Reliable Path Selection and Opportunistic Routing Protocol for Underwater Wireless Sensor Networks

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ABSTRACT The increased need to gather scientific data and the renewed drive to explore underwater natural resources has led more and more researchers to study the underwater environment. This has resulted in enormous attention being given to Underwater Wireless Sensor Networks (UWSNs) all over the world. However, UWSNs are faced with some major challenges including harsh environment, higher propagation delay, and limited battery power of the sensor nodes. To address these challenges, several routing schemes have been proposed. In this paper, we propose a routing strategy, called Reliable Path Selection and Opportunistic Routing (RPSOR) for UWSNs, which is a significantly improved version of Weighting Depth and Forwarding Area Division Depth Based Routing (WDFAD-DBR). RPSOR is based on three main factors: Advancement factor ($ADV_f$), which depends on the depth of current as well as next hop forwarding node; Reliability index ($REL_i$), which depends on the energy of the current forwarder as well as average energy in the next expected forwarding region; and Shortest Path Index ($SP_i$), which is calculated on the basis of number of hops to the sink and average depth of neighbors in the next expected hop. To deal with the void hole problem and improve the Packet Delivery Ratio (PDR), we follow the more reliable path towards the sink by calculating $REL_i$ for a node. At the end, we perform extensive simulations and compare our proposed scheme with WDFAD-DBR, the results of which prove that RPSOR shows better performance in terms of PDR and energy tax in comparison to WDFAD-DBR. However, the proposed work compromises end-to-end delay in sparse networks.

INDEX TERMS Underwater wireless sensor networks (UWSNs), reliability, potential forwarding nodes (PFNs), end-to-end delay (E2ED), packet delivery ratio (PDR), priority function (PF), void hole.

I. INTRODUCTION The planet earth is predominantly covered by water. Since the natural resources are being depleted elsewhere, humans are more focused on undersea exploration, however, low visibility and high pressure limit their ability to communicate in the water or explore the undersea environment.

Underwater Wireless Sensor Networks (UWSNs) are widely used for military defense systems, coastline surveillance and protection, resource exploration, marine environment monitoring and assisted navigation [1], etc. For terrestrial wireless communication, radio signals are used, whose propagation speed is 5-times greater than the acoustic communication [2]. However, acoustic signals are the preferred choice in underwater environments as they can travel long distances [3] when compared to radio signals, which are heavily attenuated...
in water [4]. Still, using acoustic signals as the source of communication in UWSNs poses great challenges, such as low propagation speed [5], limited bandwidth [6], dynamic nature of the network [7], limited energy resources, and high deployment costs. Long propagation delay is one of the major challenges in UWSNs, because the speed of propagation of acoustic signals is 1500 m/s (under normal conditions), which is around five times lesser than radio wave propagation speed (3 × 10^8 m/s). This may vary, depending on factors like temperature, depth, salinity, etc. Limited bandwidth is another challenge faced by UWSNs, which is caused by attenuation and high absorption of acoustic signals. Currently, the underwater communication bandwidth is approximately 40 kbps. Node mobility is another challenging factor in UWSNs. UWSNs consist of small devices, called nodes, which frequently change their positions due to water currents. These changes are recorded to be around 1-3 m/s, which are enough to make the network unstable. Due to these reasons, the traditional WSN routing protocols cannot be employed for UWSNs. Power batteries are used to provide energy for nodes; however, it is difficult to replace or recharge the batteries, especially in deep oceans. Therefore, energy consumption is considered as one of the primary concerns to be addressed. Deployment of underwater wireless sensors is costly due to its large size and it needs the aid of ships. In general, underwater wireless sensors are sparsely deployed due to high cost of sensors and large (in terms of width and depth) monitoring area, which remains a major challenge in designing and implementing UWSN routing protocols. Underwater channel properties like multi-path fading, noise, salinity, path loss and Doppler spread result in a higher bit error rate. Going through all the above challenges, we can state that the routing protocols designed for terrestrial sensor networks are not optimal to be used for underwater wireless channels. Therefore, we need to design more reliable protocols for UWSNs, which are energy-efficient and have lower End-to-End Delay (E2ED). Due to all the mentioned challenges, there is a lot of ongoing research to increase the efficiency of UWSN routing protocols.

### A. MOTIVATION AND CONTRIBUTION

Most of the depth-based routing protocols work only on packet advancement; some of them use a one-hop mechanism, while others make use of a two-hop mechanism for the sake of increasing reliability of the system. Reliability is mainly achieved only by taking the depth of the next two hops into account. These protocols cannot increase the holding time difference among the neighboring hops to avoid duplication and packet collision at the receiver end. To improve the performance of state-of-the-art routing protocols, in this paper, we propose a protocol called Reliable Path Selection and Opportunistic Routing (RPSOR) for UWSNs. RPSOR calculates the holding time for forwarders, taking the following points into consideration:

1. RPSOR uses exponential function in calculating priority function (PF) for the nodes. The proposed scheme exponentially increases the priority function value for a small decrease in depth of the forwarders. So, the farther nodes in the transmission can be successfully suppressed when RPSOR is used as a routing technique for UWSNs. Figure 1 shows that for the same depth difference among the nodes, RPSOR yields approximately two times increase in PF value as compared to that in WDFAD-DBR [17], when RELᵢ and SPᵢ are kept constant.

![Comparison of PF difference among the neighbors.](image)

2. The forwarder is selected using the forwarding region information from a region in which average energy of the forwarders is higher in order to increase reliability in the network.

3. Shortest Path Index (SPᵢ) is calculated for every forwarder to follow the shortest path towards the sink.

4. Experiments are performed under different node densities and transmission ranges, to verify the performance of RPSOR in different scenarios.

5. RPSOR is analyzed with and without mobile sinks.

RPSOR protocol is devised to make sure that it performs the following tasks: (1) avoids hitting/using any void hole in the network, (2) prevents/reduces void hole formation in the network, and (3) reduces duplicate packets.

This, in turn, leaves us with a noticeable decrease in energy consumption of the network, which is achieved by incorporating the following three key parameters into the PF while selecting the next forwarder in the upcoming hop:

1. The depth of next two-hop forwarding nodes.

2. Residual energy of the current forwarder and average energy in the next forwarding region.

3. The shortest path index of the forwarder in the current hop.

The rest of the paper is structured as follows: Section II presents the related work on UWSN routing protocols. The problem statement is presented in section III, whereas section IV explains the system model. The proposed RPSOR protocol is explained in Section V in detail. Simulations and results are discussed in section VI. Finally, section VII concludes the paper along with possible future directions.
II. RELATED WORK

After presenting a short overview of RPSOR and its goals, we now dive a little deeper into the exploration of existing routing protocols. This not only establishes the context but also provides a comparative analysis for RPSOR by having a deeper discussion on all the pros and cons of the existing routing protocols. Every single routing protocol uses a different strategy and forwarding mechanism for packet delivery from source to destination, yet all routing protocols share some common properties based on which they can be categorized into different classes, such as vector based routing, depth based routing, multi-path based routing, address based routing, and cluster based routing, as summarized in Table 1.

