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Energy Balanced Localization-Free Cooperative Noise-Aware Routing Protocols for Underwater Wireless Sensor Networks

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Abstract: Owing to the harsh and unpredictable behavior of the sea channel, network protocols that combat the undesirable and challenging properties of the channel are of critical significance. Protocols addressing such challenges exist in literature. However, these protocols consume an excessive amount of energy due to redundant packets transmission or have computational complexity by being dependent on the geographical positions of nodes. To address these challenges, this article designs two protocols for underwater wireless sensor networks (UWSNs). The first protocol, depth and noise-aware routing (DNAR), incorporates the extent of link noise in combination with the depth of a node to decide the next information forwarding candidate. However, it sends data over a single link and is, therefore, vulnerable to the harshness of the channel. Therefore, routing in a cooperative fashion is added to it that makes another scheme called cooperative DNAR (Co-DNAR), which uses source-relay-destination triplets in information advancement. This reduces the probability of information corruption that would otherwise be sent over a single source-destination link. Simulations-backed results reveal the superior performance of the proposed schemes over some competitive schemes in consumed energy, packet advancement to destination, and network stability.

Keywords: noise-aware; localization-free; underwater; routing; acoustic; DNAR; Co-DNAR

1. Introduction

The harsh and unpredictable nature of the sea is one of the major hurdles to reliable communications in underwater wireless sensor networks (UWSNs). The usually variable characteristics of the sea, therefore, need to be properly addressed so that information is reliably transmitted towards the end destination [1]. Such reliable information transmission finds applications in tactical surveillance, disaster prevention, assisted navigation, resource investigation, environmental monitoring and oil and gas spill [2–6]. The sea channel also intrinsically possesses a number of limitations [7]. They include low bandwidth (and, therefore, data rate), high bit-error-rate (BER) and saline content of water. The radio waves do not support the communications in underwater due to their high absorption and attenuation in water [8] and because of the friction of radio energy with water molecules [9]. This, however, introduces a delay in communications which is about five orders greater as the corresponding delay with radio waves [10]. The sensor nodes deployed underwater operate on limited battery power, the process of the substituting or charging a node's battery is difficult and usually not preferred [11]. There are various protocols for UWSNs that do not introduce a reliability technique in the data forwarding process [12–15]. Therefore, they have no promising results in data

delivery to the water surface, because in these protocols, a source node delivers a packet through a single path. Also, while delivering packets from a sender to a destination, they do not consider the channel conditions. Therefore, packets transfer reliability is compromised. Several routing schemes exist in the literature that incorporate reliability in packets transfer through cooperative routing [16–19]. In this type of routing, at least one relay sends a copy of the signal it receives from the sender to the destination. So, it tends to minimize adversely affected links by the harsh sea properties (noise, fading). However, these schemes are based on localization. In localization, the knowledge about the position of the coordinates of the nodes is required, which is challenging, as tides and currents in the sea change the positions of nodes regularly [20].

The authors in [21] propose a cooperative position-aware mobility pattern. In this protocol, the void zones are avoided by using multiple gliders. The gliders are capable of dynamic mobility pattern and they can also stay for a moment at sojourn positions in a specified time to collect the nodes' information. Moreover, two of the best gliders are selected by a source node that delivers data in a cooperative method. The packets' advancement to target destination is optimized at the cost of high consumed energy and latency, as the involvement of gliders. Hina et al. in [22] propose a scheme in which a sender chooses two optimal relays based on their depth. The scheme is localization free and has high packets advancement towards target destination but suffers from high energy consumption due to redundant packets transfer. It also has a high delay due to using two relays instead of one. In [23], a cooperative with an opportunistic routing scheme is presented. A sender checks the relay nodes' set, by considering only depth knowledge. The holding time logic is also used for each relay node to prevent data from collision. Moreover, an opportunistic routing technique is applied to choose an optimal node from the set of relays. The framework has a high packet delivery ratio (PDR) and consumes less energy. However, the forwarder set bears a high data load that results in an unbalanced consumption of energy. The authors in [24] propose a DEAC protocol for UWSNs. A sender chooses its relay node based on link condition, depth threshold, and residual energy. Furthermore, the packet is being forwarded in two methods. The first one is directly from a source to a destination and the second one is via the relays, which amplify and forward the data to the destination. The protocol achieves a good result for packet delivery ratio. However, for long network operation time, the performance is compromised in energy consumption. Another cooperative protocol known as SMIC is presented in [16]. In this protocol, each source selects the relay as per depth, link condition, and residual energy. The MSs proceed in the water and collect the information from each node. High PDR and improvement in consumed energy and packets drop are obtained. However, the delay is high when mobile sinks accumulate data from far nodes. To enhance the reliability in [13], the authors in [25] propose the adaptive cooperation. A source chooses the best relay only when the latter has the lowest depth and sufficient energy. The data are transmitted to the destination in cooperation mode. The destination node sends back the request when it receives the erroneous packets. The protocol achieves good performance in throughput. However, high energy nodes bear the most data burden. The authors in [26] present a region-based cooperative routing protocol. A sender transmits the packets to the relays and destination. The BER is calculated at the destination. If the data is errorless than a specific point, they are forwarded further. Otherwise, retransmission is considered. Moreover, mobile sinks that move either in a vertical or a horizontal direction to cover the entire region of the network have been used. The protocol has good results for the packet drop, alive nodes, and throughput. However, mobile sinks need to update geographical information, which increases the complexity of the operation. In [18], the depth threshold is determined for the destination, which is also known as the master node and is selected as on the lowest deepness and highest residual energy. Furthermore, the parameters used for the master node are also used for the two cooperative relays. The master node gets the data from a source node. The BER is computed at the master node. When the BER is an acceptable predefined limit, data are accepted. Otherwise, it considers retransmission. This protocol has a high throughput and network lifetime. However, it has high latency since the holding time is predefined for the relays. Secondly, when the source node transfers data, it uses three paths, which causes an

extra delay. The optimized depth-based routing (ODBR) is presented in [27]. This technique is actually a single-path routing protocol and only considers the information of depth for the data forwarding. The ODBR protocol has efficient energy consumption and network lifetime, because of the single-path routing technique. However, this single-path routing technique reduces throughput efficiency and network reliability. In depth-based routing (DBR) [12], a source node detects the packet, it sends data in the way of the sink surface. The pressure sensor is used in order to choose the best forwarder. The sender picks the forwarding node as on the lowest depth. The DBR protocol has good throughput and latency. However, the node having low depth is used multiple times during packet delivery. In this way, a die quickly having the lowest depth due to high load. Therefore, the void zone is created in the network. Junaid et al. in [28] propose a depth and noise-aware routing (DNAR) scheme in which a sender picks the closer node as a relay that has the smallest path from the surface and smallest noise over the source-relay link. This reduces the corruption of information packets by channel noise, which increases reliability in the information. The DNAR does not need the geographical location of each node. The DNAR has good throughput, residual energy and lifetime of the network. But it has high latency due to frequent checking of the channel conditions.

