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Energy-Aware and Reliability-Based Localization-Free Cooperative Acoustic Wireless Sensor Networks

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ABSTRACT In underwater wireless sensor networks (UWSNs), protocols with efficient energy and reliable communication are challenging, due to the unpredictable aqueous environment. The sensor nodes deployed in the specific region can not last for a long time communicating with each other because of limited energy. Also, the low speed of the acoustic waves and the small available bandwidth produce high latency as well as high transmission loss, which affects the network reliability. To address such problems, several protocols exist in literature. However, these protocols lose energy efficiency and reliability, as they calculate the geographical coordinates of the node or they do not avoid unfavorable channel conditions. To tackle these challenges, this article presents the two novel routing protocol for UWSNs. The first one energy path and channel aware (EPACA) protocol transmits data from a bottom of the water to the surface sink by taking node's residual energy (R_e), packet history (H_p), distance (d) and bit error rate (BER). In EPACA protocol, a source node computes a function value for every neighbor node. The most prior node in terms of calculated function is considered as the target destination. However, the EPACA protocol may not always guarantee packet reliability, as it delivers packets over a single path. To maintain the packet reliability in the network, the cooperative-energy path and channel aware (CoEPACA) routing scheme is added which uses relay nodes in packet advancement. In the CoEPACA protocol, the destination node receives various copies from the source and relay(s). The received data at the destination from multiple routes make the network more reliable due to avoiding the erroneous data. The MATLAB simulations results validated the performance of the proposed algorithms. The EPACA protocol consumed 29.01% and the CoEPACA protocol 19.04% less energy than the counterpart scheme. In addition, the overall 12.40% improvement is achieved in the packet's reliability. Also, the EPACA protocol outperforms for packets' latency and network lifetime.

INDEX TERMS Localization-free, energy-aware, acoustic, link quality, cooperative routing, EPACA, CoEPACA.

I. INTRODUCTION

In underwater wireless sensor networks (UWSNs), the unpredictable nature of the acoustic channel poses major challenges in the designing of energy-efficient and reliable protocols. Energy efficiency and packets reliability have paramount significance in a network. Protocols having efficient energy and reliability can be used for long time applications such as military defense, oil/gas exploration, disaster prevention, and marine detection [1], [2], as in Fig. 2.

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The underwater channel faces a number of challenges like multi-path fading, limited available bandwidth, and high bit error rate [3]. The radio waves produce high attenuation and absorption, therefore, the underwater networks use acoustic waves for communications [4]. However, the acoustic waves deliver packets with five times slower speed than radio waves [5].

The localization of the underwater nodes is very difficult as relative to the wireless terrestrial network. The network in underwater is dynamic as the free movement of nodes with the ocean current. This can result in frequent changes in their position. Finding and calculating of nodes position lead the

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network to high energy consumption. The underwater nodes are operated with limited energy and charging or replacing the node's battery is a challenging task because of the aqueous unpleasant environment [6]. Several protocols [7]–[9] that make use of localization techniques in the data forwarding process. Localization is employed to examine the node's coordinates in the water. However, it poses several challenges such as false position calculation, high energy consumption, and high latency. The conventional protocols for UWSNs [10]–[13] do not take reliability into consideration while delivering data packets. In these protocols, a single-hop mechanism is used in packets advancement. In consequence, they are unable to achieve maximum packets advancement at the top level of water.

In underwater acoustic networks, the ultimate consumption of the energy is because of the collision between the nodes during broadcasting the information bags. There are various protocols for UWSNs available in the literature [14]–[16] that minimize the energy consumption in the network. However, they may not achieve maximum packets at the water surface because the source node finds the least number of forwarding candidates. Therefore, the least number of forwarding candidates lead the network to less reliable. Numerous cooperative routing protocols in the literature, that are introduced to mitigate the low-reliability constraint in underwater communication [5], [17], [18]. In cooperative routing, the source node uses the two-way strategy to forwards the data to the final destination. On the one hand, it is to adopt the direct-hop communication of the sender and the point of destination. On the other hand, it can also involve the relay node(s) for the packet advancement at the water surface. This method maximizes the network reliability by avoiding the adverse channel affects. However, this type of protocol faces the problem of high latency. The forwarding of the same packet with two different ways tends to increase the network transmission delay. In addition, these protocols consume more energy as delivering the same packet via doublet as well as triplet fashion.

A. PROBLEM STATEMENT

Several challenges are confronted in [19] while delivering data from the bottom of the water towards the top surface. The scheme selects a node as a destination that has the lowest depth among all neighbors. The repeated selection of the lowest depth near the water surface drains the energy of the nodes' batteries rapidly, as illustrated in Fig. 1. This tends the network to high energy consumption by the occurrence of void regions. In addition, this scheme makes use of multiple paths for packets routing from the bottom of the water to the final destination. The packet advancement with multiple routes renders high latency in the network.

B. MOTIVATIONS

This study is motivated by the before-mentioned facts. Consequently, this paper presents two novel algorithms for UWSNs. The first one is the energy path and channel aware (EPACA) routing protocol that brings energy efficiency in the network and can be used for long term communication. While the second one is the cooperative energy path and channel aware (CoEPACA) routing protocol that enhances reliability in packet delivery from a source to the point of destination. The CoEPACA protocol finds different routing paths to successfully delivers the packets towards the water surface.

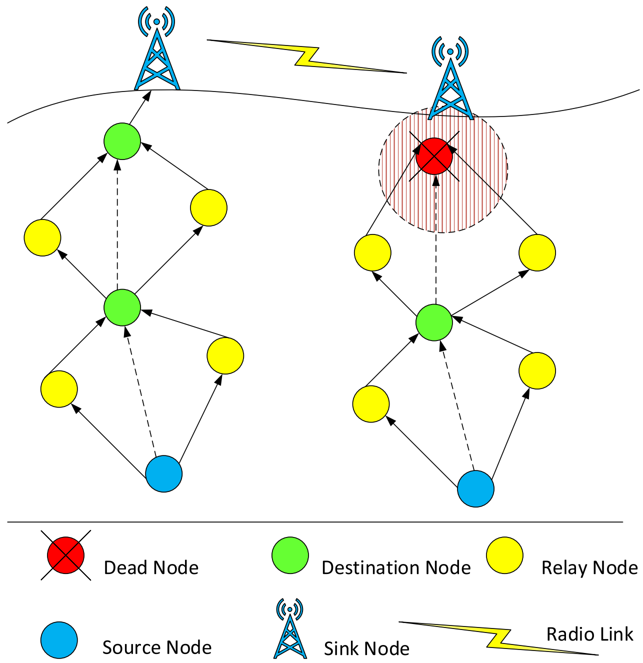


FIGURE 1. Problem in counterpart scheme.

C. CONTRIBUTIONS

Contributing to all published novel routing protocols in UWSNs, our EPACA routing scheme picks the best forwarding candidate from the neighbour node based on residual energy, packets' history, minimal distance, and BER. This robust selection of the best forwarding candidates tends the network to energy-efficient which can be used for long-lasting applications like monitoring. The CoPACA routing scheme avoids the unpleasant behaviour of the channel and forwards the packet not only in a single way but it also finds multiple routes. In essence, this study presents the following contributions.

- The EPACA protocol is presented to diminish the energy constraint in the network. The source node chooses the best forwarding node among neighbour nodes. The source node considers four metrics (residual energy, packet's history, minimal distance, and BER) in the selection of the forwarding node.
- The packets redundancy is controlled by selecting the optimal destination, which avoids retransmitting the same packets repeatedly. Consequently, the improved result is achieved in the lifetime of the networks.

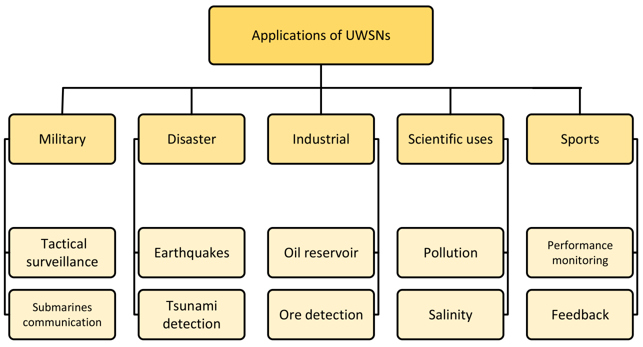


FIGURE 2. Applications of UWSNs.

- The second proposed scheme employed the cooperative technique in the delivery of data packets, whereas the destination receives various copies.
- The received data at the destination from multiple routes make the network more reliable due to avoiding the erroneous data. Furthermore, the source only transmits a robust packet to the next one, which in turn, achieves high packets advancement at the sink node.
- Various protocols exist in the literature that considers the localization of nodes. In effect, such protocols consume more energy. Unlike these protocols, the proposed protocols do not take localization into account. This, as a result, minimizes nodes' deployment complexity and also improves network scalability.
- The CoEPACA is superior in reliability in the form of delivering more packets to the destination nodes. Since this ensures packets reliable delivery, also can be used in applications requiring reliable delivery of packets such as military applications and in undersea warning and havoc identification systems.
- Thorough and careful Matlab's simulations reveal the performance analysis. An improved result is achieved in energy cost, packets advancement towards the target, and network stability.

The remaining parts of this article are partitioned as follows. Section II discusses the relative study of routing schemes. The proposed network model is described in Section III. Section V and then VI discusses the EPACA and CoEPACA protcols, respectively. Section VII contains simulation results and analysis. Finally, the entire work is concluded in Section VIII.

II. RELATED WORK

This section discusses the performance and ideas of various existing protocols. The discussion is classified into four categories such as energy-efficient, reliability aware, localization-free, and cooperative based routing protocols. Fig. 3 lists all routing schemes which are further described in this section one by one.