Taking the high mobility of underwater acoustic sensor nodes into account, Vector Based Forwarding (VBF) protocols have already been proposed in [8]. In VBF a virtual pipeline, which is centered on a virtual vector, is made from source to destination. Nodes that are located inside the pipe and fall closer to the destination, are factored out as Potential Forwarding Nodes (PFNs). VBF successfully reduces the forwarding area; however, the downfall is that taking nodes inside the pipe as PFNs over and over again will not only result in faster depletion of the nodes but will also result in over-exhaustion of nodes inside the pipe, which could cause a void hole. To overcome these shortcomings in VBF, Nicolaou et al. [9] proposed a Hop-by-Hop Vector Based Forwarding (HH-VBF) protocol in which the pipe is made on every hop. In this way, the routing strategy is more probable to find the best PFN; therefore, higher Packet Delivery Ratio (PDR) is achieved as compared to VBF. However, HH-VBF is constrained by factors like large network overhead produced due to the hop-by-hop mechanism, lack of strategy for void hole avoidance, high energy consumption due to constant pipeline radius throughout the forwarding process, and poor performance in sparse networks.

To reduce the shortcomings and further improve the performance of HH-VBF, authors in [10] proposed a routing scheme called AHV-VBF. In contrast to HH-VBF, in which a constant pipeline radius is used, AHV-VBF changes pipeline radius according to the local node density. As a result, the network energy consumption is reduced. However, AHV-VBF fails to reduce duplicate packets and balance energy consumption by not considering residual energy of the neighbors. To balance the energy consumption among neighbors and reduce duplicate packets, an Energy Scaled and Expanded Vector-Based Forwarding Scheme (ESEVBF) is proposed in [11]. It scales and expands the holding time difference by considering residual energy, ratio of projection distance to the virtual vector, and width of the pipeline. Moreover, the proposed scheme enhances the total lifetime of the network, since significantly lesser number of nodes deplete in the given time interval. However, the forwarding strategy suppresses large number of nodes due to which it does not show significant improvement in PDR. In [12], authors proposed an adaptive energy efficient and lifetime-aware routing protocol based on reinforcement learning, called QELAR. The purpose of QELAR is to prolong the network lifetime by evenly distributing residual energy of the sensor nodes.

| Protocol     | Routing strategy | Energy efficiency | Delay efficiency | PDR  | Processing complexity |
|--------------|------------------|-------------------|------------------|------|-----------------------|
| VBF [8]      | Vector Based     | Medium            | Medium           | High | Medium                |
| HH-VBF [9]   | Vector Based     | Medium            | Medium           | High | High                  |
| FBR [14]     | Vector Based     | Medium            | Medium           | High | High                  |
| DFR [15]     | Vector Based     | Medium            | Medium           | High | High                  |
| ESE-VBF [11] | Vector Based     | High              | Medium           | Medium| High                  |
| AHV-VBF [10] | Vector Based     | High              | Medium           | Medium| High                  |
| DBR [16]     | Depth Based      | High              | Medium           | High | High                  |
| WDFAD-DBR [17]| Depth Based     | High              | High             | High | High                  |
| EEDBR [18]   | Depth Based      | High              | Medium           | High | High                  |
| H2-DAB [19]  | Addressing Based | High              | High             | Medium| Medium                |
| MCCP [20]    | Clustering Based | High              | Low              | Medium| High                  |
| AMCTD [22]   | Depth Based      | High              | Low              | Medium| High                  |
| RDBF [23]    | Distance Based   | High              | Low              | Medium| Medium                |
| SBR-DLP [25] | Vector Based     | High              | Low              | Medium| Medium                |
| R-ERP²R [24] | Distance Based   | Medium            | High             | Medium| High                  |
| QELAR [12]   | Q-learning Based | High              | Medium           | High | High                  |
| EBEVBF [13]  | Vector Based     | High              | Medium           | High | Medium                |
| EBER² [30]   | Depth Based      | High              | Low              | High | High                  |
| ESEVBF [31]  | Vector Based     | High              | High             | Medium| High                  |
Implementing QELAR for mobile UWSNs is more realistic because it does not require any special devices for Angle Of Arrival (AOA), detailed geographic information, and the need for downlink communication. Nodes in the network are responsible to select the best forwarder based on the environmental conditions to improve performance of the network. In [13], an Energy Balanced Vector Based Forwarding protocol is proposed, which focuses on energy balancing among the nodes to increase lifetime of the UWSNs, and avoid void zones in the network that can result in communication breakage between certain nodes and sinks. In [30], authors proposed an Efficient Routing Protocol Based on Stretched Holding Time Difference for UWSNs, which is basically the improved version of ESEVBF protocol. It extends the holding time mechanism of the first-hop forwarder to the second hop for finding the best satisfactory path. Furthermore, it reduces the occurrence of the void hole, whether due to lack of energy or lack of potential forwarders. However, high overhead is produced due to the large number of control packets.

To reduce energy consumption and prolong network lifetime, Jornet et al. [14] proposed Focused Beam Routing (FBR). They constrained flooding with the transmission power instead of constant power level, stated from $P_1$ to $P_N$ to enhance the network lifetime and reduce the energy consumption. FBR uses location information of sensor nodes for forwarding, i.e., each node knows about its own location and the location of its destination. In this protocol, there is a transmission radius $D_i$ corresponding to each power level. $D_i$ is the area from source toward the destination within the cone of an angle. The Request to Send (RTS) packet is broadcasted by the source node with a power level $P_1$, which contains the location information of both source and destination nodes. All nodes receiving RTS reply with a Clear to Send (CTS) packet. The source node receives multiple CTS packets and then chooses a potential forwarder to forward the packet. If the source node does not receive any CTS packet, then the power level is increased to the next level. This process continues until the source node receives the CTS packet or the maximum level of power $P_N$ is reached. The cone is shifted toward the right or left of the main cone by the source node; if no CTS packet is received till the maximum power level, then the packet is transmitted from the source node toward the destination. FBR successfully reduces redundant packets and unnecessary flooding. However, E2ED is increased due to the large number of CTS and RTS packets.

In [15], Hwang and Kim proposed Directional Flooding based Routing (DFR). The flooding region of this protocol is bounded to the base angles of the source node, destination node and the previous hop forwarding node. The local node density and the quality of link determine the base angle, while the source and destination nodes determine the current angle. Source node broadcasts the packet and all nodes in the range of the base angle receive it. Nodes lying outside the base angle, simply drop the packet. DFR reduces energy consumption but uses constant power level in the whole network. However, in a sparse network, DFR cannot find the PFNs, which increases the probability of void-hole occurrence and causes extra energy consumption.

In depth based routing, underwater devices (nodes) are equipped with pressure sensors and every single node knows its depth with respect to the water surface. Routing decisions are taken using local depth of the sensor nodes. In Depth Based Routing (DBR) protocol [16], nodes embedded with pressure sensors use depth information to perform flooding. In DBR, when a node receives a packet, besides other information, it also contains depth of the transmitter, which is compared by the receiver node with its own depth. Then it is added in the depth field of the packet on the transmitter end. If the depth is higher than that of the current node, then the node is called PFN. In contrast, if depth contained in the depth field of the packet is lower than that of the current node, then such nodes are called suppressed nodes. PFNs are qualified to further broadcast the packet, whereas suppressed nodes simply drop it. In order to reduce packet redundancy, each node maintains two queues: first queue (Q1) is called priority queue and the second one (Q2) is called packet priority queue. Upon receiving a packet, each node computes holding time of the packet and adds to Q1. Holding time of the packet is calculated based on depth difference of the source node and the PFN. The information of the transmitted packet is added to Q2 in order to control redundancy. DBR only considers information in one-hop forwarding nodes, i.e., it does not care about PFNs on the second hop. A packet is more probable to encounter void hole on the second hop, when DBR is used as the routing mechanism. In order to get rid of void hole in advance, on the second hop, the authors in [17] proposed WDFAD-DBR. It is a two hop mechanism, where the routing decision is based on depth difference of the first hop and the expected next hop, which helps to reduce the probability of void-hole occurrence. This strategy improves the reliability and packet delivery ratio of the network. Furthermore, WDFAD-DBR uses neighbor prediction mechanism by dividing the forwarding area into primary forwarding and auxiliary forwarding regions, which improves the overall network performance. However, WDFAD-DBR does not consider residual energy in calculating holding time of a packet. As a result, energy consumption becomes unbalanced among neighbors, which reduces the lifetime of the network. To enhance the lifetime and stability of the network, EEDBR [18] used both residual energy and depth information of sensor nodes for calculating holding time of a packet. EEDBR efficiently deals with energy consumption and E2ED and reduces the load on nodes having median depth. The problem with EEDBR is the lack of energy balance because of unequal load distribution. In [29], an Energy Balanced Efficient and Reliable Routing (EBER\textsuperscript{2}) protocol is proposed in which energy balancing is achieved by considering energy and number of potential forwarders of the expected next hop node. EBER\textsuperscript{2} also deploys two embedded sinks due to which high packet delivery occurs at relatively low cost. EBER\textsuperscript{2} increases lifetime of the network due to energy balancing. However, the proposed scheme suffers from relatively high
E2ED due to not using pure greedy approach. Furthermore, embedded sinks communicate to surface sinks through high speed optical fibre links, which is costly.

