. Hasna and M. S. Alouini, "A performance study of dual-hop transmissions with fixed gain relays," *IEEE Transactions on Wireless Communications*, vol. 3, no. 6, pp. 1963–1968, 2004.

[13] H. Hourani, *An overview of diversity techniques in wireless communication systems*, IEEE JSAC, 2004.

[14] P. Liu, Z. Tao, Z. Lin, E. Erkip, and S. Panwar, "Advances in smart antennas - cooperative wireless communications: a cross-layer approach," *IEEE Wireless Communications*, vol. 13, no. 4, pp. 84–92, 2006.

[15] H. Nasir, N. Javaid, H. Ashraf et al., "CoDBR: cooperative depth based routing for underwater wireless sensor networks," in *Broadband and Wireless Computing, Communication and Applications (BWCCA), 2014 Ninth International Conference on*, pp. 52–57, Guangdong, China, 2014, November.

[16] J. W. Lee, J. Y. Cheon, and H. S. Cho, "A Cooperative ARQ Scheme in Underwater Acoustic Sensor Networks," in *OCEANS 2010 IEEE-Sydney*, pp. 1–5, IEEE, 2010.

[17] H. Yan, Z. J. Shi, and J. H. Cui, "DBR: Depth-Based Routing for Underwater Sensor Networks," in *International Conference on Research in Networking*, pp. 72–86, Springer, Berlin, Heidelberg, 2008.

[18] Z. A. H. Qasem, J. Wang, X. Kuai, H. Sun, and H. Esmaiel, "Enabling unique word OFDM for underwater acoustic communication," *IEEE Wireless Communications Letters*, vol. 10, no. 9, pp. 1886–1889, 2021.

[19] H. Esmaiel, Z. A. H. Qasem, H. Sun, J. Qi, J. Wang, and Y. Gu, "Wireless information and power transfer for underwater acoustic time-reversed NOMA," *IET Communications*, vol. 14, no. 19, pp. 3394–3403, 2020.

[20] T. Ali, L. T. Jung, and I. Faye, "Diagonal and vertical routing protocol for underwater wireless sensor network," *Procedia-Social and Behavioral Sciences*, vol. 129, pp. 372–379, 2014.

[21] S. Shetty, R. M. Pai, and M. M. Pai, "Energy efficient message priority based routing protocol for aquaculture applications using underwater sensor network," *Wireless Personal Communications*, vol. 103, no. 2, pp. 1871–1894, 2018.

[22] J. Yang, S. Liu, Q. Liu, and G. Qiao, "UMDR: multi-path routing protocol for underwater ad hoc networks with directional antenna," in *Journal of Physics: Conference Series (Vol. 960, No. 1, p. 012010)*, IOP publishing, 2018.

[23] R. Bu, S. Wang, and H. Wang, "Fuzzy logic vector–based forwarding routing protocol for underwater acoustic sensor networks," *Transactions on Emerging Telecommunications Technologies*, vol. 29, no. 3, article e3252, 2018.

[24] P. Xie, J. H. Cui, and L. Lao, "VBF: Vector-Based Forwarding Protocol for Underwater Sensor Networks," in *International Conference on Research in Networking*, pp. 1216–1221, Springer, Berlin, Heidelberg, 2006.

[25] H. Karimi, K. Khamforoosh, and V. Maihami, "Improvement of DBR routing protocol in underwater wireless sensor networks using fuzzy logic and bloom filter," *PLoS One*, vol. 17, no. 2, article e0263418, 2022.

[26] S. Ashraf, M. Gao, Z. Chen, H. Naeem, and T. Ahmed, "CED-OR based opportunistic routing mechanism for underwater wireless sensor networks," *Wireless Personal Communications*, vol. 125, no. 1, pp. 487–511, 2022.

[27] L. Li, Q. Yang, and X. Jing, "A K-means clustered routing algorithm with location and energy awareness for underwater wireless sensor networks," *In Photonics*, vol. 9, no. 5, p. 282, 2022.