A. ENERGY-EFFICIENT PROTOCOLS

Various protocols are proposed in the literature that provide energy efficiency during packet forwarding. Energy efficiency is defined as the node that delivers packets towards the destination with the cost of minimum energy consumption. Protocols that provide energy efficiency during packets forwarding are listed below:

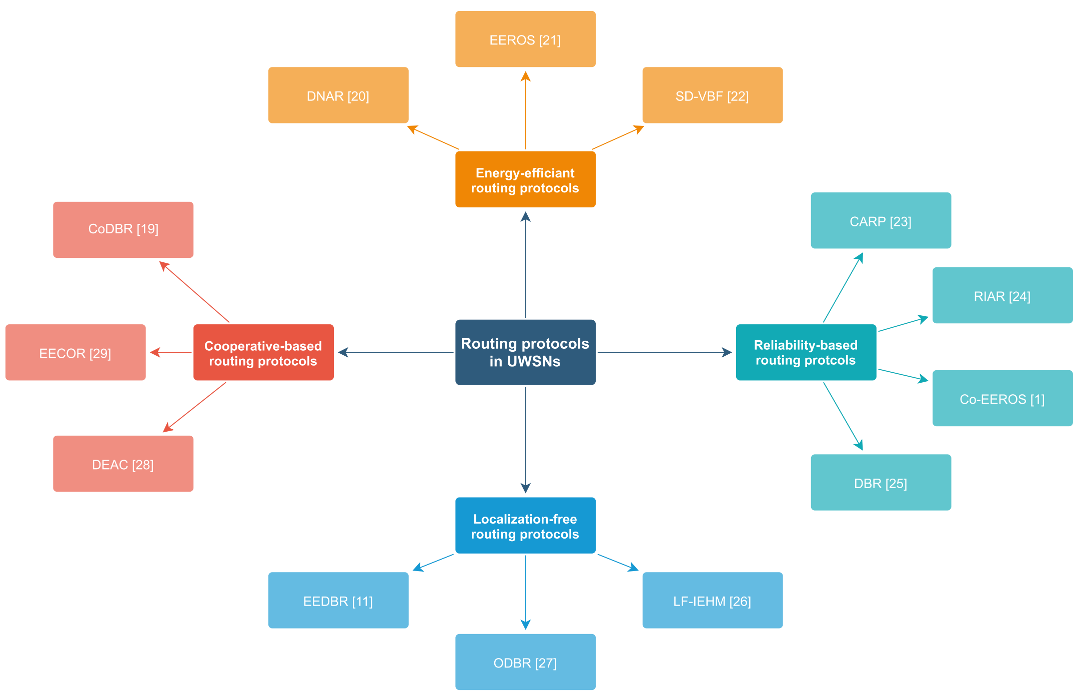


FIGURE 3. State-of-the-art of routing protocols.

1) DNAR

Junaid and his colleagues [20] proposed a depth and noise aware routing (DNAR) in the field of UWSNs. The algorithm brings energy efficiency in a network by selecting the appropriate node in data delivery. When the nodes detect the data, they first use a weighting function for choosing the best forwarding node. The weighting function consists of the node information I.e. depth, and channel noise between the sender to the receiver. When the node has greater value as per the weighting function, then it will consider as the best forwarding node. The DNAR protocol forwards the data packets with less energy consumption. Therefore, the protocol presents energy efficiency in the network. The DNAR is a localization-free protocol and delivers maximum packets at the water surface with only less amount of energy consumption. However, it faces high latency due to the checking of channel link quality.

2) EEORS

Anwar *et al.* [21] proposed an energy-efficient optimal relay selection (EEORS) approach for UWSNs. The EEORS scheme reduces the energy consumption of the nodes. The picking of the best forwarder is based on the information of the lowest depth and maximum remaining energy. A fuzzy-logic mechanism is employed to choose the best forwarder from the bunch of sensor nodes in the whole network. The relay node is selected by considering the values of the desired weighting parameters (depth, remaining energy). The delivery process of packets from a sender to the destination node is done through the optimal relay node. The best forwarder holds the information for calculated intervals of time and also examines the value of BER. If the calculated BER is less than the predefined threshold then it forwards the packet to the next one. This algorithm provides good output in terms of energy consumption. However, it has high latency and packets drop during the data delivery process.

3) SD-VBF

Khosravi *et al.* [22] introduced a spherical division vector-based forwarding (SD-VBF) routing technique for UWSNs. In this technique, an energy utilization mechanism is incorporated to reduce energy consumption during packets forwarding. The improvement of this scheme is carried out through a scenario based on physical or probable limitations. Also performed the direct or indirect action to remove some of the sensor nodes in routing which have no contribution during the packets forwarding. In addition, the optimal scheme for simplicity called scalability and efficiency are utilized to reduce network energy consumption. Like the VBF protocol, this scheme also selects the best forwarder node based on physical vector calculation from the desired destination. The SD-VBF scheme enhances the performance of the VBF routing protocol by removing some of the un contributed nodes during the routing. And reduces the net energy consumption while delivering the packet towards the destination. However, this protocol may not always deliver maximum packets due to the occurrence of void holes in the network.

B. THROUGHPUT, RELIABILITY AWARE PROTOCOLS

Several conventional routing protocols published in the literature that consider reliability during packets advancement process. The reliability of the routing protocol is defined as the maximum packet received at the sink surface. Protocols that provide reliability in the network are presented as follows:

1) CARP

The authors in [23] proposed a channel-aware routing protocol (CARP) to utilize the information of link conditions in the network. Choosing of a relay is dependent on residual energy and the history of the successful packet transmitting among the neighbors. The protocol combines the information of hop-count and link quality. This method is able to make connectivity around the shadow and nullity spaces in the network. The selection of an optimal link in the protocol gives the advantage to control the network energy. After the generation of information bags, the relay node(s) is selected through the desired parameters. The link quality of the protocol is based on the time-varying channel selection. This provides the ability to hold the same packet error rate (PER) for the data packet and controls the network power. The protocol achieves superior performance for the packet delivery ratio as compared to the counterpart scheme. Also, it has good energy consumption during forwarding the packets toward the destination. However, it delivers the packet with latency tradeoff, as it checks the history of successful transmission.

2) RIAR

A reliable and interference-aware routing (RIAR) scheme is proposed in [24] which mitigates the adverse channel effects. In the RIAR scheme, the picking of the best forwarder node depends on the desired attributes such as hop count, the neighbour in the communication dimension, and the distance. The number of hop-count is also used as a routing metric rather than physical distance. It is because the physical distance changes quickly with the water waves. This scheme sends the packet only, while if there is minimum interference. The source node detects the information packets and transmits it to the target point. The selection of the optimal target point is by using the function parameter. The node having a minimum number of hops and close of the surface level is accepted as the target destination. The destination node further selects the second destination node if the sink is not in its range. In such a way, the packets arrive at the sink node through passing multi-hoping. The protocol maximizes the rate of packets advancement and provides the minimum latency during the packet transmission. However, the node having the lowest depth and near to sink node die quickly which decreases the network lifetime.

3) CO-EEROS

The authors in [1] proposed a cooperative energy-efficient optimal relay selection (Co-EEROS) scheme for underwater WSNs. This protocol mitigates the adverse channel effects by using the cooperative technique in the data delivery process. A source node requires the depth and location information to selects a relay node. In addition, the cooperative routing technique is used to deliver a packet towards the destination point by using multiple paths instead of one route. The destination node accepts packet only that has less number of errors and delivers it to the next one. This algorithm provides a higher packet delivery ratio at the surface level. However, it faces the high consumption energy constraint because of the forwarding of the same packet via multiple routes.

4) DBR

Hai and his co-workers proposed a depth-based routing (DBR) protocol in [25]. In the DBR protocol, the nodes required no location information for each other. The source first checks the depth level of nodes which lies in its transmission range. The node having the lowest depth or near to the surface area will receive data and is considered as the first destination node. The rest of the other nodes that depth does not match with the source node packet information, will not receive data packets. The first destination node selects the second destination node for data forwarding, using this mechanism until the packet reached the sink. The DBR protocol successfully delivers information towards the sink based on only depth information. However, it faces with redundant packets' reception problem caused by flooding manner. This, in turn, high energy consumption in the network.

C. LOCALIZATION-FREE ROUTING PROTOCOLS

Localization is defined as the calculation of the geographical coordinates of the node in UWSNs. Localization itself is one of the challenging issues because the global positioning system (GPS) is unable to work in water. As it works upon radio signals which have maximum attenuation and absorption in water. Therefore, various protocols that do not take localization into consideration. The discussion of the localization-free routing protocols is presented as:

1) LF-IEHM

The authors in [26] proposed a localization-free interference and energy hole minimization (LF-IEHM) routing scheme for underwater WSNs. This protocol is localization-free whereas no geographical portions of the nodes are required. Also, the sensor nodes are capable of changing their transmission range during communication. If the source has no neighbour node then it can change the transmission range and avoid the problem of sparse node condition. In addition, it uses packets history to reduces the probability of packets collision at the destination point. The protocol has a high achievement for throughput. But, it consumes more energy during packets delivery from one point to another.

2) ODBR

Reference [27] shows the information of localization-free namely the optimized depth-based routing (ODBR) protocol. In this protocol, the source considers only depth information and forwards packets over a single-path to the destination point. The nodes that reside near the water surface are energized with more energy as compared to the farther one. Therefore, this arrangement results in better energy balancing. However, the nodes deployed at the ocean bottom die quickly due to continuous uses with less assigned energy. Also, the single-path routing does not achieve high throughput at the surface sink. Due to this reason, this protocol has less reliability in data packets.

3) EEDBR

The energy-efficient depth-based routing (EEDBR) scheme is presented in [11] for underwater WSNs. This protocol diminishes the energy constraints of the low depth nodes in [25]. In the EEDBR scheme, the source node generates a hello bag and transmits it among all the neighbors. The hello bag contains the details about the node's depth and remaining energy. The hello bag is exchanged among the neighbors in the transmission range until all the neighbors receive the packets. The node residing more deeper as compared to the source will not considers as the best forwarder. Because it has more distance from the surface level. The picking of destination is by the maximal remaining energy as well as minimal depth. The EEDBR scheme utilizes a distributed mechanism to maintain the residual energy in each node. Furthermore, it employs an energy balancing technique to balance the energy of nodes residing at a low level in the water. This protocol improves the overall network lifetime and minimizes packets' latency. But, it suffers from low-reliability issues due to unchecking of channel conditions during the packets forwarding process.