Some routing protocols are addressing based, e.g., H2-DAB [19]. H2-DAB counts the hops from the sink and dynamically assigns addresses to each node and makes routing decisions by considering the dynamic address of a sensor node. A node having larger dynamic address forwards the packet to the node having smaller dynamic address until the packet reaches safely to the water surface. This protocol reduces hardware cost of the network for localization of nodes, which is considered a major advantage of this scheme.

MCCP [20] takes advantage of the clustering technique to reduce the energy consumption of the network. In a clustering-based routing protocol, first, the cluster head is selected on the basis of location or energy. Secondly, all neighbors transmit their data to the respective cluster head. After this, all cluster heads of the respective areas forward their collected data towards the sink node. This technique efficiently reduces energy consumption of the network. However, it compromises E2ED due to which clustering based routing is not a good choice for applications where delay is the main concern. Another protocol named Energy-efficient Multilevel Clustering Protocol for UWSNs [21] is proposed in which the clusters or logical levels are developed on the basis of residual energy. Nodes having a similar level of energy are considered in the same level. The sinks always communicate with the cluster head having highest remaining energy level. This technique achieves improved network lifetime. A proactive routing protocol is proposed in [31], which aims to avoid the void hole in UWSNs. Depending on the type of the network (dense, partially dense and sparse), the proposed protocol adaptively changes its communication strategy. A vertical inter-transmission layering concept is introduced in the dense and partially dense regions. Besides, a cluster formation concept is appended for making successful transmission in the sparse region.

To make routing protocols energy efficient, various routing mechanisms are proposed. In Adaptive Mobility of Courier nodes in Threshold-optimized DBR (AMCTD) [22] routing protocol, the computations of optimal weight reduce energy consumption of lower depth sensor nodes are performed and it also provides the global balance of load in the network. In order to increase the network stability, the weight function is used, which also provides a mechanism to reduce attenuation losses and noise in lower depth regions. Relative Distance Based Forwarding (RDBF) [23] focuses on efficient transmission, low delay routing, and energy saving. The forwarding process is done by a small fraction of nodes, which helps to decrease E2ED, energy consumption and also controls the duplicate packet transmission. In Reliable Energy-efficient Routing Protocol based on Physical distance and Residual energy (R-ERP2R) [24], the routing decision is made based on physical distance between the sensor nodes. This algorithm also has some efficient mechanisms, which improve the link quality and decrease the energy consumption. Sensor nodes calculate the holding time based on their depth to suppress the duplicate forwarding of packets. In Sector-Based Routing with Destination Location Prediction (SBR-DLP), [25] the whole communication area is divided into sectors. The sector closest to the destination will be selected for communication. In this protocol, a pre-planned movement of a mobile node is considered to be known to each sensor node. Whenever a mobile sink node changes its movement trajectory, it broadcasts a notification to its first hop neighbors. To further improve the performance of WDFAD-DBR, in this paper, we propose a novel protocol called Reliable Path Selection and Opportunistic Routing (RPSOR), which makes routing decisions based on PF composed of three elements: Advancement factor ADVf, Reliability index REL, and Shortest Path index SPi.

III. PROBLEM STATEMENT

The forwarding mechanism of WDFAD-DBR is based on the depth information of two hops. It takes depth of the current as well as next hop forwarding node, as shown in Equation (2). Higher priority is given to the two-hop depth difference with greater weighting sum. Figure 2 shows how WDFAD-DBR can encounter a void hole in its forwarding process. A node, upon receiving a packet, finds out its region; a node in the suppressed region simply drops the packet. A node lying in the upper hemisphere of the forwarding range calculates the holding time for the packet, and sets a timer.

Each node waits for its holding time and the packet is forwarded after expiry of the timer. For current hop depth \(d_m\), next hop depth \(d_m^N\) (refer to Figure 2), velocity of sound \(v\) and transmission range \(T_r\) of a node, WDFAD-DBR calculates \(H_{time}\) given in Equation (1) [17]:

\[
H_{time} = \beta(T_r - D)
\]

where, \(\beta = \frac{(2T_r \gamma \rho)}{T}\), \(\gamma \in (0, T_r]\) and D is the weighting sum of the depth difference of the current hop and the next hop.
forwarding neighbor. Mathematically:

\[ D = \alpha(d_m) + (1 - \alpha)d_{NF}^m \]  

(2)

where,

\[ d_m = \text{depth}(S) - \text{depth}(n_1) \]

\[ d_{NF}^m = \text{depth}(n_1) - \text{depth}(n_3) \]

\( \alpha \) is a constant value, \( \alpha \in (0,1) \). \( \alpha \) is used to prioritize either first hop or second hop forwarding neighbor. WDFAD-DBR calculates the holding time based on weighting sum of depth differences of the two hops. Node n1 is selected as forwarder of S. Node n2 discards the packet when it receives its copy from n1. Node n1 continues forwarding as long as it lies within the transmission range of S. After a few transmissions, the energy of the node will drop due to which link breakage occurs. This problem occurs on the current hop. In the second case, the current node selection of the forwarder leads to energy hole in the next hop; if the current node selects a forwarder, which has lower average energy in its forwarding region, then the energy hole problem occurs in the second hop. To address these problems, RPSOR uses the current forwarder’s energy information and the next expected forwarding region information to cater for energy as well as coverage hole in advance.

**FIGURE 3.** Duplicate packet transmission in WDFAD-DBR.

The design of the fitness function in WDFAD-DBR is not efficient in terms of increasing the holding time difference among neighbors. Therefore, duplicate packets are transmitted over and over again, resulting in extra network energy consumption. Most of the time, the farther neighbors (node A in Figure 3) forward their packet after expiry of the timer, because the propagation delay between the forwarder and the neighbor is greater than the holding time difference between them. To handle this problem, the proposed scheme uses exponential function for calculating the depth difference of two hops. The advantage of exponential function is that it increases the holding time difference among the neighbors with smaller depth difference.

**IV. SYSTEM MODEL**

This section further investigates a three-dimensional UWSN architecture for multi-sink scenario. In addition, we also inspect channel properties in underwater communication, like propagation speed, path loss, noise, etc.