1.1. Motivation

Addressing the noise constraint in underwater medium, Arnisha et al. [29] presented a new protocol that avoids the high noise while data forwarding. A criterion is applied by the sender in which the value of residual energy, distance and the noise calculation is considerable. The checking of the noise level in the delivery of the packets lead the protocol to achieve high reliability. However, a large number of nodes are involved in the delivery of the same packet, which results in high energy consumption. Shakeel et al. introduced a reliability technique in Ref [30], in which the forwarder node considers both the depth and the link information for data transmission. The frequent checking of the link's condition ensuring the high packets' reliability at the destination point. However, the high data traffic on the low depth nodes consume more energy and hence die early. The fundamental energy problem is addressed in [31] and an energy balancing technique is incorporated by using the varied radius cylindrical path. A few nodes are involved for the delivery of the packet from a sender to the destination, as a lower radius of the cylindrical path. The protocol has ability conferred upon each node with information of its position as well as the destination node. The restriction of the data delivery in the cylindrical way outperforms in energy with compromising in the reception of packets at the surface sink.

To address the aforementioned challenges, this paper presents the cooperative DNAR (Co-DNAR) protocol for UWSNs. This paper is the extended version of our depth and noise-aware routing (DNAR) protocol [28]. In the proposed routing scheme, the overall network is divided into five equal zones in which five minor sinks are deployed in order to minimize the probability of packets lost, as nodes are less affected by the channel properties by reducing path length with minor sinks. The destination node has the minimum depth and it is connected with the source node with the minimum noise over the source-destination link. This avoids data corruption by noise over the channel. To further add reliability in information transfer, cooperative routing is added, in which the source forwards the same packets to relay as well as the destination nodes. Moreover, the relay follows re-transmission only when the destination point receives erroneous data. The destination finally combines multiple data copies using the maximum-ratio combining (MRC), for further processing.

1.2. Contributions

To mitigate the issue of packets drop, the overall network is split into five equal sections in which five minor sinks are placed, one at each region. The advantage of the minor sinks is to reduce the path length so channel properties are less likely to affect the information. A source picks a neighbor node as a destination that has minimum depth and with low noise along with the source-destination link. This avoids the noise that is added unnecessarily to data packets and challenges their information content. Also, it reduces the complexity of electronics to process such signals. Furthermore, picking a destination by a source node controls redundancy in packets transmission, which in turn, minimizes the energy consumed in transmitting the same packets again and again. As a result, network stability and lifetime are improved. Moreover, cooperative routing is used, in which destination gets multiple copies of data packets so that to have diversity in packets advancements paths and avoid data corruption over a single link. This further adds to the reliability of the proposed scheme. The condition of the requirement of the localization of nodes is relaxed, as required in some schemes existing in the literature. This, in consequence, reduces complexity in deployment of the nodes and, in effect, enhances the scalability of the network. Performance analysis, backed by simulations, is indicative of improvement in energy cost, the stability of the network and packets advancement to the target destination. Table 1 refers to the comparison of the contribution with the existing protocols. Table 2 shows the comparison of the state-of-the-art of routing protocol.

This article is explained as: the channel model of the underwater medium is discussed in Section 2, respectively. Section 3 gives the brief idea of the proposed work. Section 4 presents the behaviour of the proposed scheme with our existing scheme. The simulation setting is described in Section 5. In the last, the conclusions of the overall work are described in Section 6.

Table 1. The comparison of our contributions with existing protocols.

The Types of Technologies Analyzed	Hop Count	Link Delay	Transmission Rate	Bandwidth Consumption	Link Capacity	Year
DBR, [12]	No	No	Yes	No	Yes	2008
EE-DBR, [13]	Yes	No	No	Yes	No	2012
SMIC, [16]	No	Yes	Yes	Yes	No	2016
Co-PAMP, [21]	No	Yes	Yes	Yes	No	2017
Co-DNAR	No	Yes	Yes	Yes	Yes	2019
Co-DBR,[22]	No	Yes	Yes	Yes	Yes	2014
RBCRP,[26]	No	No	Yes	No	No	2017
ODBR, [27]	No	Yes	No	Yes	Yes	2016
H2-DAB, [32]	Yes	No	Yes	No	Yes	2012
Co-LFEER, [33]	Yes	Yes	Yes	Yes	Yes	2018
VAPR, [34]	Yes	No	Yes	Yes	Yes	2013
EEIRA, [35]	Yes	Yes	No	Yes	No	2016
CARP, [36]	No	No	Yes	Yes	Yes	2015

Table 2. The state-of-the-art of routing protocols in underwater wireless sensor networks (UWSNs).

Protocol	Approach	Flaws/Limitations	Achievements	Year	Reference
DBR	The pressure sensor is used in orders to select the lowest depth node	The low depth node die quickly, because of high data burden	It has a good result for throughput and latency	2008	[12]
SMIC	Uses amplify and forward cooperative technique	More consumption of energy because it introduces relay cooperation	High packet delivery ratio	2016	[16]
IACR	Depth threshold is determined to the master node, select only a node which has the highest residual energy and lowest depth	High consumption in energy and greater delay due to redundant packets transmission	Good result in throughput and network lifetime	2015	[18]
Co-PAMP	Used multiple gliders for the avoidance of the void zones in the network	High consumption of energy and high latency due to cooperation involved in data forwarding	High throughput efficiency	2017	[21]
Co-DBR	Forwarder and relay selection is based on depth, utilize cooperation technique	Unbalanced energy consumption, high latency because the cooperation take extra time to reach the packet to the destination	High packet delivery ratio	2014	[22]
EECOR	A sender checks the set of relay nodes basis of its depth, FLRS technique is applied to choose the optimal relay	The forwarder set among all the nodes consume more energy with a cost of latency	Good energy efficiency and high throughput	2017	[23]
DEAC	Uses cooperative technique while forwarding the data	High consumption of the energy due to cooperative routing	Delivers the data packet with a high efficiency	2016	[24]
ACE	Relay node is chosen if it has the lowest depth and enough energy	High consumption in the energy, high latency, low network lifetime	High throughput, less packet drop, greater reliability	2014	[25]
RBCRP	Uses mobile sinks (MSs) either in a vertical or horizontal direction, also uses diversity technique	High energy consumption in a sparse network	Adopted an efficient delivery for the packets	2017	[26]
ODBR	A single-path routing scheme, only depth information is enough for data forwarding	maximizes the packets drop and reduces the network reliability	Good energy consumption and network life-span	2016	[27]
DNAR	A criterion is used to choose the best forwarder, the high value of the criterion leads to select the forwarder node	It has high latency, because of the frequent checking of the channel condition	DNAR has good packet delivery ratio, residual energy, dead and alive nodes	2018	[28]

2. Channel Model

The underwater medium is influenced by multiple factors like speed of sound, channel noise and channel attenuation. The description of each one is presented below.

2.1. Transmission Loss

The transmission loss is the reduction of acoustic intensity from a source to a destination [37]. When acoustic waves propagate underwater, their intensity drops. The transmission loss consists of spreading loss and absorption loss [38]. Transmission loss can be expressed as

$$TL = -10 \log \left(\frac{I(r, d)}{I_0} \right) \quad (1)$$

$$TL = -20 \log \left(\frac{P(r, d)}{P_0} \right) \text{ dB}, \quad (2)$$

where I_0 is the intensity at a source, I is the intensity at a distance r and depth d . The variable P and P_0 are the acoustic pressure at the distance and source point, respectively. Figure 1 shows the transmission loss of acoustic waves.