D. COOPERATIVE ROUTING PROTOCOLS

Cooperative routing is defined as the forwarding of the same packet via multiple routes. Cooperative routing diminishes the unfavorable channel effects. The forwarding of packets along single-hop may not always ensure efficient packets delivery. Therefore, the cooperative routing technique is introduced to tackle this issue. The conventional routing protocols that use cooperative routing in the delivery of packets are listed below:

1) DEAC

The depth and energy-aware cooperative (DEAC) routing scheme is proposed for underwater WSNs [28]. The DEAC protocol increases reliability by varying the optimized depth threshold (Dth). It also uses a cooperative technique in the broadcasting of packets between the sensor nodes. In this scheme, the nodes initially are not familiar with the remaining energy and depth information of each one. Therefore, a hello packet generated by the source node is broadcasted to exchange the information. The hello packet contains the depth position and energy left in the node. The source stores nodes' information in a table. In addition, the plodding approach is used to carry the information without any collision. Furthermore, the best forwarder is selected with the help of a function parameter. The second best forwarding candidate is selected with the help of the second-highest function parameter and so on. The destination gets multiple copies of the packet such as a direct and relaying packet. It combines all the copies of the packet via the maximal-ratio combing (MRC) technique and transmits it to the sink node. The scheme has good performance for the packets delivery ratio. However, it consumes more energy because of data forwarding in a cooperative fashion.

2) EECOR

An energy-efficient cooperative opportunistic routing (EECOR) is presented for UWSNs [29]. The EECOR scheme employs the cooperative technique in the packet delivery process. This, cooperative routing diminishes the unpleasant behaviour of the channel during packet forwarding. In cooperative routing, the destination ensures reliable packets reception due to multi variants of the packets. Furthermore, the source accepts the node for packets advancement only if it has high residual energy as well as low depth level. The protocol improves network reliability and minimizes energy consumption because of a fuzzy logic algorithm. In the fuzzy logic approach, the best forwarding node is selected in the set of relay nodes. The EECOR scheme increases the network life-span and maintains the nodes active for a long period. Also, it decreases the latency during packet transmitting and enhances packet advancement. But on the other side, the sink receives a packet having no method to checks the status of the link.

3) CoDBR

Hina and her co-workers proposed a cooperative depth-based routing (CoDBR) protocol for UWSNs [19]. In this scheme, the information is carried out by using the best forwarding node. The best forwarding candidate is choosing by only depth knowledge. Furthermore, the data cooperation is applied whereas the destination node receives many copies from multiple routes. This type of routing ensures high packets reception at the sink and overcomes the issue of packets dropped in the networks. CoDBR scheme is a localization free where the coordinates of the nodes are not required. The protocol achieves high packet advancement at the destination of the target but consumes more energy. Also, the nodes deployed close to the water surface died soon because of high data traffic and redundant packet transmission. Moreover, the packets in the network take more time while delivering towards the surface area. Table. 1 presents the comparison of routing schemes.

III. PROPOSED NETWORK MODEL

The proposed schemes are based on energy efficiency as well as packets reliability, therefore this section presents the overview of network configuration, energy, and channel model. The detail of each one presented as follows:

A. NETWORK CONFIGURATION

The network is simulated in three-dimensional space with 500 m of length, where the deployment of nodes is accomplished in a random fashion. The upper portion of the water surface depicted the position of the sink nodes. The sink node collected data packets and further forwards the packets towards the onshore data collecting center. The data collecting center extracts the desired information from the received packets and processes the data packets further, as showcases in Fig. 4. The deployed nodes are energized with confined power through batteries. The nodes are capable of calculating its neighbors' depth level. The nodes in the network broadcast with each other through acoustic waves. The sinks are hybrid nodes and facilitated with acoustic as well as radio communication. The modem generated radio waves are responsible for broadcasting with data collection centers while the acoustic one is helpful for communicating with the nodes in water. Acoustic waves provide a better solution in underwater communication because the radio waves suffer from various factors like signal attenuation, the time variation of a channel, multi-path fading, and small available bandwidth.

B. ENERGY MODEL

This model is the auditing of energy consideration in three different stages such that transmitting, receiving, and idling modes. It concludes all the energy information by simply using mathematical equations. Each sensor node consists of an acoustic modem which is used for the sending and receiving of the packets. The consumption of transmitting the packets of length P_l with its distance $dist$ is follows as [30]:

$$En_{tr}(P_l, dist) = (En_{di} \times P_l) + (b_p \times P_l) \tag{1}$$

where En_{tr} is the energy used for transmitting of P_l to $dist$. The variables b_p and En_{di} represents the bits period and radio dissipation, respectively. The sensor nodes consume the battery energy while they receive data packets from the neighbour nodes. The receiving energy En_{re} of the node can be calculated as presented in the equation below:

$$En_{re}(P_l, dist) = (En_{di} \times P_l) \tag{2}$$

The remaining energy in the node's battery also know as residual energy En_{res} that can be calculated as:

$$En_{res} = En_{in} - (En_{tr} + En_{re}) \tag{3}$$

where En_{in} is the energy before start up the network. The overall network's energy can be formulated as follows:

$$En_{to} = En_{in} \times SN \tag{4}$$

TABLE 1. Analysis of the existing routing protocols.

Protocol Name	Technique	Accomplishment	Deficiency	Reference	Year
DNAR	Uses a weighting function for selecting the best forwarder node	Good energy efficiency, throughput and network lifetime	High delay because of checking of channel quality	[20]	2018
EEROS	Non-cooperative protocol, packet forwarding mechanism considers on lowest depth and maximum residual energy	Balanced consumption of energy and increased life period of the network	Provides high latency, low packets delivery ratio	[21]	2015
SD-VBF	Spherical region based routing algorithm, best forwarder nodes are chosen over the calculation of physical distance and nodes' ID	Reduces consumption of energy, provides good throughput and PDR	High latency during packets transmission	[22]	2015
CARP	Non-cooperative protocol, choosing the best forwarding node through the maximum remaining energy and best packet transmission history	Superior performance for packets reliability, low energy consumption	High latency during packets forwarding	[23]	2015
RIAR	The selection of relay and destination node is depend on hop-count, neighbors-count and physical distance	Achieves high packets delivery ratio, decrease the latency	Unbalance energy consumption, nodes die quickly	[24]	2001
Co-EEORS	Cooperative routing scheme, the relay and then the destination is chooses by the lowest depth and physical distance	Improves the network PDR, ensures maximum packet delivery towards the surface	High energy consumption, high dead nodes ratio	[1]	2015
DBR	Protocol forwards the packet by considering lowest depth value	High packet's reliability, relaxes the localization condition	Unbalanced energy consumption, early death of nodes whose level is low	[25]	2008
LF-IEHM	Localization-free, capability of variable transmission range, introduces packets holding time technique	No requirement of localization, achieves high throughput at water surface	Consume high energy because of unstable transmission range	[26]	2018
ODBR	Localization-free routing protocol, forwarding of data packets over single-path, assign more energy to nodes near water surface	Good energy consumption, relaxes node's position calculation	Low packets reliability and high packets drop	[27]	2018
EEDBR	Does not use localization, non-cooperative protocol, the picking of the best node is by depth and remaining energy	Balanced energy consumption, high network lifetime, low latency	High packets drop, decreased network reliability	[11]	2012
DEAC	Cooperative protocol, depth threshold, and information of energy are used to choose the destination point	Ensures maximum packet delivery at sink node, increased PDR	High energy consumption, short node lifetime	[28]	2016
EECOR	Cooperative protocol, choosing of the destination is by the depth and remaining energy, the fuzzy logic approach is employed for energy balancing	Increased network lifetime, consumes minimum energy, high throughput	The bunch of nodes produces more delay during packet advancement, low network accuracy	[29]	2015
CoDBR	Cooperative algorithm, the lowest depth information is taking into account for the selection of the destination as well as the relay node	Achieves good result for the packets delivery ratio	Unbalanced energy consumption, node short lifetime	[19]	2014

the variable SN is the total nodes that take participation in the network. The power dissipation in the case of transmission can be calculated as:

$$P_{tr} = P_{at} + P_{dt} + P_{am} + P_{st} \tag{5}$$

$$P_r = P_{ar} + P_{dr} + P_{ln} \tag{6}$$

here, P_{at} and P_{dt} is the analog and digital circuit losses at transmission side, and P_{ar} and P_{dr} are at receiving side, respectively. The power consumption of the amplifier and signal transmission is denoted by P_{am} and P_{st}, respectively. The low noise amplification consumption is indicated with P_{ln}. The overall power consumption of the transmitter and receiver is shown by P_{tr} and P_r.