**A. NETWORK ARCHITECTURE OF UWSN**

RPSOR makes use of a multi-sink UWSN architecture, which is composed of sink nodes, relay nodes, and anchor nodes, as shown in Figure 4. Sink nodes are onshore stations (also called destination nodes) located on the surface of water and equipped with radio as well as acoustic modems. They receive data from relay nodes and send it to the offshore stations, which further send it to the satellite. Sink nodes can directly communicate with each other via radio link. Packet arriving at any of the sink nodes is assumed to be a successful packet because it can be accessed from other sinks or any remote center through radio links. Relay nodes are deployed at different positions under the water. These nodes are used to sense the underwater environment as well as forward the packets received from anchor nodes. Anchor nodes - also called source nodes, are fixed at the bottom section of the sea, which can only sense and collect data. Anchor nodes use relay nodes to send the collected data towards the destination. Both relay and anchor nodes use acoustic waves for communicating with sink nodes located above the sea surface.

**FIGURE 4.** Network architecture.

**B. UNDERWATER CHANNEL CHARACTERISTICS**

The nature of acoustic communication is affected by different parameters. To achieve approximate results, the proposed scheme also considers various channel characteristics of underwater acoustic communication in the simulation analysis, which are discussed as follows:
1) PROPAGATION DELAY
The speed of the acoustic signal is calculated using Equation (3) [26]. It shows that the speed of the acoustic signal is affected by changes in temperature, depth and salinity of the environment. For a given salinity and depth, the speed of acoustic signal increases with increase in temperature, as shown in Figure 5a. Similarly, for a given depth and temperature, the speed of the acoustic signal increases with increase in salinity, as shown in Figure 5b.

\[
c = 1448.96 + 4.591T - 5.304 \times 10^{-2}T^2 \\
+ 2.374 \times 10^{-4}T^3 + 1.340(S - 35) + 1.63 \\
\times 10^{-2}D + 1.675 \times 10^{-7}D^2 - 1.025 \times 10^{-2} \\
\times T(S - 35) - 7.139 \times 10^{-13}TD^3
\]  
(3)

where; \( c \) = speed of acoustic signal  
T = temperature in underwater environment (0°C ≤ T ≤ 30°C)  
D = depth of sea water (0 ≤ D ≤ 8000 m)  
S = salinity of sea water (30 ≤ S ≤ 40 PPT)

2) PROPAGATION LOSS
Acoustic communication is mainly affected by path loss. Due to this, the quality of signal in UWSNs is degraded. For distance d and frequency f, the underwater channel path loss is given by Equation (4) [27]:

\[
10\log A(d,f) = k \cdot 10\log d + d \cdot 10\log \alpha(f)
\]  
(4)

The first term on the right side represents spreading loss and the second term represents absorption loss. \( k \) is the spreading factor, which expresses the geometry of propagation. Geometry of propagation for different values of \( k \) is as follows: for cylindrical spreading, \( k = 1 \); for practical spreading, \( k = 1.5 \); and for spherical spreading, \( k = 2 \). \( \alpha(f) \) represents the absorption coefficient in dB/km for \( f \) in kHz and is given by Equation (5) [28].

3) ABSORPTION COEFFICIENT
Attenuation also occurs due to absorption whereas absorption occurs due to the conversion of acoustic signal energy into heat. The level of attenuation is frequency dependent; absorption increases with increase in frequency and vice versa. Equation (5) gives the absorption coefficient according to the underwater environment and signal characteristics.

\[
10\log \alpha(f) = \frac{0.11f^2}{1 + f^2} + \frac{44f^2}{4100 + f^2} + \frac{2.75f^2}{10^4} \\
+ 0.003[\text{dB/km}]
\]  
(5)

This formula is generally used for high frequencies. Whereas, the following formula may be used for lower frequencies:

\[
10\log \alpha(f) = \frac{0.11f^2}{1 + f^2} + 0.001f^2 + 0.002
\]

4) NOISE
Noise is a property common to all communication channels, and cannot be ruled out. It decreases the signal strength of any communication system. Noises in underwater communication are categorized into two types: ambient noise, and noise caused by human beings. Ambient noise has a continuous power spectral density and can be represented as Gaussian noise. The four prominent sources for ambient noise are given as follows: turbulence noise; shipping noise; noise caused by waves; and thermal noise. Mathematically, ambient noise can be represented as [26]:

\[
N(f) = N_t(f) + N_s(f) + N_w(f) + N_{\text{th}}(f)
\]

where \( N_t(f) \), \( N_s(f) \), \( N_w(f) \) and \( N_{\text{th}}(f) \) represents turbulence, shipping, waves, and thermal noise respectively. These noises influence the frequency spectrum as follows: turbulence noise is dominant in the range \( f < 10 \text{Hz} \); shipping noise is dominant in the frequency range \( 10 \text{Hz} < f < 100 \text{Hz} \); noise caused...
by waves largely contributes in ambient noise; it affects the frequency range upon which most of the acoustic systems work (100 Hz < f <100 kHz); and thermal noise becomes dominant in frequencies greater than 100 kHz.

C. PRELIMINARIES

The notations are briefly discussed below, which are used in the computation of holding time and the forwarding algorithm for RPSOR.

- Network size $|\mathbb{N}|$: it is the total number of nodes $\mathbb{N}$, on which the whole network is built.
- The set of receiver nodes $G_s$: the set of nodes that are in the transmission range of node S, as shown in Figure 7:

$$G_s = \{m \in \mathbb{N} | z_m < z_s \land \text{dist}(m,s) \leq T_r\}$$

where, $z_s$ and $z_m$ are the depths of the source node S and receiver node m respectively. According to Figure 7, $G_s = \{A,B\ldots\}$.
- The set of next hop forwarders $G_m^{NF}$: the set of nodes that are in node m’s transmission range:

$$G_m^{NF} = \{n \in \mathbb{N} | z_n < z_m \land \text{dist}(m,n) \leq T_r\}$$

where, $z_n$ and $z_m$ are the depths of the next hop forwarding node n and receiver node m respectively. The next hop forwarders of receiver A, $G_A^{NF} = \{1,2,3,4\}$, as shown in Figure 7.
- Advancement factor $ADV_f$: it is a depth based parameter that helps in selecting a node of lower depth among the neighbors.
- Set of battery levels $E_m$: the battery levels of nodes in $G_s$.

$$E_m = \{e \in R | e \geq 0 \land e \leq E_o\}$$

where, $E_o$ represents initial energy of the node.
- Set of battery levels $E_m^{NF}$: the battery levels of nodes in $G_m^{NF}$.

$$E_m^{NF} = \{e \in R | e \geq 0 \land e \leq E_o\}$$

For receiver node B, $E_B^{NF} = \{20,30,25,30\}$.
- Reliability index $REL_l$: it is an energy-based parameter that helps to balance the energy consumption on the first hop and selects a higher energy next forwarding region.
- Shortest Path index $SP_l$: it makes RPSOR more intelligent in selecting a node having shortest link towards the sink.

V. RPSOR PROTOCOL

In this section, we describe the RPSOR protocol in more detail. It works in two stages: knowledge acquirement stage and packet forwarding stage. In the knowledge acquirement stage, we collect the information, and make decision for PFN selection in the packet forwarding stage.

A. KNOWLEDGE ACQUIREMENT STAGE

During this stage, all neighbors share their information with each other. For designing $PF$, sensor nodes share depth, number of neighbors, residual energy, and number of hops to the sink. RPSOR uses four types of packets, which are as follows:

1) Neighbor Request: NR is used to find all the neighbors within the transmission range of a sensor node. It contains type ID; depth, number of neighbors, and ID of the node sending NR. For limiting the overhead of control packets, type ID is of type Boolean and has a value of “00” for NR.