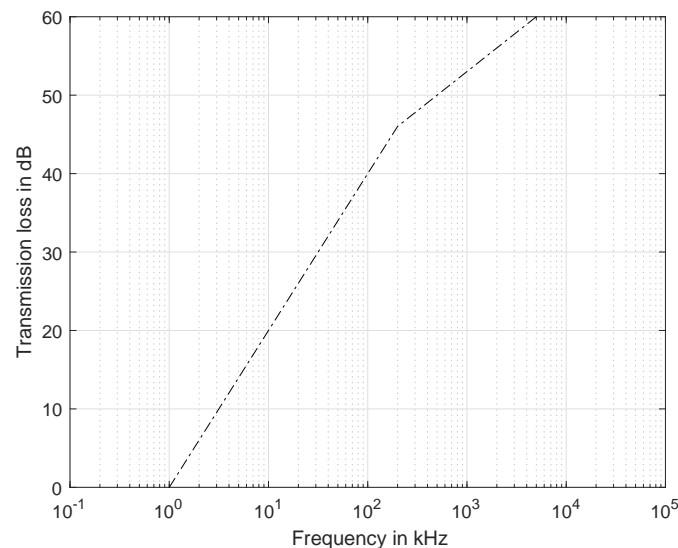


Figure 1. Transmission loss of acoustic waves.

2.2. Channel Attenuation

Underwater, when the acoustic signal is travelling from the source to the destination, its strength reduces as the channel has a great effect on the signal. The attenuation A depends upon the distance l of acoustic signal from source and its frequency f is modeled by the expression [39]:

$$A(l, f) = A_0 l^c \alpha(f)^c \quad (3)$$

where α , A_0 and c are the absorption factor, normalization constant and spreading factor, respectively. The attenuation can be denoted as in decibel (dB).

$$10 \log A(l, f) / A_0 = 10 \log d * k + 10 \log \alpha(f) * d. \quad (4)$$

Thorp model for the absorption coefficient of higher and lower frequencies in kilohertz as

$$10\log\alpha(f) = 0.11 + \frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 2.75 * 10^{-4}f^2 + 0.003 \quad (5)$$

$$10\log\alpha(f) = 0.002 + \frac{f^2}{1+f^2} + 0.011f^2. \quad (6)$$

Figure 2 shows the attenuation coefficient of the acoustic waves in seawater.

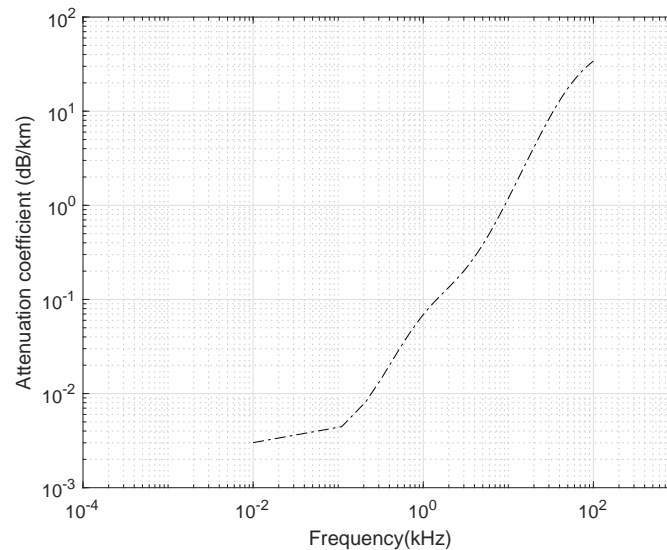


Figure 2. Attenuation coefficient in water.

2.3. Speed of Sound

The acoustic waves are used in underwater communication, as the electromagnetic waves have greater attenuation in water. The acoustic waves speed changes in the range of 1450 m/s to 1550 m/s, due to depth, salinity and temperature of the water. Mackenzie modelled an empirical equation for the speed of acoustic waves in the water [40] as:

$$\begin{aligned} c = & 1448.96 + 4.591T - 5.304 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 \\ & + 1.340(S - 35) + 1.630 \times 10^{-2}D + 1.675 \times 10^{-7}D^2 \\ & - 1.025 \times 10^{-2}T(S - 35) - 7.139 \times 10^{-3}TD^3, \end{aligned} \quad (7)$$

where c is the speed of sound in water, variable T represents the water temperature in (degree Celsius) °C, S shows the water salinity in parts per thousand (ppt) and D is the water depth in meters (m).

2.4. Channel Noise

The underwater channel suffers from different noise types, which corrupt the data packets. This makes extraction of information challenging [41]. The underwater ambient noise can be classified into four major types: turbulence, shipping, waves and thermal [42]. The power spectral density (PSD) of each noise sources are represented as N_{tr} , N_{sh} , N_{wv} and N_{th} respectively. Figure 3 shows the different noise level in seawater. The PSD of turbulence noise $N_{tr}(f)$, in dB re μ Pa [42] for frequency f is modeled as:

$$10\log N_{tr}(f) = 17 - 30\log(f). \quad (8)$$

The PSD of shipping noise $N_{sh}(f)$, in dB re μ Pa for frequency f and shipping activity factor s is modeled as:

$$10\log N_{sh}(f) = 40 + 20(s - 0.5) + 26\log(f) - 60\log(f + 0.03). \tag{9}$$

The PSD of waves noise $N_{wv}(f)$, in dB re μ Pa for frequency f and wind speed w is modeled as:

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

the PSD of thermal noise $N_{th}(f)$, in dB re μ Pa, frequency f is modeled as:

$$10\log N_{th}(f) = -15 + 20\log(f). \tag{11}$$

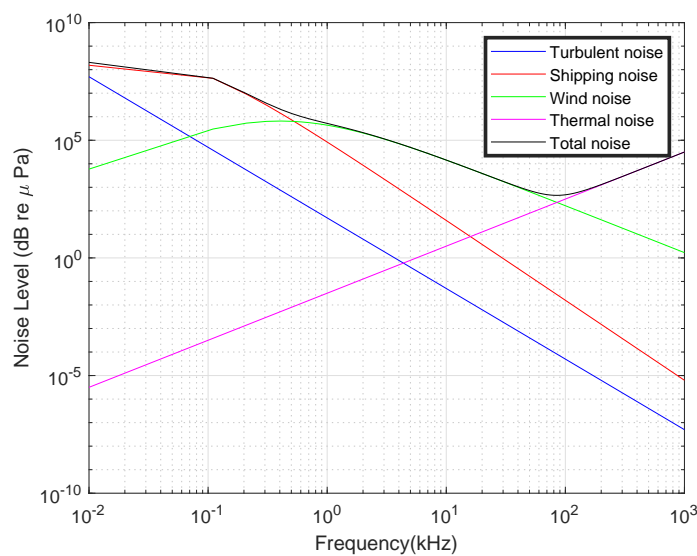


Figure 3. Ambient noise (dB re μ Pa) level in seawater.

2.5. Link Budget

Link budgeting is a method which analyzing the performance of wireless communications. A link budget is a tool which predicts signal-to-noise ratio (SNR) at the receiver side by considering multiple parameters: transmit power, gain, losses and interference etc. Figure 5 shows a plot for the link budget of wireless communications. A simplified link budget equation for wireless communication is modeled by the expression [43] as:

$$P_{re} = P_{tr} + G_{tr} + G_{re} + L_s + L_n, \tag{12}$$

where P_{re} is received power, P_{tr} = transmitted power, G_{tr} = transmitter gain, G_{re} = receiver gain, L_s = path loss and L_n is the noise factors. Figures 4 and 5 shows the simplified block diagram and plot of the link budget.