[28] Z. Liu, X. Jin, Y. Yang, K. Ma, and X. Guan, "Energy-efficient guiding-network-based routing for underwater wireless sensor networks," *IEEE Internet of Things Journal*, 2022.

[29] S. Chinnasamy, J. Naveen, P. J. A. Alphonse, C. Dhasarathan, and G. Sambasivam, "Energy-aware multilevel clustering scheme for underwater wireless sensor networks," *Access*, vol. 10, pp. 55868–55875, 2022.

[30] K. Latif, N. Javaid, I. Ullah, Z. Kaleem, Z. Abbas Malik, and L. D. D. I. E. E. R. Nguyen, "DIEER: delay-intolerant energy-efficient routing with sink mobility in underwater wireless sensor networks," *Sensors*, vol. 20, no. 12, p. 3467, 2020.

[31] A. Yahya, S. U. Islam, M. Zahid et al., "Cooperative routing for energy efficient underwater wireless sensor networks," *IEEE Access*, vol. 7, pp. 141888–141899, 2019.

[32] A. Ezzat, H. Esmaiel, and H. S. Hussein, "Efficient real time image transmission over underwater acoustic mmwave channel," in *In 2018 International Conference on Computing, Electronics & Communications Engineering (iCCECE)*, pp. 230–235, IEEE, Southend, UK, 2018.

[33] A. Khan, N. Javaid, I. Ali et al., "An energy efficient interference-aware routing protocol for underwater WSNs," *KSII Transactions on Internet and Information Systems*, vol. 11, no. 10, pp. 4844–4864, 2017.

[34] N. Javaid, T. Hafeez, Z. Wadud, N. Alrajeh, M. S. Alabed, and N. Guizani, "Establishing a cooperation-based and void node avoiding energy-efficient underwater WSN for a cloud," *IEEE Access*, vol. 5, pp. 11582–11593, 2017.

[35] N. Javaid, S. Hussain, A. Ahmad, M. Imran, A. Khan, and M. Guizani, "Region based cooperative routing in underwater wireless sensor networks," *Journal of Network and Computer Applications*, vol. 92, pp. 31–41, 2017.

[36] M. A. Rahman, Y. Lee, and I. Koo, "EECOR: an energy-efficient cooperative opportunistic routing protocol for underwater acoustic sensor networks," *IEEE Access*, vol. 5, pp. 14119–14132, 2017.

[37] S. Ahmed, N. Javaid, F. A. Khan et al., "Co-UWSN: cooperative energy-efficient protocol for underwater WSNs," *International Journal of Distributed Sensor Networks*, vol. 11, no. 4, Article ID 891410, 2015.

[38] Y. Wei and D. S. Kim, "Cooperative relay for reliable communications in underwater acoustic sensor networks," in *Military Communications Conference (MILCOM)*, pp. 518–524, Baltimore, MD, USA, October 2014.

[39] D. D. Tan, T. T. Le, and D. S. Kim, "Distributed cooperative transmission for underwater acoustic sensor networks," in *2014 IEEE Military Communications Conference*, pp. 205–210, Baltimore, MD, USA, April 2013.

[40] H. Tran-Dang and D. S. Kim, "Efficient relay selection algorithm for cooperative routing in underwater acoustic sensor networks," in *2018 14th IEEE international workshop on factory communication systems (WFCS)*, pp. 1–9, Imperia, Italy, June 2018.

[41] M. Mostafa, H. Esmaiel, and O. A. Omer, "Hybrid energy efficient routing protocol for UWSNs," in *2020 2nd International Conference on Computer and Information Sciences (ICCIS)*, pp. 1–6, Sakaka, Saudi Arabia, Oct 2020.

[42] J. G. Proakis, *Digital Communications*, McGraw-Hill, New York, 1995.

[43] P. Wang, L. Zhang, and V. O. Li, "Asynchronous cooperative transmission for three-dimensional underwater acoustic networks," *IET Communications*, vol. 7, no. 4, pp. 286–294, 2013.