2) ACK Packet: ACK sent by a node in response to NR. Similar to NR, it contains type ID, which has a value of “01”; depth, number of neighbors, and ID of the node sending ACK. NR and ACK packets are broadcasted after a specific time interval.

3) Hello packet: It contains type ID, which has a value of “11”; ID of the node transmitting hello packet, and $Hop_m$, which represents the number of hops to the sink.

4) Data Packet: Data Packet consists of type ID, which has a value of “10”; ID of the sender, ID of the destination, depth of the sender, data bits, and sequence number.

A simple hello packet is transmitted from the sink throughout the sensor network. The value of $Hop_m$ is incremented by one unit after the packet is received by a sensor node, as shown in Figure 6. Sink node transmits the hello packet with $Hop_m = 0$; when node A receives the packet, it increments the $Hop_m$ value and transmits it towards node B. Upon successful reception of the packet, node B repeats the same procedure by incrementing the $Hop_m$ value and its further transmission downstream. The same procedure is followed by each node until the last node in the network is reached. The $Hop_m$ value for a particular node remains the same due to the slight motion of the nodes in the vertical direction. We give lesser priority to hello packets as compared to neighbor requests and ACK packets. A queue has been designed and the hello packet waits till the node gets free. In order to reduce the overhead due to control packets, each sensor node maintains a routing table, which updates synchronously after a specific time span. A node maintains three types of tables, which are as follows: source info table, first hop info table, and routing table.

Source info table is designed where each sensor node keeps its own information. The format of the source info table consists of four tuples: ID of the source node, depth of the source node, number of neighbors of the source node, and $Hop_m$ extracted from hello packet, which represents the number of hops to the sink.

First hop info table is designed to store the information of first hop neighbors. It contains $G_s$, depth information of first hop neighbors, total number of neighbors on the first hop, and the specific time period for synchronous updating of first hop info table. In order to reduce the overhead due to control packets, each sensor node maintains a routing table, which updates synchronously after a specific time period. The routing table is updated based on source info table and first hop info table. It contains ID and depth of source node, depth of
current forwarding node, depth of next hop forwarding node, and value of \( Hop_m \) extracted from hello packet.

**Algorithm 1** Knowledge Acquisition Scheme

1: \( Hop_m = Node(m).Hop \)
2: \( G_{NF}^m = \text{List of receiver’s Neighbors} \)
3: \( \text{PKT} = \text{Packet} \)
4: \( \text{PQ} = \text{Packet Queue} \)
5: \( \text{Input: } \{\text{PID, SID, count}\} \leftarrow \text{Hello} \)
6: \( \{\text{PID, SID, Depth, } G_{NF}^m\} \leftarrow \text{NR} \parallel \text{ACK} \)
7: \( \{\text{PID, SID, Depth, } G_{NF}^m\} \xrightarrow{\text{send}} \text{ACK} \)
8: \( \{\text{Discard(Hello)} \parallel \text{Update } G_{NF}^m \}
9: \text{Initialization: } \text{Hop}_m \rightarrow \text{zero} \)
10: \( G_{NF}^m = \{\emptyset\} \)
11: \( \text{Sink} \xrightarrow{\text{broadcast}} \text{Hello} \)
12: \( \text{if} \ Hello \xleftarrow{\text{receive}} \text{PKT} \text{ then} \)
13: \( \{\text{PID, Node}(m).id, \text{count++}\} \xrightarrow{\text{broadcast}} \text{Hello} \)
14: \( \text{Hop}_m = \text{count} + 1 \)
15: \( \text{end if} \)
16: \( \text{end if} \)
17: \( \{\text{PID, Node}(m).id, G_{NF}^m\} \xrightarrow{\text{send}} \text{ACK} \)
18: \( \text{end if} \)
19: \( \text{if} \ ACK \xleftarrow{\text{received}} \text{PKT} \text{ then} \)
20: \( \text{Update } G_{NF}^m \)
21: \( \text{end if} \)

**FIGURE 6.** Mechanism for calculating number of hops.

**B. PACKET FORWARDING STAGE**

RPSOR selects forwarders based on \( PF \) composed of three elements:

1) Forwarding region information, called Reliability index in our proposed model and represented by \( REL_i \) in the \( PF \).
2) Advancement factor represented by \( ADV_i \), which is completely based on depth difference of the current as well as next hop.
3) Shortest Path index (\( SP_i \)), which is calculated on the basis of number of hops of a node to the sink and average depth of nodes in the next expected hop.

1) **CALCULATION OF RELIABILITY INDEX FOR A NODE**

\( REL_i \) helps in detecting and limiting energy holes in the network to reduce the probability of packet loss and make sure that the network survives for a longer period of time. Reliability index is calculated on the basis of energy of the current forwarder and average energy in the next forwarding region. For calculating \( REL_i \), all the neighbors share their residual energy \( E_m \). The forwarding neighbor then normalizes its own energy with maximum energy in the current hop, as shown in Equation (6). After finding \( E_m \), each forwarder calculates average energy of their own forwarding region and normalizes it with maximum energy on the second hop (20J and 30J in Figure 7). Mathematically,

\[
REL_i = \frac{1}{2} \left\{ \frac{E_m}{E_{max}} \times d_m + \frac{\text{Avg}(E_{NF}^m)}{E_{NF_{max}}} \times d_{NF} \right\} \quad (6)
\]

where,

\[
\text{Avg}(E_{NF}^m) = \frac{\sum_{m=1}^{|G_{NF}^m|} E_{NF}^m}{|G_{NF}^m|}
\]

\[
E_{max} = \max(E_i | \forall i \in G_s)
\]

\[
E_{NF_{max}} = \max(E_j | \forall j \in G_{NF}^m)
\]

The first term on the right side of Equation (6) represents the current forwarding node information; the second term represents the next forwarding region information.

2) **ADVANCEMENT FACTOR**

Advancement factor is calculated based on purely greedy mechanism as in WDFAD-DBR. RPSOR uses depth difference of current as well as next hop forwarding node.
However, WDFAD-DBR cannot suppress neighbors successfully because the weighting depth difference among the neighbors increases linearly, as shown in Figure 1, rather than exponentially. To calculate the advancement factor, RPSOR uses exponential function to reduce duplicate packets, as shown in Equation (7). RPSOR exponentially increases the advancement factor among the neighbors. Mathematically,

$$ADV_f = \frac{e^{\frac{d_m}{Tr}} - 1 \times d_m + e^{\frac{d_{NF}}{Tr}} - 1 \times d_{NF}}{2}$$  \hspace{1cm} (7)$$

where,

$$Tr = Transmission\ range, \quad Tr \epsilon [0, Tr]$$

$$ADV_f = Advancement\ factor, \quad ADV_f \epsilon [0, Tr]$$

3) SHORTEST PATH INDEX
WDFAD-DBR is based on depth of current and next hop forwarding nodes. It does not show any mechanism to guide the packet on the shortest path towards the destination. It considers only local information rather than global information. Therefore, there is a possibility that the packet follows longer path towards the sink, which raises the probability of packet loss and higher E2ED in sparse networks. RPSOR exponentially increases the advancement factor among the neighbors.