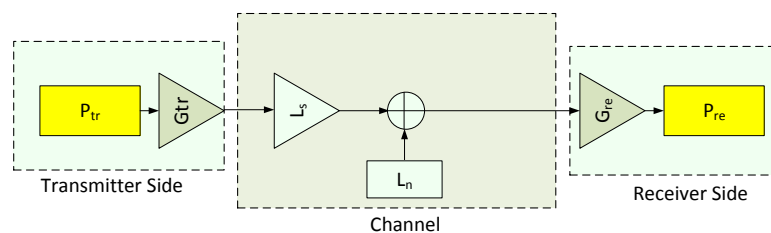


Figure 4. Block diagram of the link budget as expressed in Equation (12).

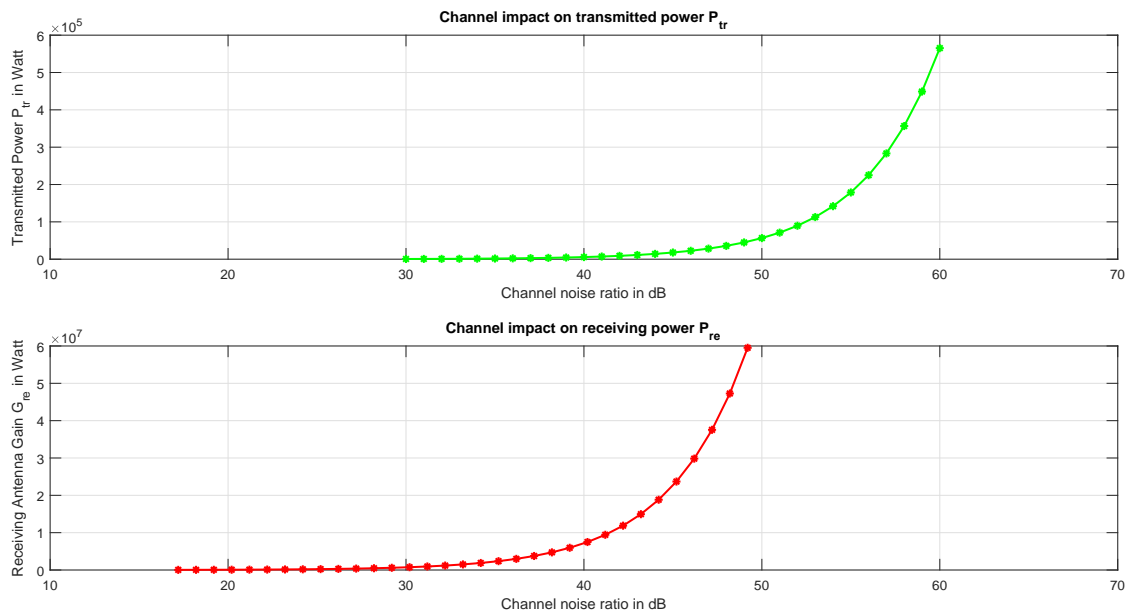


Figure 5. Link budget plot for wireless communication.

2.6. Sleeping Scheduling Energy Calculation

In Co-DNAR protocol, sensor nodes consume their energy while transmitting and receiving a data packet from a source to the destination node. Therefore, considering this assumption, a weighting function is formulated as expressed by [44]:

$$Min \sum_{r=1}^{r=Max} E_{cons}(r) ; r \in R, \tag{13}$$

where E_{cons} is the consumed energy by sensor node during a packet exchanging that is calculated as given in equation below:

$$E_{cons} = \sum_{n=1}^{k=n} D_i \times (E_{tr} + E_{re} + E_{id}), \tag{14}$$

where D_i shows the distance between node i_{th} with transmitting E_{tr} , receiving E_{re} and an idle energy E_{id} , respectively. The transmission energy can be calculated as;

$$E_{to-re} = P_{re}(PL/DR), \tag{15}$$

where P_{re} is receiving power, PL is packet length and DR is data rate. The total energy in the network is formulated as given below:

$$EL_{total} = E_{init} \times L, \tag{16}$$

where L shows the number of sensor node in the network and E_{init} is the energy of the node at the time of network initialization.

$$E_{cons} = \sum_{r=1}^{r=r} (EL_{total(r)} - E_{cons}(r)). \tag{17}$$

2.7. Absorption

The absorption of the acoustic wave varies with frequency F and is dependent on salinity S , temperature T , depth D and the water pH level. There are many expressions for the absorption of the acoustic waves. A semi-empirical expression is formulated by Francoise and Garrison [45].

$Total_{absorption} = \text{Boric acid contribution} + MgSO_4 + \text{Pure water contribution}$

$$\alpha = \frac{A_1 P_1 f_1 f^2}{f^2 + f_1^2} + \frac{A_2 P_2 f_2 f^2}{f^2 + f_2^2} + A_3 P_3 f^2 \quad (18)$$

Boric Acid Contribution:

The contribution of the boric acid is given as:

$$A_1 = \frac{8.86}{C} \times 10^{(0.78pH-5)}; \text{ dB km}^{-1} \text{ kHz}^{-2}. \quad (19)$$

$$P_1 = 1 \quad (20)$$

$$f_1 = 2.8 \left[\frac{S}{35} \right]^{0.5} \times 10^{(4-1245/\theta)}; \text{ kHz} \quad (21)$$

$$C = 1412 + 3021T + 1.19S + 0.0167D, \quad (22)$$

where C is the speed of sound in (m/s), T is the temperature $^{\circ}\text{C}$, S is the salinity in ppt and D is the water depth, respectively. The value of the $\theta = 273 + T$.

Magnesium Sulfate Contribution:

The contribution of the $MgSO_4$ is expressed by:

$$A_2 = 21.44 \frac{S}{C} (1 + 0.025T); \text{ dB km}^{-1} \text{ kHz}^{-1} \quad (23)$$

$$P_2 = 1 - 1.37 \times 10^{-4}D + 6.2 \times 10^{-9}D^2 \quad (24)$$

$$f_2 = \frac{8.17 \times 10^{(8-1990/\theta)}}{1 + 0.0018(S - 35)}; \text{ kHz} \quad (25)$$

Pure Water Contribution:

The contribution of the pure water for $T \leq 20^{\circ}\text{C}$, is presented as:

$$A_3 = 4.937 \times 10^{-4} - 2.59 \times 10^{-5}T + 9.11 \times 10^{-7}T^2 - 1.50 \times 10^{-8}T^3; \text{ dB km}^{-1} \text{ kHz}^{-2}. \quad (26)$$

For $T > 20^{\circ}\text{C}$

$$A_3 = 3.964 \times 10^{-4} - 1.146 \times 10^{-5}T + 1.45 \times 10^{-7}T^2 - 6.5 \times 10^{-10}T^3; \text{ dB km}^{-1} \text{ kHz}^{-2}. \quad (27)$$

$$P_3 = 1 - 3.83 \times 10^{-5}D + 4.9 \times 10^{-10}D^2. \quad (28)$$

Figure 6 shows the transmission lobes of the above real parameters.