C. CHANNEL MODEL

Several challenges such as channel noise, low speed of acoustic waves, attenuation, and absorption, etc. are associated with the underwater medium which hinders the successful transmission of packets. The detail of each one is discussed below:

1) CHANNEL NOISE

In underwater wireless acoustic sensor networks, different types of noise sources are associated with the acoustic medium. As a result, the data packets get corrupted and the performance of the network is reduced due to information loss. Hence, the acquisition of the desired information is quite challenging. The underwater noise can be categorized

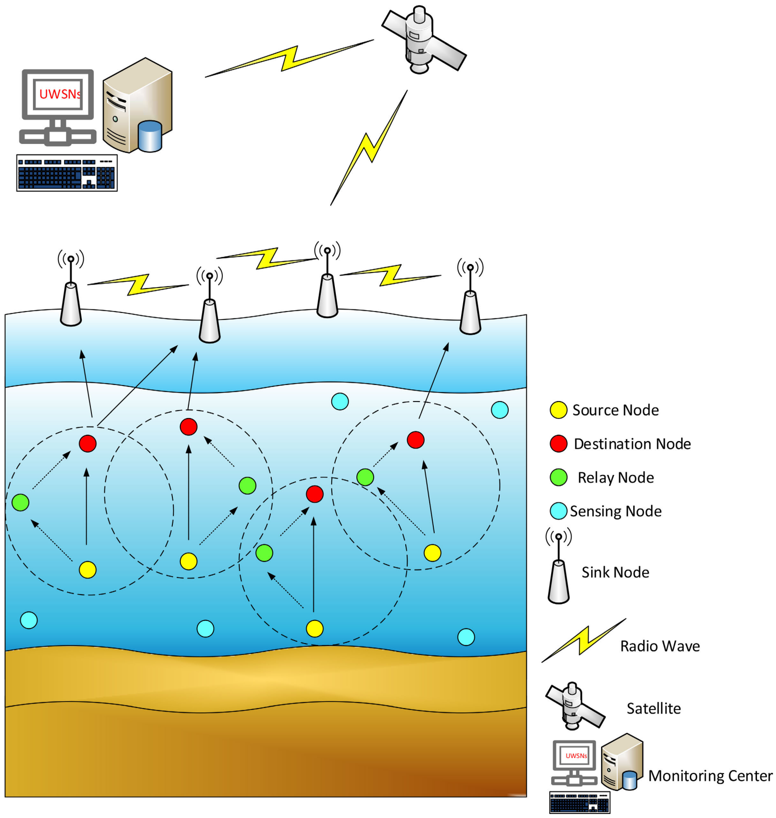


FIGURE 4. Illustration of system model.

into two classes such as the site-specific and the ambient noise. The first one, noise occurs only assertive domains that contain significant non-Gaussian components, while the ambient noise is usually associated with the background of the ocean environment. The generation of ambient noise takes place due to shipping sources, waves generated on the ocean surface by wind, the temperature of the sea, and turbulence. Each noise component has its power spectral density (PSD), and can be modeled as in [31]:

$$10logN_{sh}(f) = 40 + 20(s - 0.5) + 26log(f) - 60log(f + 0.03) \tag{7}$$

$$10logN_{wv}(f) = 50 + 7.5w(1/2) + 20log(f) - 40log(f + 0.04), \tag{8}$$

$$10logN_{tb}(f) = 17 - 30log(f) \tag{9}$$

$$10logN_{th}(f) = -15 + 20log(f), \tag{10}$$

$$N = N_{sh} + N_{wv} + N_{tb} + N_{th} \tag{11}$$

where N_{sh}, N_{wv}, N_{tb} and N_{th} represent PSD of shipping, waves, turbulence and thermal, respectively. The PSD of total noise N can be expressed in decibel (dB). The variable s represents the shipping activities in water by taking the value in [0,1] interval, the frequency f denotes with kHz and w indicates the wind's speed in meter per second at the ocean top. Fig. 5 shows different noise levels in seawater.

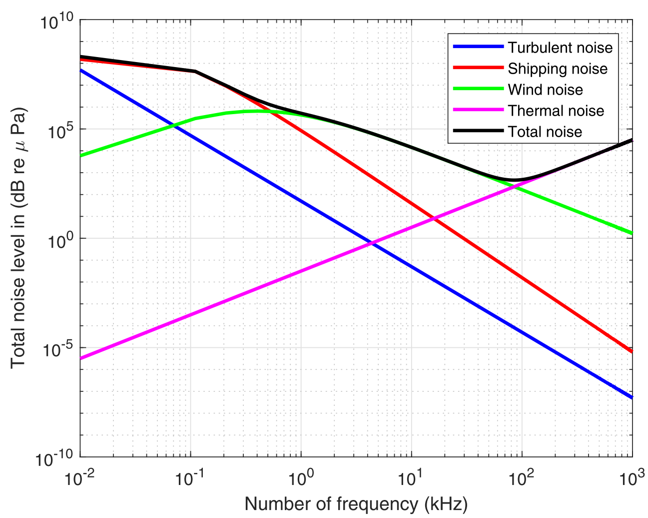


FIGURE 5. Noise level in seawater.

2) PROPAGATION DELAY AND ATTENUATION

The acoustic waves cover the distance with a speed of 1500 m/s in the water. The channel opposes greatly on a signal which degrades the performance while traveling from a sender to the point of destination. Similarly, the absorption and spreading loss in the acoustic channel also cause attenuation. The attenuation factor A(d, f) in terms of distance d in km and frequency f in kHz, which is computed in $dB\ re\ \mu\ Pa$

by Thorp's formula [32].

$$A(d,f) = A_0 d^k \alpha(f)^d \tag{12}$$

where A_0 is the regularizing constant, k represents the spreading loss, and practically renders the value of k = 1.5. However, the initial values of k = 1 and k = 2 are for the process of cylindrical and spherical spreading. The symbol $\alpha(f)$ represents the coefficient of absorption. The absorption computation in dB/km for higher and lower frequency in kHz is:

$$10log\alpha(f) = 0.11 + \frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 2.75 * 10^{-4}f^2 + 0.003 \tag{13}$$

$$10log\alpha(f) = 0.002 + \frac{f^2}{1+f^2} + 0.011f^2 \tag{14}$$

The attenuation of the acoustic waves in seawater is presented in Fig. 6.

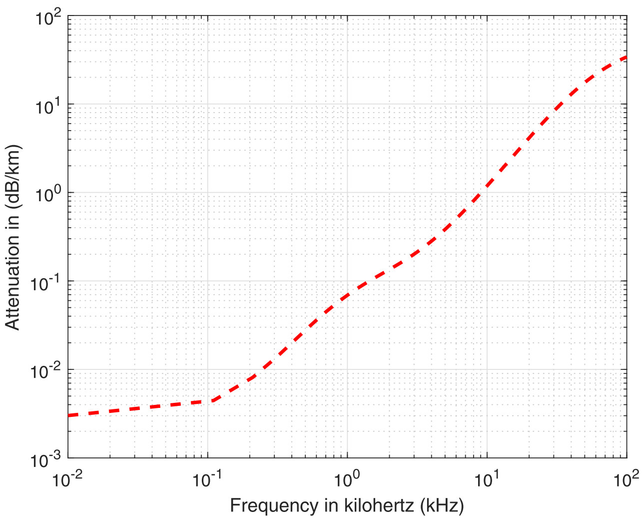


FIGURE 6. Attenuation in seawater.

3) SOUND SPEED PROFILE

Speed of sound in water influenced by fundamental aqueous behavior. There are different parameters such as salinity, depth, and temperature, that affect the acoustic speed from 1450 m/s to 1550 m/s. Mackenzie empirical expression in [33] for acoustic speed is following as:

$$v = 1448.96 + 4.591T - 5.304 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 + 1.340(S-35) + 1.630 \times 10^{-2}D + 1.675 \times 10^{-7}D^2 - 1.025 \times 10^{-2}T(S-35) - 7.139 \times 10^{-3}TD^3 \tag{15}$$

where T shows the temperature of water in °C (degree Celsius). The variable D is the water depth and can be calculated in meters (m). The salinity S in the water can be measured in parts per thousand (ppt). Fig. 7 depicts the sound speed profile in deep water.

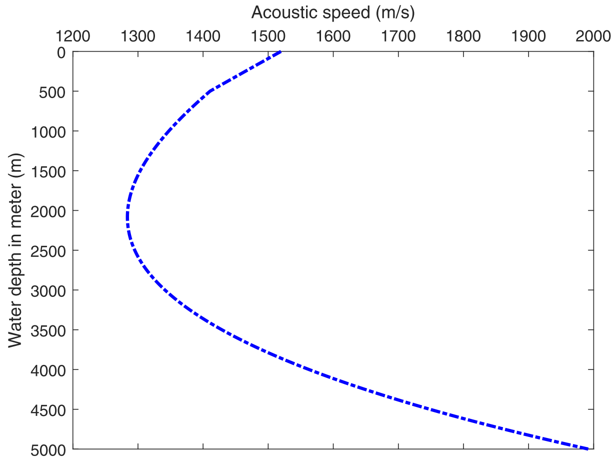


FIGURE 7. Sound speed profile.

IV. PROPOSED WORK

This section presents the two proposed routing protocols in detail. The first protocol energy path and channel aware (EPACA) brings energy efficiency, while the rest one cooperative energy path and channel aware (CoEPACA) enhances packets' reliability in the network. The detail of each one is given as follows:

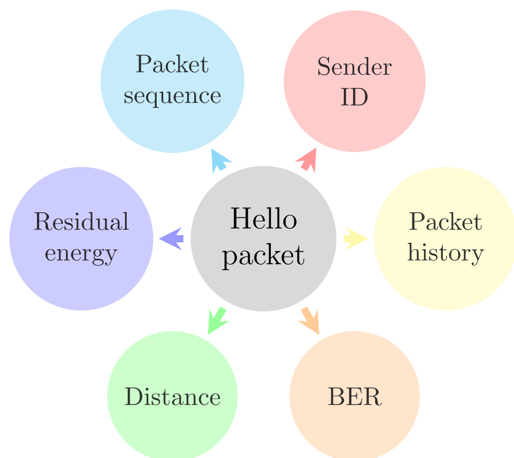


FIGURE 8. Hello packet format.