$$SP_i = \frac{1}{2} \left\{ \left(1 - \frac{Hop_m}{Hop_{max}}\right) \times d_m + \frac{Avg(d_{m \ NF})}{d_{NF \ max}} \times d_{NF} \right\}$$  \hspace{1cm} (8)$$

where,

$$Avg(d_{m \ NF}) = \sum_{m=1}^{G_{NF}} d_{m \ NF}$$

$$Hop_m = number\ of\ hops\ of\ mth\ node\ (on\ first\ hop)\ to\ the\ sink$$

$$Hop_{max} = max(Hop_m | \forall m G_i)$$

$$d_{NF \ max} = max(d_i | \forall i G_m)$$

Algorithm 2 Packet Forwarding Scheme

1: Input: $Node m \leftarrow PKT(data)$
2: Output: Forward PKT || Drop PKT
3: Initialization: $TIME_{PKT} \rightarrow zero$
4: if $PKT \epsilon PQ$ then
5:  Update Neighbour Table
6:  Discard(PKT)
7:  else
8:  $PQ \leftarrow PKT(data)$
9:  if $E_m \neq 0 \& |G_{NF}| \neq 0$ then
10:   calculate $REL_i$ by using equation(6)
11:   calculate $ADV_f$ by using equation(7)
12:   calculate $SP_i$ by using equation(8)
13:   $PF \leftarrow \{ADV_f, REL_i, SP_i\}$
14:   compute $H_{time}$ for $PF$
15:   $TIME_{PKT} = H_{time}$
16:   else
17:     Drop(PKT)
18:   end if
19: end if

C. HOLDING TIME OF PACKET
RPSOR calculates the holding time for every packet. Holding time is the time for which a particular node holds a packet before forwarding. Holding time helps to suppress duplicate transmission of the neighbors. When a node receives a packet, it calculates the holding time for it based on a multitude of information (depends on the forwarding mechanism of a routing protocol) of the current node, like depth, energy, number of neighbors, etc. Holding time prioritizes the best forwarder; node with the shortest holding time is considered a best forwarder. After calculating the holding time, the node sets a timer. The packet is forwarded if the particular node does not receive duplicate of the holding packet before expiry of the timer. RPSOR only takes the nodes of the upper hemisphere as the forwarding neighbors. Therefore, nodes having higher depth than the current node simply drop the packet. Nodes lying in the upper hemisphere calculate the holding time for the packet, as shown in Equation (9).

$$H_{time} = D_{max} (2T_r - PF)$$  \hspace{1cm} (9)$$

where,

$$PF = ADV_f + \frac{REL_i + SP_i}{2} \hspace{1cm} (PF \epsilon [0, 2T_r])$$
The forwarder with a higher value of PF among other neighbors is considered the best forwarder to further broadcast the received packet. For high value of PF, the proposed scheme calculates small value for the holding time. $D_{\text{max}}$ is the maximum delay among all the neighbors receiving the packet and it depends on the transmission range $T_r$, speed of acoustic signal $v$, and $\gamma$.

D. SINK MOBILITY

In our proposed work, two sinks are mobile. Mobile sinks are used to visit denser regions of the network that are creating heavy traffic. The network checks the node density at different hops using hello messages at the start of each simulation round and then allows the sink to visit those hops of the network that have high node density. Denser regions of the network generate high load that has to be relayed by the nodes that lie at the next hop. When this high traffic enters the sparse section of the network, it cannot manage such high amount of traffic due to which majority of the packets are lost. The sink calculates the vertical trajectory using the position information of the denser hop, which was obtained through the hello message. Afterwards, the sink moves vertically downward and collects the packets directly from the nodes in the vicinity. Therefore, the sink motion is directional and the direction is towards high traffic region of the network (refer to Figure 8).

FIGURE 8. Sink mobility model.

VI. SIMULATIONS AND RESULTS

In this section, we experimentally describe the performance of RPSOR under different network scenarios. First, we introduce some metrics, based on which RPSOR and WDFAD-DBR are compared. Then, we discuss the simulation results in terms of the given performance metrics in detail.

A. PERFORMANCE METRICS

1) PACKET DELIVERY RATIO

It is the ratio between the numbers of packets successfully received by any of the sink nodes to the total number of packets sent. It is represented by PDR in the proposed model. Mathematically,

$$PDR = \frac{P_{\text{successful}}}{P_{\text{sent}}}$$

2) ENERGY TAX

The average energy consumption to deliver the packet to the sink node is defined as energy tax. It covers transmission energy, receiving energy, and idle state energy. Mathematically, it is calculated by the following equation:

$$ETX = \frac{E_{\text{total}}}{(N \times P_{\text{successful}})}$$

where $E_{\text{total}}$ is the total energy consumed in the whole network, $N$ is the total number of nodes in the whole network and $P_{\text{successful}}$ is the total number of packets successfully received.

3) END TO END DELAY

It is the average time taken by a packet to successfully reach from source to any of the sink nodes. It consists of transmission delay, holding time, processing time, propagation delay and receiving time. It is represented by E2ED in the proposed model.

4) ACCUMULATED PROPAGATION DISTANCE

It is the total distance covered by a packet to reach from the source to the destination node. It is represented by APD in the proposed model. Mathematically,

$$APD = \frac{1}{P_{\text{successful}}} \sum_{Y=1}^{P_{\text{successful}}} \sum_{X=1}^{\text{count}} \text{dist}^Y_X$$

where count is the total number of hops covered by a packet to reach from source to destination and $\text{dist}^Y_X$ is the propagation distance of $X^{th}$ hop for the $Y^{th}$ packet.

B. COMPARISON OF PDR

PDR is the ratio of successful packets to the packets sent. As discussed, it depends on various parameters, such as node density of the network, packet collision, modulation technique, noise, path loss, etc. In our simulations, we analyze PDR for different node densities in the network. PDR increases by increasing the node density in the network for both WDFAD-DBR and RPSOR. The reasons are as follows: (1) the probability of packet loss decreases because both can easily find the forwarder when the node density is high, (2) large numbers of duplicate packets are transmitted, and (3) as the number of nodes becomes higher, it means that the...
average energy in the network increases, so the network can survive for longer periods of time.

Figure 9 shows that the PDR of RPSOR is higher than that of WDFAD-DBR. The reasons are as follows: firstly, the routing decision of WDFAD-DBR is purely based on greedy mechanism; it selects the node having higher weighting sum of depth difference of two hops and does not care about other parameters like energy, number of neighbors, etc., which need to be considered while forwarding the packets. The proposed scheme considers energy of the current forwarder as well as average energy in the upcoming forwarding region unlike WDFAD-DBR, which can encounter void hole on the coming hop and result in packet loss. For this purpose, RPSOR calculates the reliability index, which is based on the current node energy as well as average energy in the forwarding region of the upcoming hop. This not only detects energy holes but also balances energy consumption among the neighbors in the network due to which the probability of packet loss decreases. Secondly, WDFAD-DBR cannot successfully suppress its neighbors because the depth difference among the neighbors increases linearly unlike RPSOR in which it increases exponentially. For small difference in depth, RPSOR produces large differences in $ADV_f$; this results in large differences among holding times of the neighbors. As a result, small numbers of duplicate packets are transmitted, which result in decreased packet collision at the receiver and eventually increased PDR.

Figure 10 shows that the percentage improvement in PDR for RPSOR is lower on 100 nodes. This is caused by the sparse deployment of nodes, which leads to packet loss and decreased PDR. Furthermore, average percentage improvement gradually decreases for denser networks, as presented in Table 3. This is explained by the fact that above some level of duplication, packets collision starts at the receiver, which results in decreased PDR.