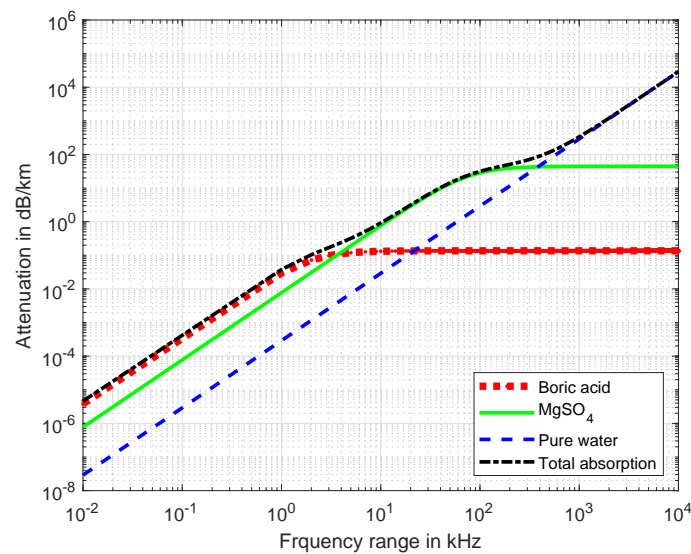


Figure 6. Transmission lobes in environments with water and other real parameters.

3. Proposed Protocol: Co-DNAR

This section explains the proposed Co-DNAR scheme in detail.

3.1. Network Settings

A 3D space of size 500 m × 500 m × 500 m was considered as the network, which was divided into five equal zones. Each zone had a height of 100 m. Five minor sink nodes were deployed in these zones in a random manner, as illustrated in Figure 7. The minor sink node in each zone is represented by MS1. Besides the minor sink nodes, major sink nodes are positioned at the top of the surface of the water at a distance of 100 m from each other. The sensor nodes use the acoustic waves for communications with each other as the radio waves are highly absorbed in underwater. A sink node has the capability to use the acoustic communications with nodes in water and the radio communications with the onshore data centre.

3.2. Neighbours Identification

After random deployment of the nodes in the network, initially, all these nodes were unaware of each other. The source node broadcasts a hello packet in order to identify the neighbors. The acknowledgment in response to the hello packet is received from those nodes which are in the transmission range of the source node. A hello packet consists of sender node ID, depth and a specific predefined bit pattern. This bit pattern is known to every node, so that the changed bits in the pattern are detected and information about the link noise from the source to the node that receives the hello packet is obtained. Figure 8 shows the bit pattern and the changed bits, which are an indicative measure of the noise over the sender-receiver link. The reciprocity of the channel is assumed, which means the behavior of the channel from a sender to a receiver is the same as when the same receiver replies back to the original sender.

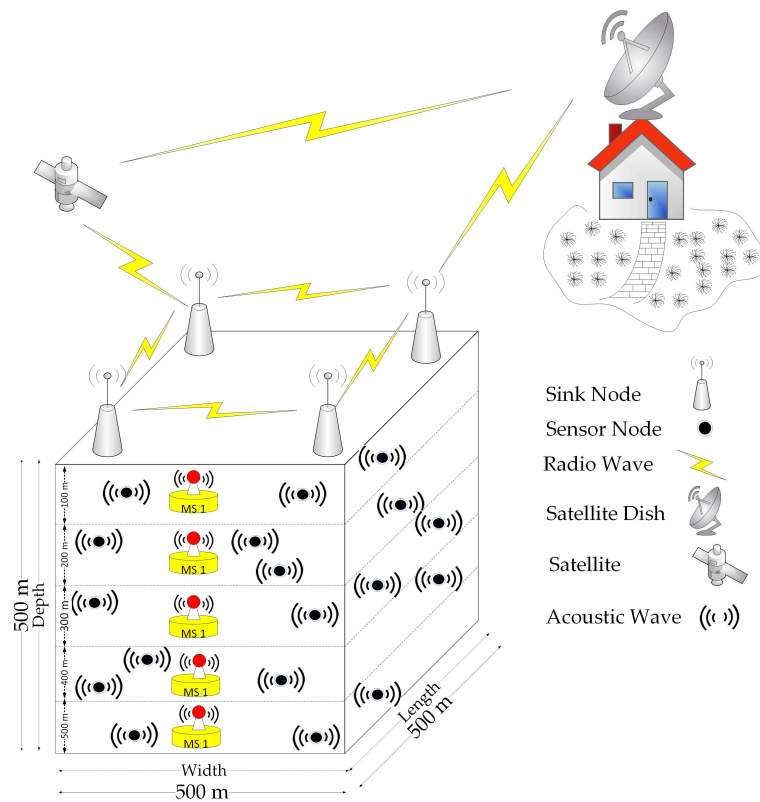


Figure 7. The cooperative depth and noise-aware routing (Co-DNAR) network architecture.

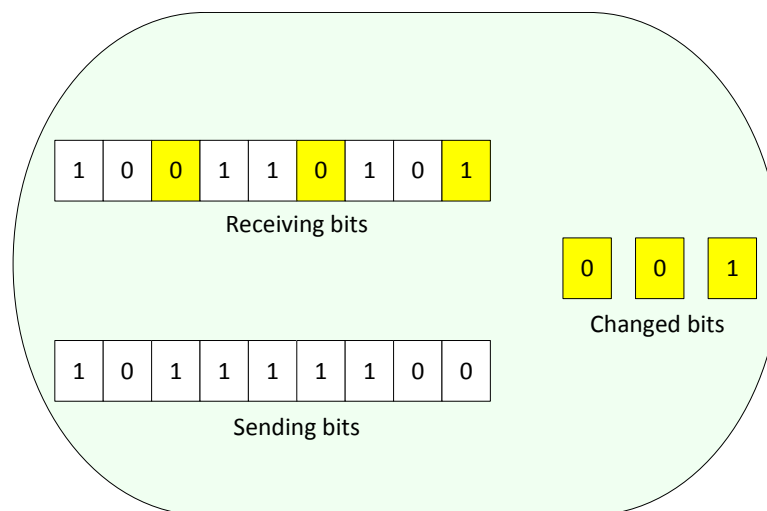


Figure 8. Bit pattern.

The size of a hello packet is 8 bytes [46]. The hello packets exchange is accomplished by all nodes so that every node can obtain an estimation of the link conditions from itself to its neighbors. Every neighbor node responds to the source node. In this response, the neighbor node informs the source node about its own depth, ID and any change in the bit pattern. This information is now enough for the source node to decide the relay and destination nodes. The selection of these nodes is accomplished by using a weighting function as below:

$$Function(f) = \frac{1}{D_i \times N_i'} \tag{29}$$

where D_i represents the depth value of the node of interest (a relay or a destination node) for the source node. The variable N_i is expressive of the extent of the noise over the link from source to the node of interest. The first neighbor of the source node with the highest value of the weighting function is chosen as a destination node. The relay nodes are selected based on the same criterion after the destination node is selected by the source node. That is, neighbor nodes of a source node having the second and third highest values of the weighting function are selected as relay nodes. If two or more nodes have the same values of the weighting function, the source node can opt any one of them as the node of interest. Broadcasting of the hello packets is accomplished by all nodes. If a broadcasting node obtains no response to its hello packet, it identifies himself as neighborless when a predefined time-threshold expires.

3.3. Data Forwarding

After deciding destination and relay nodes based on the weighting function, the source node embeds the IDs of these nodes and broadcasts data packets. After receiving the source broadcasted packets, the destination and relay nodes know that they have been selected by the source for further data forwarding by looking at their IDs in the data packets. The relay nodes amplify the packets and further forward them towards the destination. As can be seen in Figure 9, a set of three data copies is received at the destination point: one copy is directly from source or sender and two copies from two relays (relays 1 and 2 in the depicted Figure), one copy from each relay.