V. FIRST PROPOSED APPROACH: THE EPACA PROTOCOL

A. NETWORK INITIALIZATION AND NEIGHBOR RECOGNITION

Sensor nodes which are distributed in a random arrangement, are fully charged initially and are not aware of one another. The source, first of all, generates a hello packet which consists of a total of eight bytes [34]. Only that node acknowledges the hello packet that is in the source node's range. The hello packet holds the information of all the sensor nodes as shown in Fig. 8. A source uses the information of sender ID, packet sequence, residual energy R_e, packet history H_p, bit error

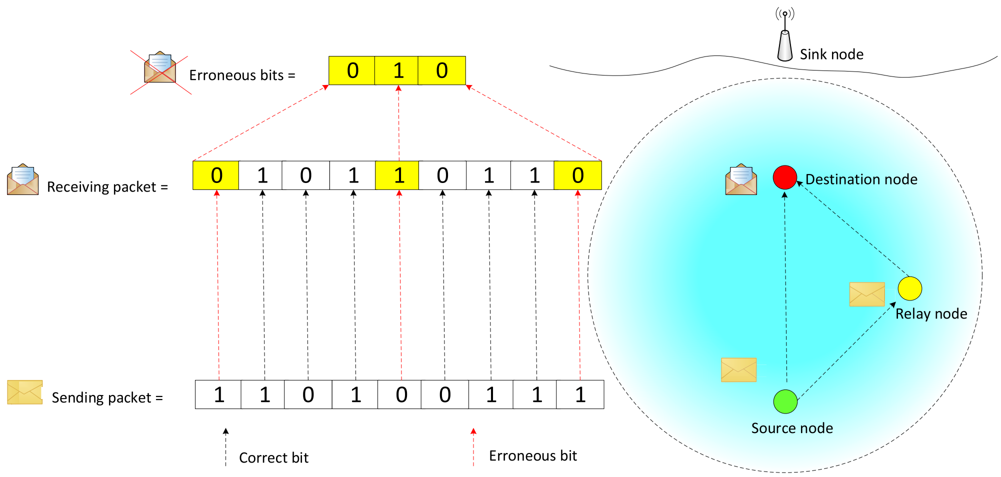


FIGURE 9. **The calculation of bit-error rate (BER).**

rate (BER), and distance d to identify the best forwarder node. Those nodes which received a hello packet can be able to calculate the desired function values. The nomination of the best candidate is based on the desired function which is embedded in the hello packet. In the function, the distance d between source i to the neighbour j can be calculated by using the Euclidean distance equation as follows bellow:

$$(d) = \sqrt{(S(i).xd - S(j).xd)^2 + (S(i).yd - S(j).yd)^2} \quad (16)$$

where the terms xd shows the x-axis and yd shows the y-axis coordinates of the node. To find the BER, let us consider an example where the source transmits a packet to destination node that consists of total nine bits. The number of changed bits at the destination indicates the quality of packet. In this protocol, we consider a threshold T that's mean If the destination receives a number of changed bits more than three. It will not accept the packet to forward it to the next destination. The Equation 17 below shows the calculation of BER, where N_{err} denotes the number of corrupted bits and N_{tra} the total bits transmitted. The concept of BER is shown in Fig.9 below.

$$BER = \frac{N_{err}}{N_{tra}} \quad (17)$$

Furthermore, a source retransmits the hello packet when it does not receive any response from its neighbor nodes inside the transmission range. This process is continued for a specific time and then the packet is discarded in case no neighbor is available in the transmission range. Once the node receives the data, it checks and extracts the desired information. Each node is passed through this process and the completion of this procedure makes every node able to know all the information about each other. The identification of the neighbor node is explained in Algorithm.1.

$$f = \frac{R_e \times H_p}{BER \times d} \quad (18)$$

B. DATA FORWARDING

This subsection presents the description of path establishment. The path establishment consists of explaining how information packets reach the sink node? And how the destination node contributes to the packets forwarding mechanism? In the proposed scheme, the source node embeds the relay(s) and destination node's ID to the generated data packets and then forwards it towards the water surface. The picking procedure of the point of destination is purely based on the function parameters. The node that achieves the maximum outcome from the weighting function is considered as the best forwarding candidate. The nomination of best forwarding candidates is based on the highest R_e, history of packets, lowest BER, and the shortest distance among the nodes as shown in Fig. 11 and 10. The process is the same for all rounds and the destination is selected through this process. A packet reaches from the underneath of the water to the top is considered as a successful complete round. By using the proposed weighting function, the proposed scheme delivers the maximum packets to the surface area with the cost of low energy consumption. Fig. 12 shows the flowchart of data forwarding in the EPACA protocol.

C. JUSTIFICATION OF EPACA

Our first approach EPACA is the energy-efficient protocol which ensures less exhaust of energy. The reason for the low consumption of energy is based on the picking of the best node via calculated function attributes. During the optimal relay selection, the factor lowest physical distance decreases the latency. Therefore, this scheme ensures not only energy efficiency, but it can also deliver packets to the surface sink with minimal time latency. Hence, this routing scheme is applicable for applications requiring long-lasting communication as well as for delay-sensitive such as undersea warning and havoc identification systems.

Algorithm 1 Neighbor Identification, Node Selection and Data Forwarding

S_n:Source Nodes
D_n:Destination Nodes
R_n:Relay Nodes
D_n:Destination Nodes
H_p:Packet Transmitting History
BER:Bit Error Rate
d:Distance from Destination Node
  S_n sends a Data Packet
  Sink is in Range **do**
if BER < 0.2
  Packet Received at the Sink = **true**
  Data Packet Accepted
  while
  Sink is not in the Range **then**
  Find Destination Node
  Calculate Function for the Selection- of D_n
  $f = R_e * H_p / BER * D$
  D_n found
  Send Data Packet to D_n **do**
if BER < 0.2
  Packet reached = **true**
  else if
  Select Relay Node
  Forward Data Packet by R_n Node
  end else if
if BER < 0.2 **then**
  Packet Accepted
  Packet Received at the Sink Node = **true**
  end if
  end if
end while
end if
break

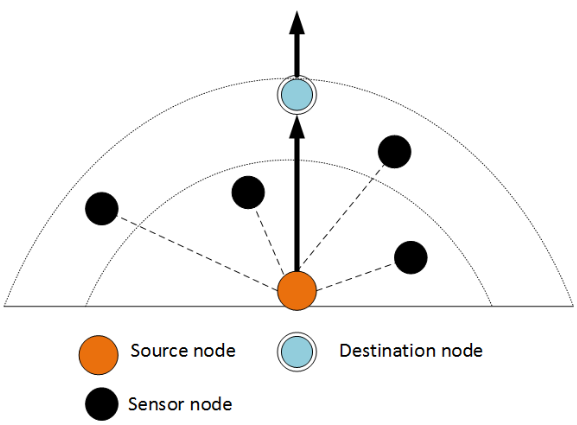


FIGURE 10. EPACA best forwarder node selection.

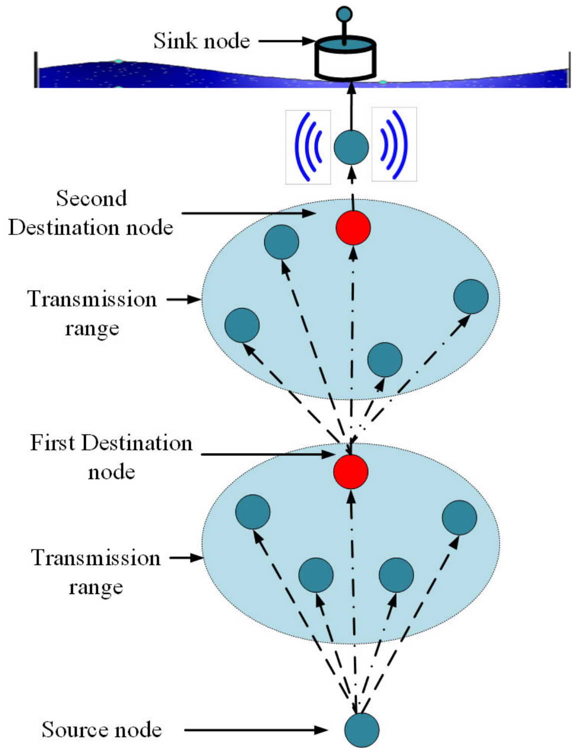


FIGURE 11. EPACA packet forwarding.

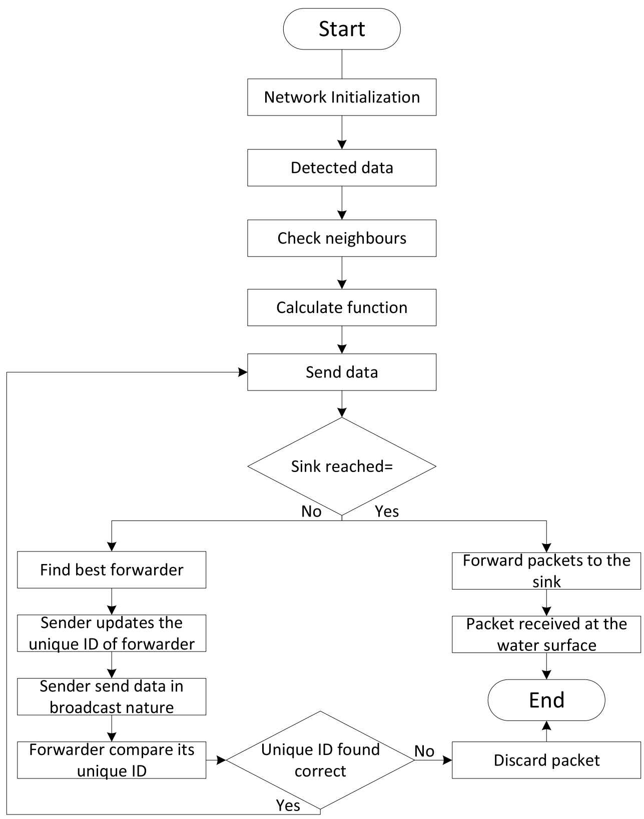


FIGURE 12. The flow chart of EPACA protocol.

VI. SECOND PROPOSED PROTOCOL: CoEPACA

In the EPACA routing scheme, the source node uses a single link to forwards the packets towards destination point. Using a single route may not always ensure reliability in data exchanging. To handle this issue, the CoEPACA protocol is proposed which presents the solution in an effective way. The network modeling and initial broadcasting are similar as in EPACA scheme. The selection of relay(s) and then the destination node in a cooperative fashion are discussed below in subsections.

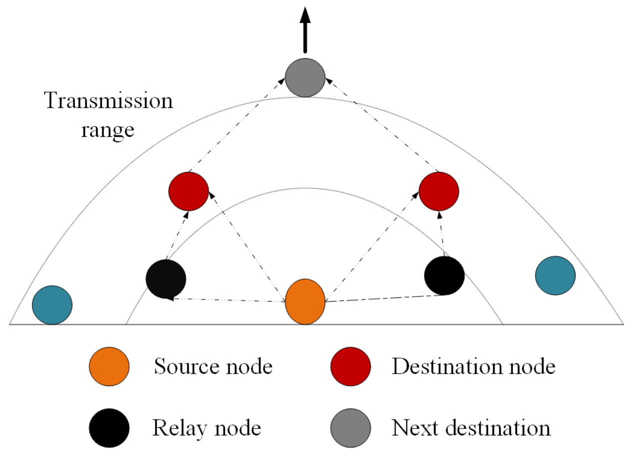


FIGURE 13. CoEPACA packet forwarding.