### C. ENERGY TAX COMPARISON

Energy tax depends on the total energy consumption, number of nodes in the network, and total number of successfully delivered packets to the sink. Figure 11 shows that energy tax is high in sparse networks for both WDFAD-DBR and RPSOR. This is because in sparse networks, large numbers of holes are encountered, which result in failure of packets, eventually leading to an increased energy tax. Simulation results show that RPSOR performs much better than

### TABLE 2. Simulation setup.

| Variable                     | Value          |
|------------------------------|----------------|
| Nodes deployed              | 100:50:500     |
| Sinks deployed on water surface | 9              |
| Mobile sinks                 | 2              |
| Total network area (3D region) | 10 km × 10 km × 10 km |
| Transmitting power           | 50 W           |
| Receiving power              | 158 mW         |
| Frequency                    | 12 KHz         |
| Bandwidth                    | 4 KHz          |
| Signal propagation speed     | 1500 m/s       |
| Random walk                  | 2 m/s          |
| Probability of node moving left | 0.5          |
| Probability of node moving right | 0.5       |
| Size of ACK packet           | 50 bits        |
| Size of NR                   | 50 bits        |
| Data rate                    | 16 Kbps        |
| Size of Payload of data      | 72 Bytes       |
| Size of header of data       | 11 Bytes       |
| Maximum power for transmission | 90 dB re Pa   |
| Minimum power for receiving  | 10 dB re Pa    |

### FIGURE 9. PDR vs number of nodes.

### FIGURE 10. Percentage improvement of PDR vs number of nodes for RPSOR using different transmission ranges.
TABLE 3. Percentage improvement in PDR for RPSOR.

| Nodes | $T_r=1400m$ | $T_r=1700m$ | $T_r=2000m$ | Imp.  |
|-------|-------------|-------------|-------------|-------|
| 100   | 10.34%      | 21.06%      | 12.75%      | 14.71%|
| 200   | 23.44%      | 25.15%      | 15.42%      | 21.33%|
| 300   | 28.29%      | 24.29%      | 8.28%       | 20.28%|
| 400   | 34.51%      | 17.58%      | 6.00%       | 19.36%|
| 500   | 35.15%      | 12.27%      | 2.36%       | 16.59%|

FIGURE 11. Energy tax vs number of nodes.

WDFAD-DBR in terms of energy tax. This is due to the following reasons:

1) WDFAD-DBR fails to cater for void holes successfully due to which large numbers of packets cannot reach the sink nodes and according to the definition, it results in increased energy tax.

2) RPSOR calculates reliability index for a node, which enables the forwarding mechanism to avoid high traffic path. The second term in the reliability index selects the next forwarding region having lesser number of nodes but of higher average energy. Besides, RPSOR balances energy among the neighbors due to which the probability of energy holes is small as compared to that in WDFAD-DBR. Figure 11 shows that the energy tax decreases with node density; this is due to the fact that for higher number of nodes, the probability of void hole reduces to a large extent. Smaller number of void holes means more successful packets, which ultimately decreases the energy tax. According to the definition, energy tax is inversely proportional to the number of nodes in the network. The proposed scheme decreases energy consumption by guiding packets towards the shortest path using $SP_i$. The packet reaches the destination covering relatively lesser number of hops, which results in decreased energy consumption in the network.

3) The design of $ADV_f$ also contributes to decreased energy consumption, because it exponentially increases the priority function difference among the neighbors unlike WDFAD-DBR, where it is linear (refer to Figure 1). Due to this, duplicate transmissions are reduced, which result in decreased energy consumption and energy tax of the network. Moreover, when we analyze the performance on different transmission ranges, it is observed that the energy tax is relatively lower in case of lower transmission range of the nodes. This is because for higher transmission range, larger number of forwarders are available for a node and there is a high probability that the optimal forwarder will be present to forward the packet. Furthermore, the design of the advancement factor can suppress large numbers of neighbors for higher transmission ranges, which results in decreased duplicate transmissions, which further lead to decreased energy consumption of the network. Hence, RPSOR shows increased percentage improvement with increase in the number of nodes, as presented in Table 4 and Figure 12.

TABLE 4. Percentage improvement in ETX for RPSOR.

| Nodes | $T_r=1400m$ | $T_r=1700m$ | $T_r=2000m$ | Imp.  |
|-------|-------------|-------------|-------------|-------|
| 100   | 8.35%       | 12.38%      | 29.84%      | 16.85%|
| 200   | 23.33%      | 42.67%      | 54.21%      | 40.07%|
| 300   | 35.20%      | 59.82%      | 65.32%      | 53.44%|
| 400   | 46.11%      | 64.11%      | 67.70%      | 59.30%|
| 500   | 16.73%      | 68.77%      | 70.03%      | 51.84%|

FIGURE 12. Percentage improvement of energy tax vs number of nodes for RPSOR using different transmission ranges.

D. COMPARISON OF E2ED AND APD

We also analyze RPSOR for E2ED to find the behavior of the network in terms of delay when the proposed scheme is used as a routing mechanism for UWSNs. Simulations are
performed on different numbers of nodes and various transmission ranges to validate RPSOR. Figures 13 and 15 show that for a sparser network, the proposed RPSOR scheme has higher E2ED and APD than WDFAD-DBR. This is because WDFAD-DBR is purely based on greedy algorithm implying that WDFAD-DBR will always go for a node having lower depth. Whereas, RPSOR builds on top of an opportunistic model in its forwarding process. In the sparse network scenario (nodes < 200), the forwarding process of RPSOR has one or maximum two paths toward the sink and there is a high probability that the proposed scheme cannot find the shortest path due to lesser number of nodes in the network. Moreover, shortest path index (SPI) of our proposed protocol also calculates average depth of the neighbors of the current forwarder on the second hop. In the sparse network scenario (nodes < 200), the average depth difference comes out to be low because, due to random deployment, a neighbor can have lower depth difference compared to another having higher depth difference. This is the reason that a forwarder having a neighbor of highest depth difference cannot forward packet due to its higher value of the holding time. Consequently, the proposed RPSOR has higher E2ED and APD than that of WDFAD-DBR for sparse network scenario.

On the other hand, in the dense network scenario (nodes > 200), the forwarder has high number of neighbors with a considerable number of lowest depth. In this case, the average depth comes out to be high. So, the forwarder with high average depth difference of neighbors is selected for the forwarding process. Eventually, it results in faster delivery of data to the destination, which is the reason for lower E2ED in dense networks (refer to Figure 14 and Table 5). Furthermore, for dense networks, larger numbers of paths are available towards the sink and the proposed scheme can select the shortest path, unlike WDFAD-DBR, which considers only local depth difference. WDFAD-DBR does not care whether the current forwarder will result in shortest path towards the sink or not. In addition to the current forwarder’s depth difference, the proposed scheme also considers the number of hops to the sink, which is the reason for lower E2ED and APD in dense networks. In short, $ADV_f$ is used to select the forwarder of lower depth in the local region and $SP_i$ helps to prioritize such a forwarder, which results in lesser number of hops that the packet will travel to reach the sink node.

### E. SIMULATION IN MOBILE SINK SCENARIO

Underwater sensor nodes are deployed randomly resulting in non-uniform node density all over the network. In other words, traffic is not uniform in all sections of the network. It is generally observed that traffic increases as we go up in

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**TABLE 5. Percentage improvement in E2ED for RPSOR.**

| Nodes | $T_s=1400m$ | $T_s=1700m$ | $T_s=2000m$ | Imp.  |
|-------|-------------|-------------|-------------|------|
| 100   | -6.25%      | 6.00%       | 15.60%      | -9.28% |
| 200   | 0.42%       | 8.30%       | 13.69%      | 7.47% |
| 300   | 4.27%       | 4.90%       | 15.00%      | 8.05% |
| 400   | 5.54%       | 3.30%       | 12.53%      | 7.12% |
| 500   | 5.09%       | 2.85%       | 11.01%      | 6.31% |
the network, which means that the upper nodes suffer from more traffic as compared to the lower nodes in the network. We analyze the network for traffic density at different sections of the network and allow the mobile sink to visit other parts of the network.