The MRC technique is implied at the destination, which calculates BER of received data from the source and relay nodes. The destination node only accepts the data, when the $BER \leq 0.5$. Otherwise, it drops the packet and sends the requests to the source to send the data again. This process continues unless the destination gets data within the acceptable BER limit or drops the packets.

The flow chart for the Co-DNAR routing scheme is shown in Figure 10.

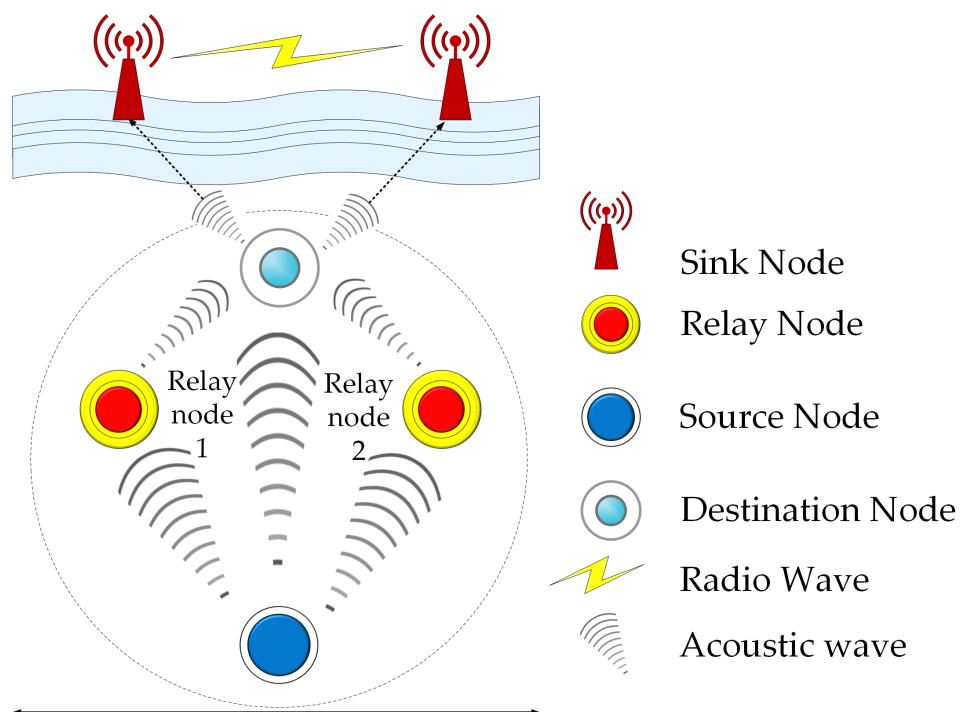


Figure 9. Cooperation of relay nodes.

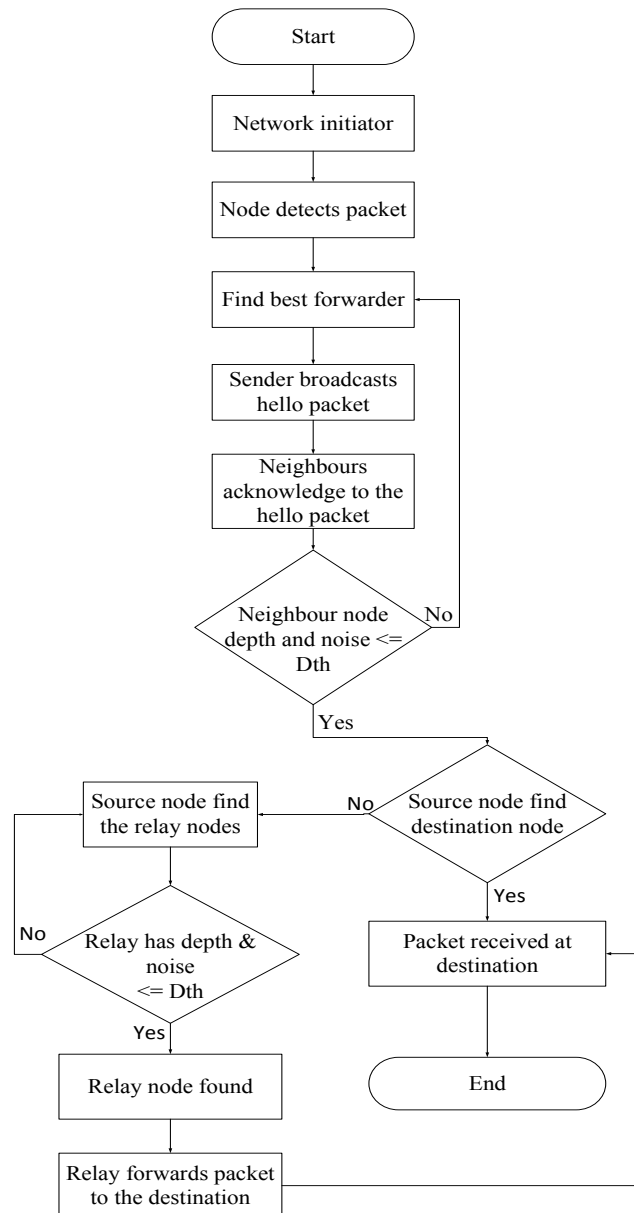


Figure 10. Flow chart showing the working mechanism of Co-DNAR.

3.4. Cooperation of Relay Nodes

The Algorithm 1 shows the data cooperation in Co-DNAR protocol. Due to data broadcasting, all the neighbour nodes received the data sent by a source S . In the critical situation, S follows cooperation in data forwarding. Figure 11 shows a simple model of cooperation in which S transmits the same signal to relay $R1$, $R2$ and destination D . The signal received by D , $R1$ and $R2$ is modeled as [47]:

$$Y_{sd} = X_s h_{sd} + n_{sd}, \quad (30)$$

where X_s is the original transmitted signal. The symbols h_{sd} and n_{sd} are the channel gain and noise from S to D , respectively. Y_{sd} is the output signal at D . The signals transmitted from S to $R1$ and $R2$ are presented, in a respective manner, as:

$$Y_{sr1} = X_s h_{sr1} + n_{sr1} \quad (31)$$

$$Y_{sr2} = X_s h_{sr2} + n_{sr2}, \quad (32)$$

where Y_{sr1} and Y_{sr2} are the output signals at relay 1 and relay 2, respectively. The h_{sr1} n_{sr1} are the gain of the channel and noise over the link from S to $R1$, respectively. The channel gain and channel noise from S to $R2$ are represented by h_{sr2} and n_{sr2} , respectively. The signals received from $R1$ and $R2$ at D , in a respective manner, are modeled as:

$$Y_{r1d} = \beta Y_{sr1} h_{r1d} + n_{r1d} \quad (33)$$

$$Y_{r2d} = \beta Y_{sr2} h_{r2d} + n_{r2d}, \quad (34)$$

where Y_{r1d} and Y_{r2d} are the signal received at D from $R1$ and $R2$, respectively. The channel gains and channel noise from $R1$ to D are h_{r1d} and n_{r1d} , respectively. The channel gains and channel noise from $R2$ to D are h_{r2d} and n_{r2d} , respectively. When the relay has data for transmitting, it first amplifies the data. The factor by which the data is amplified is denoted by β and mathematically is modelled as [48]:

$$\beta = \sqrt{\frac{1}{|h_{sr}|^2 + \sigma^2}}, \quad (35)$$

where σ^2 is the Gaussian random variable with zero mean and unity variance.