A. RELAY AND DESTINATION SELECTION

This phase presents the packets forwarding mechanism of our second proposed protocol (CoEPACA), which is the amended interpretation of EPACA protocol. The destination selection criteria of the CoEPACA protocol are the same as EPACA protocol. In CoEPACA the source transmits the information packets towards the sink node using a single-hop method as shown in Fig. 13. When the information bags are forwarded to the destination, at the same time relay node also receives the data packet because of the broadcast nature. Though, the packet is then forwards towards the target destination in a cooperative fashion. Sink node extracts information from the data packet and transmits it to the data collection center. In CoEPACA the choosing of relay and the target destination is the same as discussed in EPACA protocol. When the source broadcasts the information packets, all of its neighbors are capable to receive it. The decision of the destination is based on the desired attributes as given in Equation 18. The source then selects that node as a destination which has maximum function value. If the selected node meets the desired parameters then it is considered as the first destination. However, if the selected destination does not meet the desired attributes then a source transmits a request (REQ) to the second priority node which is known as the relay. The selection of the relay node is also specified similar to the target selection definition. The relay sends an acknowledgment (ACK) in response to the request (REQ) of the destination, as shown in Fig. 14. Once the relay node and destination are selected then it sets a sequential arrangement for data forwarding.

B. DATA COOPERATION

The approach of cooperation is used to diminish the adverse channel effects in a network. As shown in Fig. 15, the relay, and destination receive information bags in broadcasting nature. Furthermore, the relay node also amplifies the packet arrived from a source by using an amplifying factor (AF) as discussed in [35]. The point of destination receives two variants of the same packet. The one packet through direct transmission from a source while the rest one via relay to the target destination. The packet received from destination d to relay r and source s is modeled as [35]:

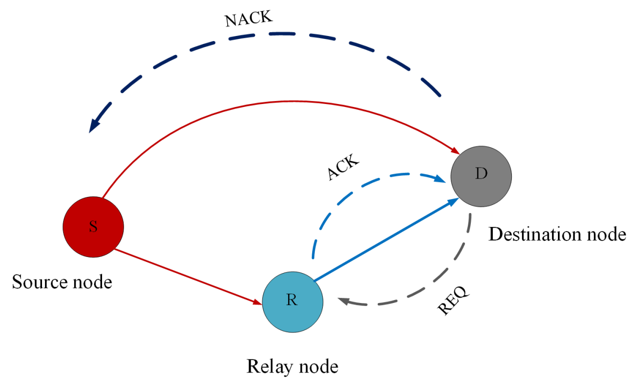


FIGURE 14. Packet exchanging scenario.

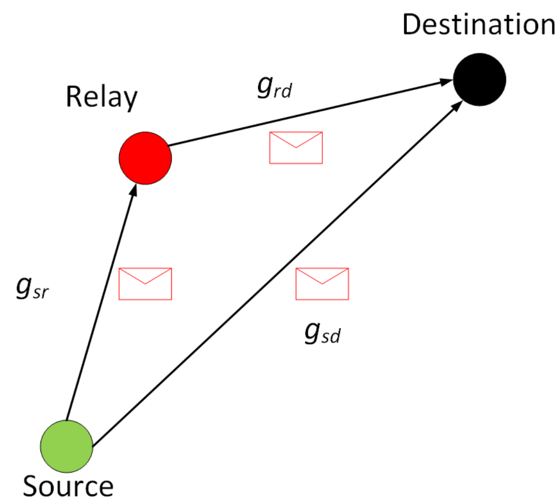


FIGURE 15. Data forwarding via cooperative method.

$$Y_{sd} = X_s \times g_{sd} + n_{sd} \tag{19}$$

where Y_{sd} is the received information signal from a source to the point of destination. X_s is the original information signal, g_{sd} and n_{sd} is the gain of channel and noise from a source to the target destination.

$$Y_{sr} = X_s \times g_{sr} + n_{sr} \tag{20}$$

$$Y_{rd} = X_s \times g_{rd} + n_{rd} \tag{21}$$

where Y_{sr} and Y_{rd} is the output signal from a source to the relay node and then relay node to the point of destination. The terms g_{sr} and g_{rd} are the gain of the channel from a source

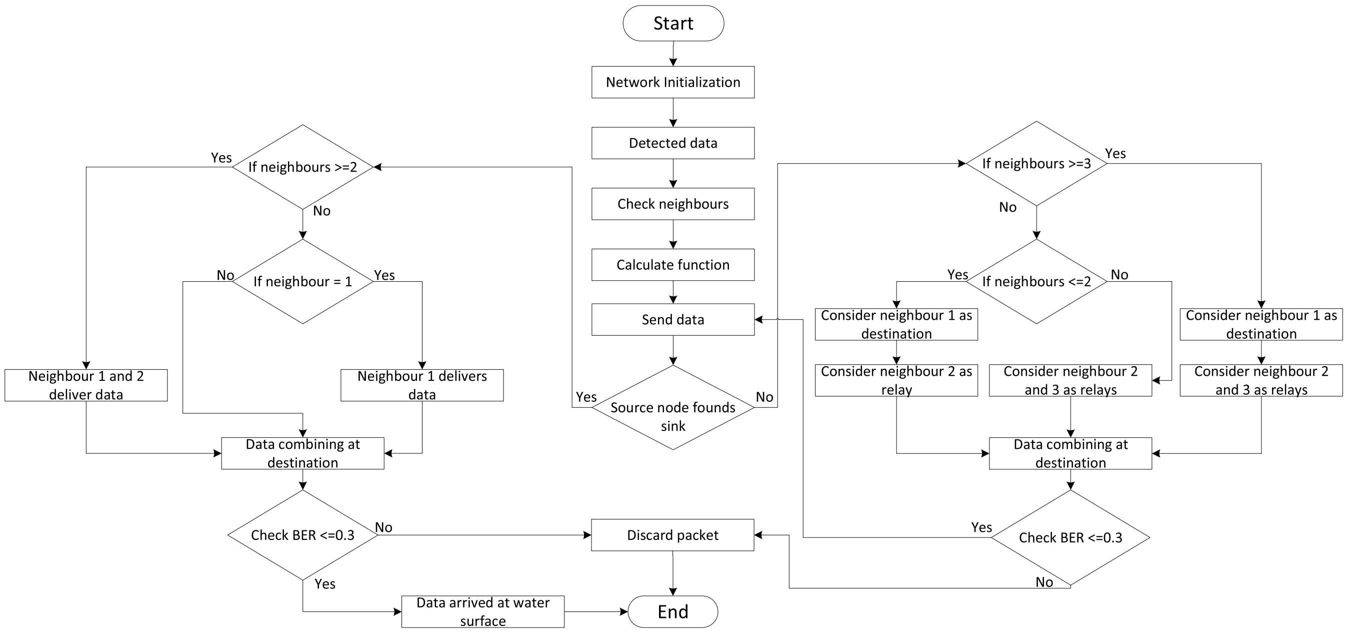


FIGURE 16. Data forwarding mechanism of the CoEPACA protocol.

node to relay and then relay to the destination, respectively. The variables n_{sr} and n_{rd} are the noise combined with the underwater channel. The variant of an amplified arrived signal at the point of destination via the relay node is given as:

$$Y_{rd} = \beta(X_s \times g_{sr}) \times g_{rd} + n_{rd} \tag{22}$$

the variable β is the amplification factor and can be modelled as [36]:

$$\beta = \sqrt{\frac{1}{|g_{sr}|^2 + \sigma^2}} \tag{23}$$

where σ is the noise power with unity variance and is computed as [37]:

$$\sigma = \eta d_{sd}^{\alpha} \tag{24}$$

the symbol η is the propagation constant. The terms d_{sd} and α are the distance from source to destination and propagation loss, respectively.

C. DATA COMBINING TECHNIQUE

In the proposed CoEPACA routing scheme, the destination combines multiple data copies by using maximal ratio combine (MRC) [35] technique and forwards the optimal packet to the next one. The MRC first checks the BER of both the copies i,e from source, and relay. If the data packet is counted as ≤ 0.3 then it will accept the packet, otherwise, it will not forward further. This procedure will continue until the data arrives at the top area. The proposed work is discussed in the flow chart as depicted in Fig. 16. If the sink comes close to the source range, then it receives the packets directly. Otherwise, the desired sink node will repeat the process unless the packets reached the onshore data center. The received signal from multiple sources is given as [37]:

$$Y_d = \sum_{k=1} g_{kd} \times Y_{kd} \tag{25}$$

where Y_{kd} is the received signal and g_{kd} is the channel gain between source and destination from multiple links. The total number of branches M = 2 is given as:

$$Y_d = g_{sd} \times Y_{sd} + g_{sr} \times Y_{sr} \tag{26}$$

this shows that multiple copies are received by destination where the MRC technique is used to reduce to the probability of corrupted data. The BER can be computed as given in [35]:

$$BER = \frac{1}{2}\left(1 - \sqrt{\frac{S_e/N_e}{1 + S_e/N_e}}\right) \tag{27}$$

the terms S_e and N_e are the signal and noise energy, respectively. The transportation of the packets from one node to another is by using binary phase-shift keying (BPSK) technique.

D. JUSTIFICATION OF THE CoEPACA

The second proposed scheme CoEPACA protocol improves the network link quality and provides reliability in a network. The achievement of the improved reliability is because of the optimal picking of the node forwarders and then transmitting the packets in a cooperative fashion. As delivering the packet with multiple paths avoid the adverse channel effects, which reduce the probability of packets loss. This ensures to achieve maximum packets at the sink surface. The main focus of the CoEPACA protocol is to achieve high reliability, which can be used in applications requiring reliable delivery of packets such as military applications and in an undersea warning.