This strategy results in significant improvement in all of the performance metrics, i.e., ETX, PDR, APD and E2ED. Simulation results show that the performance of RPSOR can be further improved using mobile sinks in the network. We analyze the network for one as well as two mobile sink scenario. Figure 16 shows that for RPSOR, ETX is considerably decreased in case of one mobile sink and further decreased in two mobile sinks scenario. Since high traffic regions are very sensitive parts of UWSNs, we allow the mobile sink to visit these sensitive regions and collect the higher amount of data gathered by the nodes. Since the packets are not required to move further to surface sinks, it is instead collected by the respective local sinks in a region. Therefore, by using mobile sinks, packets can be delivered at relatively low cost, i.e., lower energy, which results in decreased energy tax. A packet that has large number of hops to reach the surface sink has higher probability of getting lost because in sparse UWSNs, packets have higher probability to encounter a void hole. On the other hand, in case of mobile sink scenario, the problem is significantly reduced because the mobile sink visits high traffic areas of the network where it can collect high percentage of data, so large numbers of successful deliveries occur by using this strategy, resulting in increased PDR, as shown in Figure 17 for RPSOR. Furthermore, it shows that the percentage improvement in PDR becomes slightly greater in dense networks, because for dense networks, larger number of regions will have higher node density. In this case, large number of packets can be collected by the mobile sinks, which results in increased PDR. However, the relation is not a direct one, rather in case of extremely dense networks – the percentage improvement in PDR is decreased because mobile sinks cannot manage such large numbers of dense areas in the network due to which high collision takes place and some percentage of packets are lost resulting in decreased PDR. This problem can be overcome by increasing the number of mobile sinks in the network. The only downside for this is the higher cost.

Figures 18 and 19 show the comparison of E2ED and APD, respectively, for RPSOR in case of mobile sinks. We observe that the performance of the network in case of RPSOR is much better when we deploy mobile sinks to collect data packets from denser regions. Furthermore, it can also be observed that the performance improves with increase in the number of mobile sinks. This is because major part of the traffic (data packets) lies in dense regions of the network. According to the definition, when data packets travel from source to destination, E2ED and APD are the overall performance parameters of the network in terms of delay and average distance of packets. In case of mobile sinks, the packet arrives at sink nodes in one, or a maximum of two hops at most, thereby improving the overall performance of the network.
F. COMPARISON ANALYSIS ON VARYING DATA RATE AND PAYLOAD

For further validation of our proposed scheme, we analyze RPSOR on different data rates, i.e., 16kbps, 32kbps and 64kbps. Figure 20a shows that for RPSOR, while shifting from lower to higher data rate, i.e., from 16kbps to 64kbps, PDR increases significantly. This is due to the fact that in case of lower data rate, the time gap between sending and receiving a packet is large, resulting in higher probability of collision. With increase in data rate, the time taken by a packet to reach the destination reduces, leading to decreased collision probability and consequently increased number of successful packets. However, it is very important to note that the direct relation between PDR and data rate is not true for ever increasing data rate, because acoustic communication offers limited bandwidth and PDR cannot increase further when it reaches a certain peak value.

Figure 20b shows that energy tax and data rate have inverse relation, i.e., energy tax decreases from 16kbps to 64kbps. This is due to two main reasons:

1) Packet loss reduces while proceeding from 16kbps to 64kbps; extra network energy consumption is reduced.
2) For constant packet size and transmission power, the cost of sending a packet reduces, which is also a reason for decreased total energy consumption of the network.

Furthermore, the phenomenon is more obvious for sparse networks due to small number of successful packets.

Figure 20c shows that for RPSOR, E2ED also varies inversely with respect to data rate. With increase in data rate, the time taken to transmit one bit decreases, which results in reduced sending time and according to the definition, E2ED decreases. Moreover, at low data rates, the collision probability is higher and some packets avoid shortest path to reach from source to destination due to which average APD increases and causes high E2ED.

Figure 21a shows that for RPSOR, E2ED has inverse relation with the payload size. It can be easily observed that when we shift from small to large payload, E2ED decreases significantly. This is because at constant data rate, increase in payload size directly increases the time to send and receive a packet, which increases E2ED. Due to increase in sending and
receiving time, the probability for packet collision increases as well, thereby reducing the number of packets delivered successfully as well. According to the definition, PDR is the ratio of successful packets to generated packets, so PDR is reduced by increase in payload size in RPSOR, as shown in Figure 21b. According to the definition, energy tax is inversely proportional to the successful packets, hence energy tax increases with increase in payload, as shown in Figure 21c for RPSOR. Packet collision leads to increased packet loss due to which the network energy is wasted and causes high energy tax.

**G. ROUTING OVERHEAD**

It is represented as the number of routing overhead packets (NR, ACK and HELLO) calculated for a complete simulation period. It is noted that redundant packets are generated once in a complete simulation round and periodically repeated at the start of each round. On the other hand, the data packets are generated continuously with a data rate shown in Figure 20. Figure 22a quantitatively shows that a significant amount of redundancy is created comparative to payload especially in denser network. However, Figure 22b shows that less than...
1% of the simulation period is occupied by the redundant packets as there is a huge difference between the size of data packets and redundant packets, as shown in Table 2. Therefore, it can be safely concluded that there is no or negligible effect created on the basic trend of performance metrics due to the routing overheads.

VI. CONCLUSION

Underwater wireless sensor nodes are commonly deployed sparsely. Due to the scattered deployment of nodes and dynamic topology of the network, there is a high probability of void-hole occurrence. Therefore, to improve network reliability and decrease the energy consumption, this paper proposes a novel protocol called Reliable Path Selection and Opportunistic Routing (RPSOR) for Underwater Wireless Sensor Networks (UWSNs). The proposed scheme is an improved version of WDFAD-DBR, which not only recognizes but also solves the potential barriers to the effective performance in WDFAD-DBR without compromising much in terms of E2ED, PDR, cost and other parameters. Unlike WDFAD-DBR, RPSOR utilizes an opportunistic approach rather than greedy approach to improve the performance of UWSNs. RPSOR ensures reliability by adding information of the next forwarding region in the priority function, due to which the chances of void hole and packet loss decrease. 

ADV is purely based on depth difference of two hops like WDFAD-DBR but the exponential approach increases the holding time difference among the nodes, which has eventually reduced the duplicate packets. The forwarder is selected based on SP, which makes the priority function more intelligent to select nodes having less number of hops to the sink. The performance of RPSOR is analyzed for different transmission ranges of nodes and number of nodes in the network to compare it with WDFAD-DBR and validate the proposed scheme. Simulation analysis shows that the PDR improves by 18.45%, ETX decreases by 44.30%, and E2ED decreases by 3.93%, when RPSOR is used as a routing protocol for UWSNs. However, E2ED is higher as compared to that of WDFAD-DBR in sparse networks.

In the future, the performance of RPSOR can be improved by having a relation between the number of mobile sinks and the network structure, i.e., how we can increase or decrease the number of sinks with the number of nodes in the network. Secondly, it is recommended to design a strategy in which the E2ED can be improved in sparse networks.

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