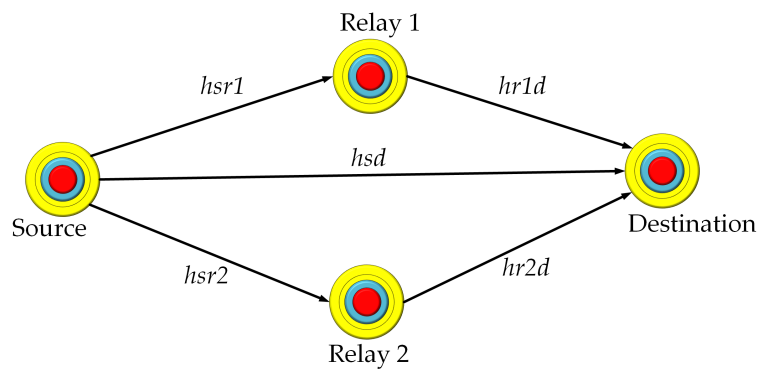


Figure 11. A simple model of cooperation.

Algorithm 1: Data Cooperation.

```

BR ← The best relay node
SS ← Sink Surface
SN ← Sender node
RN ← Receiving node
Di ← Depth of the sensor node i
Ni ← Neighbour of the source node i
for i = 1 : 1 : S do
    BR forwards a data packet
    while(data packet not reached(to the SS)) do
        if SN.Nexthop = SS then
            if BER < Threshold then
                packet accepted
                find neighbours N
                Sort the depth of N neighbours in ascending order
            else if
                Make N1 as 1st relay node
                Make N2 as 2nd relay node
                Packets reached to the SS = True
                while packets not reached to the SS
            else
                Packets drop
        end if
        else
            Nodes consume all of the energy and have no battery power
        end while
    end if
end for

```

3.5. Combining Diversity Technique

The maximum ratio combining (MRC) is applied as a diversity combining technique because it does not take into consideration the geographical information of nodes. It combines the multiple signals at the destination point, which are sent from a source and the relay nodes. The overall signal that is received at destination point is given as [47],

$$Y_d = \sum_{k=1}^M h_{kd}^* \times Y_{kd}, \quad (36)$$

where Y_{kd} is the signal that is received at destination from k th branch (link), h_{kd}^* is the channel gain between destination and the k th branch. In this case, three independent copies i.e., from source, relay 1 and relay 2 are combined at the destination point. Hence, the total number input branches is $M = 3$, which is given as

$$Y_d = h_{sd}^* Y_{sd} + h_{r1d}^* Y_{r1d} + h_{r2d}^* Y_{r2d} \quad (37)$$

which shows that the destination receives more copies and MRC is used to minimize the probability of error in the data. The calculation of BER follows the same model as described in [22].

4. Proposed Protocol: DNAR

This protocol has the same working mechanism as the Co-DNAR protocol except that it does not involve relay nodes in data forwarding. Rather, a source node sends data to the destination and decides the destination based on its depth and the noise over the source-destination link. The destination further forwards the data and this process carries on unless data packets reach sea surface or drop during the journey.

5. Simulation Settings

MATLAB is used to perform the simulations. A 3D region of each side of 500 m is considered for the deployment of 225 nodes [22], which is random. The static surface sinks are installed at the surface of the water. A depth sensor is attached with each node, which is used to measure the node's depth from the water surface. The communication range for each sink and node is 100 m. The commercial LinkQuest UWM1000 modem data rate of 10 kbps is used [49]. Each node transmits the packet having the size of 50 bytes. The MAC protocol as in Xie et al. [10,50] is used, which advances packets are on the free channel and drops them when congestion occurs even after attempting predefined multiple times. Energy of 10 J energy is assigned to every node, except in the proposed schemes that assign more energy to low depth nodes to avoid their early death. The sensor nodes consume 2 W, 0.1 W, and 10 mW power in transmit, receive and idle mode, respectively. In Table 3, simulation parameters are shown.

Table 3. Simulation parameters.

Operations	Values
Frequency	30 kHz
Packet size	50 bytes
Initial energy	10 J
Network depth	500 m
Network width	500 m
Network height	500 m
Depth threshold	60 m
Receiving power	0.1 W
Transmission range	100 m
Transmission power	2.0 W
Total rounds	1400
Total sink nodes	4
The speed of sound in water	1500 m/s
Total number of sensor nodes	225

We select the DBR [27], Co-DBR and ODBR [27] to compare it with proposed schemes. The reason is that these protocols consider the lowest depth for data forwarding and they are also localization-free protocols just like the proposed protocols. The total residual energy for each protocol is depicted in Figure 12. The residual energy of DNAR and Co-DNAR is greater than the other schemes due to suppression of greedy forwarding in the latter in which a node forwards data to every possible route except to the one from which it receives the data. This causes excessive energy load on nodes and they consume energy rapidly. In addition, DNAR and Co-DNAR assign more energy to low depth nodes so more energy is preserved with these protocols. DBR preserves more energy than Co-DBR due to the cooperation of relays in the latter, which consumes more energy. At the same time, ODBR preserves less energy than DBR as the former assigns less energy to high depth nodes than DBR which assigns equal energy to all nodes.

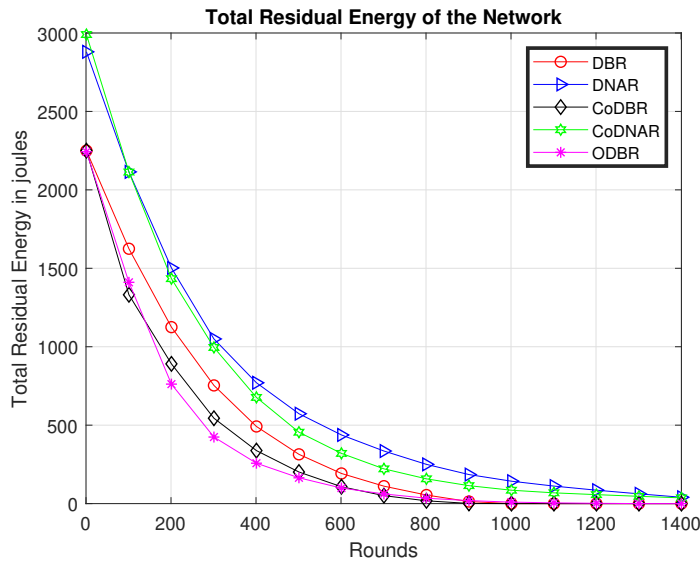


Figure 12. Total residual energy.

In Figure 13, initially, the PDR of DBR is greater than DNAR, because a greedy method is used in the data forwarding in DBR. In this method, the same packet is transmitted by more than one forwarder. Later on, the nodes that are close to the sinks become dead quickly, as such nodes have more packets load. Thus, PDR of DBR falls in subsequent rounds and becomes the minimum. In the DNAR protocol, the source node checks the condition of the channel when it has a packet to be transmitted. Therefore, it excludes all noisy links while forwarding the data packets. The avoiding of a noisy channel assures high packet delivery in DNAR. The PDR Co-DBR is greater than the rest of the schemes as it involves cooperative routing; which increases packets delivery to the sea surface, and assigns more energy to low depth nodes so they remain active for a long time to deliver packets. In addition, the involvement of minor sink nodes further adds to packets delivery in Co-DNAR. Co-DBR has initially greater PDR than ODBR, DBR, and DNAR due to cooperative routing. However, redundant data transmission in combination with cooperative routing in Co-DBR puts a high load on low depth nodes. So, these nodes dying is what affects packet delivery to the sea surface. As a result, the PDR of Co-DBR falls later on. The redundant packets transfer in a greedy manner in ODBR makes its PDR greater than DNAR.