TABLE 2. Simulation parameter.

Parameter	value
Total sensors nodes	225
Total sink nodes	4
Width	500 m
Depth	500 m
Total initial energy	11 Joules
Transmission range	100 m
Bandwidth	30000 hz
Frequency	30 khz
Packet length	1600 bits
Hello packet length	8 bytes
Idle power	10 mW
Transmission power	2 W
Receiving power	0.8 W

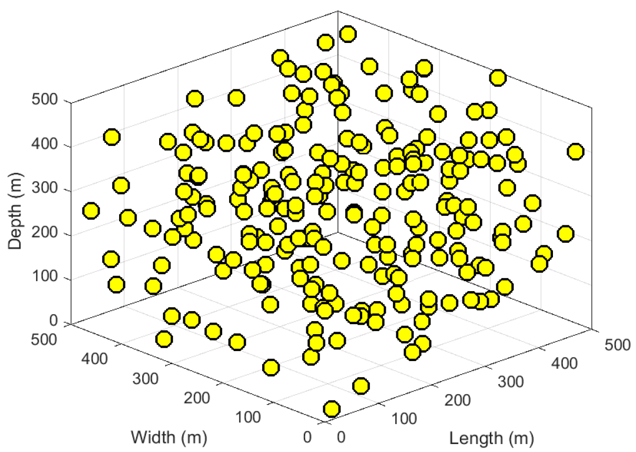


FIGURE 17. Random distribution of the sensor nodes.

VII. SIMULATION RESULTS AND ANALYSIS

All experiments were performed using MATLAB. We compared our result with CoDBR [19], as both protocols avoiding adverse channel effects by taking cooperation into account. However, unlike the CoDBR protocol, the proposed schemes make use of function criteria which avoids the rapid death of low depth nodes. Hence, the void-hole problem is solved in this method. Table. 2 lists the parameters used in the simulation. The considered area is in three-dimensional (3D) whereas the nodes are distributed in an unsequenced position, as shown in Fig. 17. The size of each wall is considered as 500 m. The total number of nodes is considered 225, as in counterpart scheme. The sinks are fixed at the surface area and are connected to the information collection center. The LinkQuest UWM1000, acoustic modem with a bit rate of a size 10 (Kbps) is used in simulations [38]. The sinks utilize the sound modem for packet exchanging with the nodes in water, while the modem generating radio waves is for an onshore data center. The sensors used for pressure are installed with the nodes that help in the measurement of depth information from the surface level. The range of transmission of each node is considered as 100 m in every direction. All the nodes consume 2 W, 10 mW, and 0.8 W of power for transmission, idle, and reception purposes, respectively. The amount of start-up energy for every node is considered 11 J. The source node exchanges a hello packet with a size of 8 bytes [34] and 50 bytes [39] for a single packet.

A. PERFORMANCE PARAMETERS

The proposed protocols, evaluate the following parameters by using evaluation metrics.

1) ROUND

It is the time that lapses in the transferring of data from a source to the sink at the sea surface.

2) TOTAL ENERGY CONSUMPTION

It is calculated as the energy required for the data that reach the sea surface. The total average energy of nodes used for sensing, receiving, and transmitting data packets. In other words, it is the complement of residual energy and can be calculated as in [40]:

$$TEC = \frac{TE}{TN \times DP} \tag{28}$$

where TEC represents the overall energy consumption. The terms TE, TN, and DP denote total energy in the network, total nodes and data packets, respectively.

3) PACKETS DELIVERY RATIO

It is the proportion of packet reception successfully at the surface to the packet transmission from a source. It can be modeled as in [40]:

$$PDR = \frac{\text{Total successfully received packets}}{\text{Total packets generated}} \times 100 \tag{29}$$

4) END-TO-END DELAY

It is calculated as the total time required by the data from a source to the point of destination. It contains all types of delays experienced in a complete round from the underneath of water to the surface area. The average delay can be calculated as in [40]:

$$\text{End-to-End delay} = \frac{\sum_{n=1}^{N}(R_n - T_n)}{N} \tag{30}$$

where sending and receiving time for the number of packet N is denoted by T_n and R_n, respectively.

5) DEAD NODES

The nodes in the network that consume the overall energy that is assigned initially.

6) ALIVE NODES

The nodes that still contain energy and have not drained the overall energy which is assigned at the start of the network.

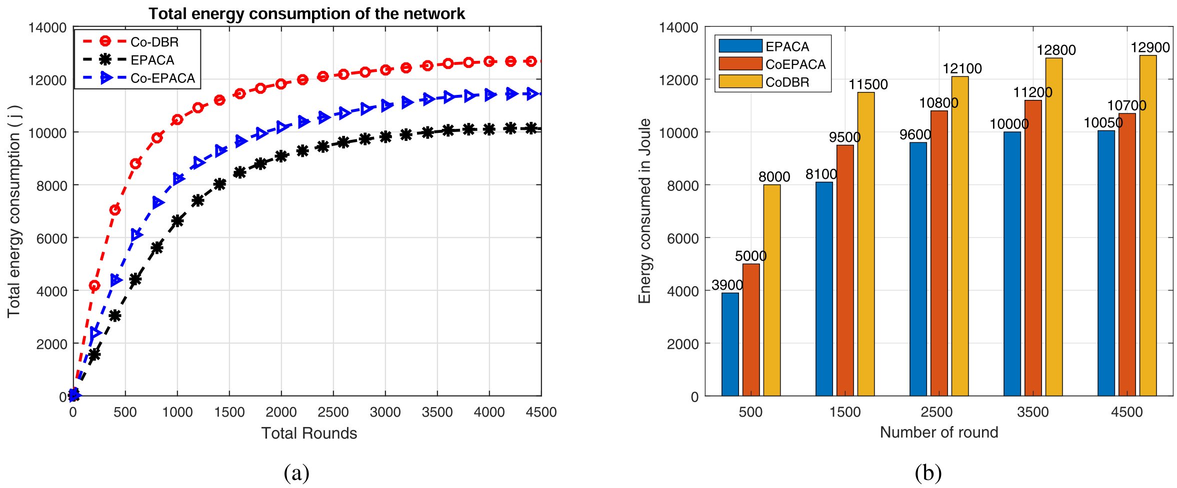


FIGURE 18. **(a) Total energy consumption. (b) Comparison of energy consumption with counterpart scheme.**

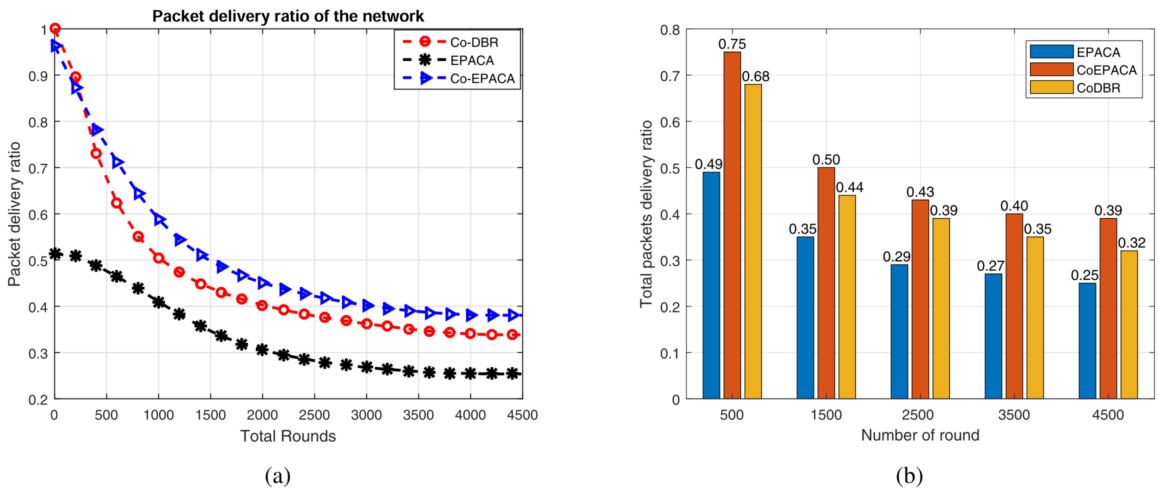


FIGURE 19. **(a) Packets delivery ratio (PDR). (b) Performance analysis of packets delivery ratio.**

B. TOTAL ENERGY CONSUMPTION

The result of the consumed energy is depicted in Fig. 18. As the number of rounds increases the energy consumption of the nodes increases in all protocols. The consumption of energy of the counterpart scheme is greater than the proposed protocols. This is because of the high death rate of the nodes residing near the water surface. Also, forwarding the same packet by many paths leads the network to consume high energy. In CoEPACA protocol, the source utilizes the status of the residual energy during the selection of the best forwarder. This method consumes less energy during packet transmission in the network. The probability of packet failure in the EPACA protocol is low therefore the retransmission of the same packet is not needed. In other words, the EPACA protocol forwards the packets without any cooperation, so it consumes very little energy as compared to CoDBR and CoEPACA protocol.