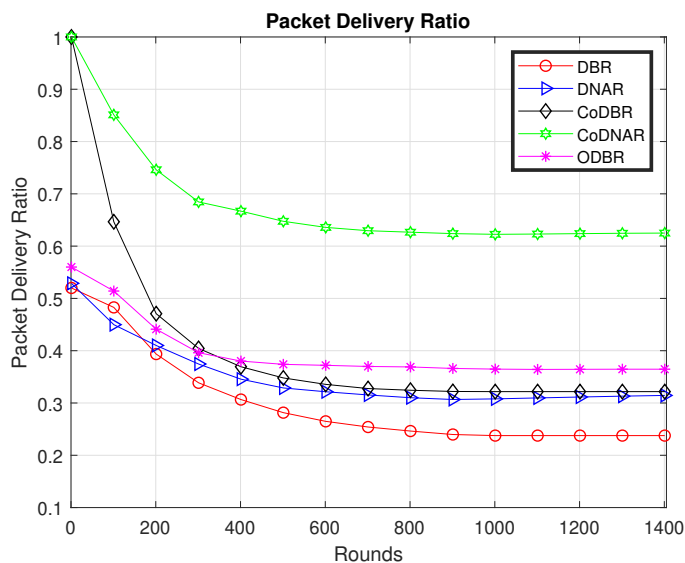


Figure 13. Total packets received at the sink surface .

The plot about dead nodes is depicted in Figure 14. Initially, the dead nodes in DBR and DNAR protocols are almost the same. After that from round 100 onward, the dead nodes count in DBR is higher than DNAR, because, the low depth nodes are used frequently for the packets forwarding plus in combination with greedy routing. Therefore, such the nodes dies quickly. Initially, nodes death is minimum in ODBR due to the way depth threshold is defined in this protocol, which keep the load balanced on low depth nodes initially. However, later on these low depth nodes are used and high depth nodes participate in routing. The high depth nodes are, however, assigned lower energy in ODBR as compared to other protocols. Therefore, such nodes die with the highest rate. Nodes in Co-DNAR and Co-DBR die more quickly than DBR and DNAR due to cooperative routing in the latter.

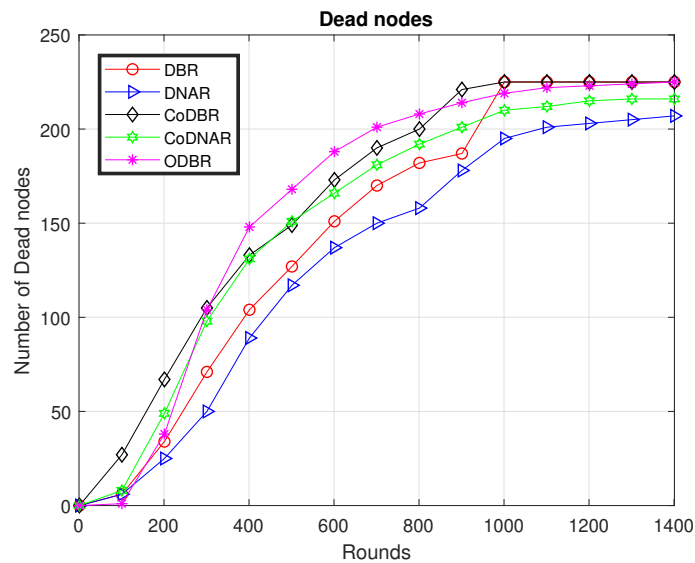


Figure 14. Total numbers of dead nodes.

As shown in Figure 15, the delay for each protocol increases as the number of rounds increases. It is because the sender node can detect few nodes which can qualify to forwards the packets. The delay of the DBR protocol is lower than their counterparts because the packets utilize the shortest path to forward toward a surface sink. Therefore, the DBR protocol has the best result in terms of delay. The technique for the selection of the relay node used in the DNAR protocol is the same as the DBR protocol, but it also checks the noise in the channel. Therefore, in DNAR, the delay is higher than the DBR protocol. The ODBR protocol has the lowest delay. In the ODBR scheme, the only depth information is used for the selection of the best forwarder with time division of the network for keeping destination nodes close to the water surface. This causes the lowest delay in the ODBR scheme. The Co-DBR and Co-DNAR both use cooperation in data forwarding. But Co-DNAR also checks the channel conditions. This takes extra time to select the relay nodes. Thus Co-DNAR has the highest delay.

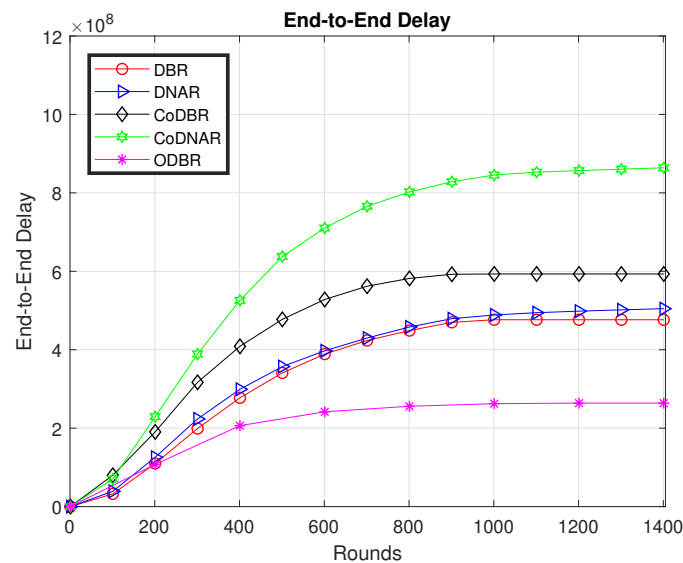


Figure 15. Average end-to-end delay.

6. Conclusions and Future Work

In underwater wireless sensor networks, due to the unpredictable and harsh aquatic environment, the reliable delivery of information is a challenging task, because the channel unfavorable behavior affects the reliable data delivery. Therefore, this paper presents two protocols: DNAR and Co-DNAR, to cope with these challenges. The entire network is divided into five equal zones, where five minor sinks are deployed. The splitting of the network and deployment of minor sinks ensure the reception of the maximum packet at the final destination. In DNAR, the destination node is chosen when it has the lowest depth and also lowest noise along the source-destination channel. Cooperative routing is added to the DNAR protocol to make Co-DNAR protocol for further reliability in packets transfer, which involves relay nodes with the source-destination pair to achieve spatial diversity. Simulation results proved the promising behavior of the proposed schemes in consumed energy, packets advancement to destination and network stability.

In the future, the opportunistic routing can be used in order to overcome the high data traffic on the relay and the destination nodes. This type of routing consists of a set of nodes that forwards the packets to the destination rather than burdening the data traffic on a single destination node.

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Abbreviations

AF	Amplify and forward
BER	Bit error rate
dB	Decibel
FLRS	Fuzzy logic relay selection
MSs	Mobile sinks
MAC	Medium access control
MRC	Maximal combining ratio
PSD	Power spectral density
UWSNs	Underwater wireless sensor networks

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