C. PACKETS DELIVERY RATIO

The average PDR of all the protocols is plotted in Fig. 19. The PDR of the CoEPACA is higher than the other protocols because it avoids the adverse channel effects by taking SNR and BER into account. Also, it excludes the relays that deployed in the same depth or at a higher depth than the source, provides the greater PDR. In addition, CoEPACA forwards the packets not only in a single way, but it can also forward the packets via multiple paths, this causes high packets acceptance ratio at the sink surface. The PDR of the CoDBR protocol is higher than EPACA but less than CoEPACA. It is due to the packets forwarding in a cooperative manner, therefore it achieves better PDR than EPACA. However, there is no checking mechanism of the channel condition, so it has a lower PDR than CoEPACA. The EPACA protocol utilizes the channel condition mechanism, however, in case of no optimal node in the transmission range of the

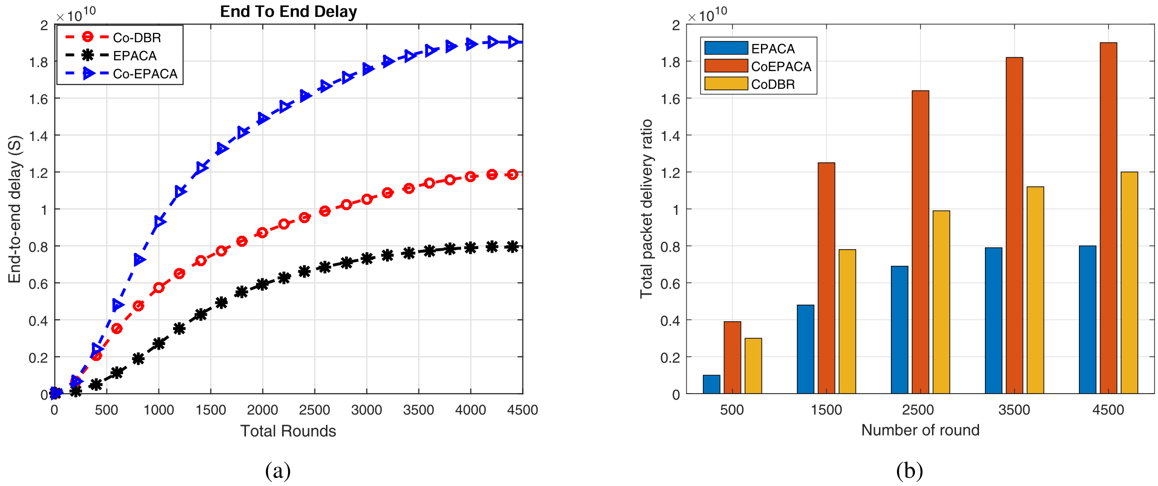


FIGURE 20. **(a) End-to-End delay. (b) Delay comparison of each protocol.**

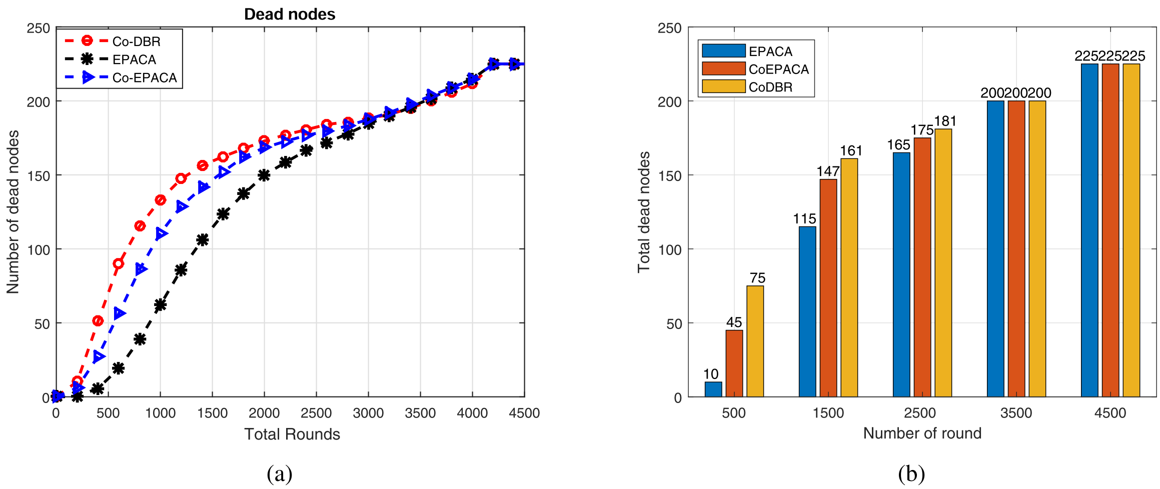


FIGURE 21. **(a) The plot of dead nodes. (b) Performance analysis of the dead nodes.**

source node. It simply holds the packet until there is no optimal node, this cause less PDR in the network.

D. TOTAL END-TO-END DELAY

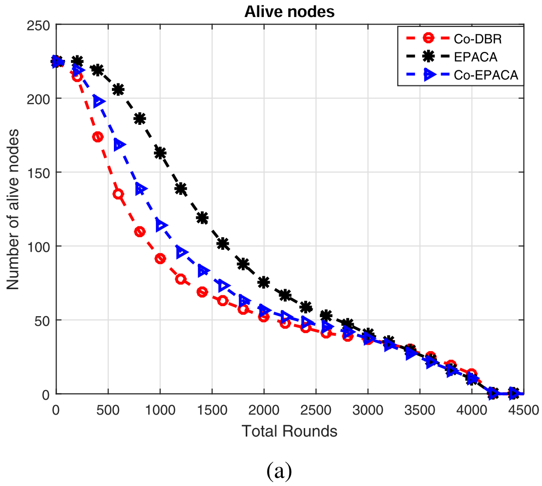
The plot of end-to-end delay of all protocols is shown in Fig. 20. The delay of CoEPACA is greater than the other protocols. It is due to the data forwarding in a cooperative manner. In the cooperative approach, the source makes use of multiple paths during forwarding the data to the point of destination. The destination acknowledges the packet receiving source. In other words, a source checks the condition of the link while sending data. If the link is found robust then it delivers the packet to the target destination, otherwise, it waits. This results in high latency in the network. The delay of the CoDBR protocol is higher than the EPACA protocol because it uses a cooperative routing technique. Also, it has no checking mechanism therefore it has a lower delay than the CoEPACA protocol. The EPACA has the best delay and it does not take a long time during delivering the packets to the surface sink.

E. DEAD NODES

The result of the dead nodes of all protocols is illustrated in Fig. 21. As plotted in Fig. 18, the energy consumption in the EPACA protocol is less than the other two protocols. Therefore, the death ratio of the EPACA protocol is lower than the CoDBR and CoEPACA protocols. Same as in the case of CoDBR protocol, the packets transmitted with the cost of high energy consumption which tends the network to high death ratio of the node. In the CoEPACA protocol, the packets' failure probability is lower therefore low energy is consumed during data delivery. The retransmission of the packet is no longer needed so the rate of the dead nodes is lower than the CoDBR protocol.

F. ALIVE NODES

The plot of alive nodes is depicted in Fig. 22 which is reciprocal of Fig. 21. As the rapid death ratio of the CoDBR causes the network to unstable for a long time, therefore a few nodes remain alive for communication in the network. In the same way, the greater number of nodes are alive in EPACA and CoEPACA protocols.



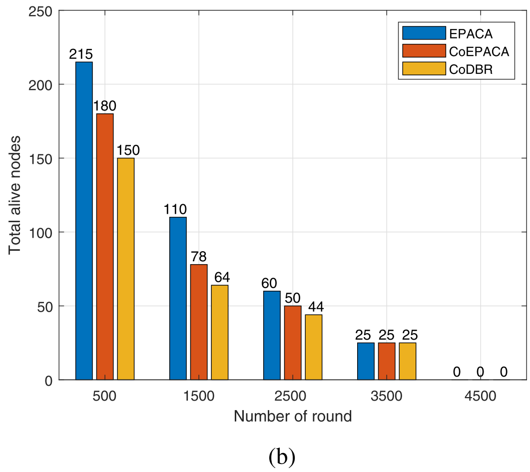


FIGURE 22. (a) Alive nodes. (b) Comparison of alive nodes for all protocols.

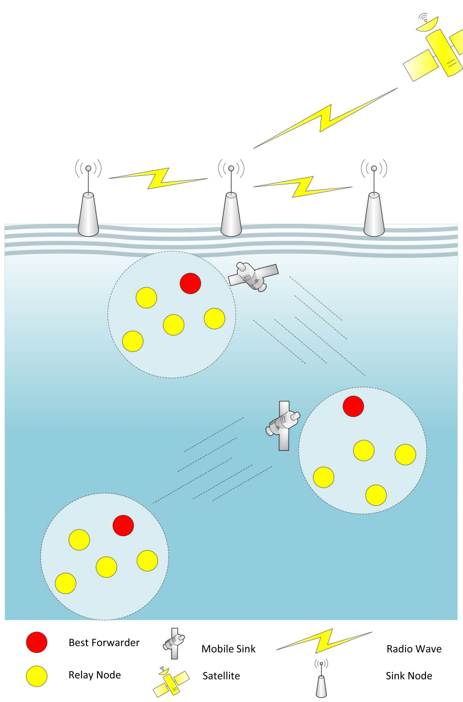


FIGURE 23. The idea of opportunistic routing and deployment of mobile sinks.

VIII. CONCLUSION AND FUTURE WORK

Routing protocols in the underwater face the number of challenges due to the unpleasant aqueous environments. The nodes residing nearer the water surface consume more energy because of the high data burden. The early death of nodes having low depth creates void holes in a network. To avoid the void holes and prevent the low depth nodes from early depth. This paper discusses the two routing schemes, namely energy path and channel aware (EPACA), and cooperative energy path and channels aware (Co-EPACA) to enhance energy efficiency and network reliability in UWSNs. The EPACA algorithm minimizes the energy consumption by taking into account the node's residual energy (R_e), history of packet transmitting(H_p), lowest distance from sink node (d) and bit error rate (BER). Furthermore, the Co-EPACA algorithm delivers the packets in a cooperative method to improve the reliability of the network. The MATLAB simulations validated the performance parameters: energy consumption, packets delivery ratio, delay, dead and alive notes. The result clearly demonstrates that the proposed algorithms achieve good performance than the CoDBR protocol in terms of reliability, energy efficiency, and network lifetime. In the future, the opportunistic and mobile sink idea can be implemented to collect the packets from the bunch of nodes, which further transmit them to the water surface within low latency. In opportunistic routing, the sensor nodes are combined and make a group that delivers the packet towards the final destination instead of via single node selection. This method relaxes high traffic on a single node and prevents the node from early depth. The idea of future work is illustrated in Fig. 23.

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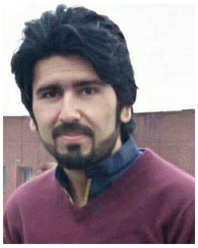

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