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An Energy Balanced Efficient and Reliable Routing Protocol for Underwater Wireless Sensor Networks

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ABSTRACT Underwater Wireless Sensor Networks (UWSNs) face numerous challenges due to small bandwidth, long propagation delay, limited energy resources and high deployment cost. Development of efficient routing strategies is, therefore, mandatory and has remained the focus of researchers over the past few years. To address these challenges and to further improve the performance of the existing protocols, many routing protocols have been designed. In Weighting Depth and Forwarding Area Division-Depth Based Routing (WDFAD-DBR), the forwarding decision is based on the weighting depth difference, which is not an efficient way for void hole avoidance. In this paper, we propose a depth-based routing mechanism called Energy Balanced Efficient and Reliable Routing (EBER^2) protocol for UWSNs. First, energy balancing among neighbors and reliability are achieved by considering residual energy and the number of Potential Forwarding Nodes (PFNs) of the forwarder node, respectively. Secondly, energy efficiency is enhanced by dividing the transmission range into power levels, and the forwarders are allowed to adaptively adjust their transmission power according to the farthest node in their neighbor list. Thirdly, duplicate packets are reduced by comparing depths, residual energy and PFNs among the neighbors. Moreover, network latency is decreased by deploying two sinks at those areas of the network that have high traffic density. The results of our simulations show that EBER^2 has higher Packet Delivery Ratio (PDR), lower energy tax, and lesser duplicate packets than the WDFAD-DBR routing protocol.

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

I. INTRODUCTION

Exploration of underwater environment cannot be ignored, because a major part of our planet Earth is covered by water. Underwater Wireless Sensor Networks (UWSNs) [1] face a lot of challenges due to high pressure, dynamic temperature and low visibility, etc. UWSNs are nowadays widely used for monitoring, coastline protection, disaster and military surveillance, etc. [2], as shown in Fig. 1.

UWSN is composed of sensor nodes, interconnected through acoustic links that communicate through a set of rules called protocols. These nodes gather data from the harsh aquatic environment and relay it towards the offshore stations deployed at the water surface, also known as sinks. Sensor nodes have acoustic modems that enable them to communicate with their neighbours, while sink nodes employ both acoustic and radio modems. UWSNs use acoustic signals for communication as they are least attenuated in water as compared to the traditional radio waves that are heavily attenuated in water. Further differences between UWSNs and Terrestrial Wireless Sensor Networks (TWSNs) are listed in Table 1.

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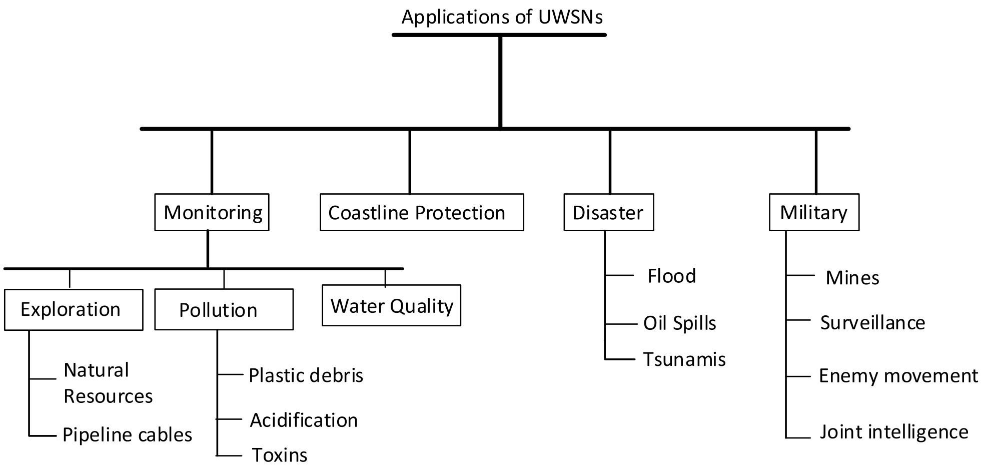


FIGURE 1. Applications of underwater wireless sensor networks.

Underwater acoustic communication suffers from numerous problems, which are briefly summarized as follows:

1) The acoustic signal propagates at a speed that is five orders less than the radio signal, resulting in longer end-to-end delay (E2ED).
2) Frequent change in the topology of sensor nodes due to water currents causes imbalanced node densities in various regions in the network, due to which the nodes in regions with low density will deplete in a relatively short period of time.
3) Acoustic communication also offers low bandwidth, resulting in low data rate, and hence a very slow information exchange mechanism.
4) Physical properties of the acoustic signals are severely affected by reflection, refraction and diffraction mechanisms. For instance, the speed of acoustic signals fluctuate due to change in temperature, pressure and salinity, etc.
5) Energy is a scarce resource because underwater sensors are battery powered and it is costly to recharge or replace these batteries.
6) Water currents frequently change the network topology and depending on the rate of change, the system needs to periodically adapt to new topological changes.
7) Delay and Doppler spreads are the major causes of Inter Symbol Interference (ISI) due to which the reliability of data originality suffers.

Because of the above-mentioned issues, the routing protocols designed for traditional sensor networks cannot work properly for UWSNs. Moreover, environmental effects like fouling and corrosion affect the physical nature of sensor nodes, thereby reducing the network lifetime of underwater network devices.

Many routing mechanisms have been proposed for UWSNs. Geographic routing protocols consider the complete location information of the sensor nodes, e.g., Vector Based Forwarding (VBF) [3]. Gathering complete location information is another challenging task in UWSNs. On the other hand, depth-based routing protocols do not require full location information but consider only local depth of sensor nodes each time a packet arrives on a sensor node, e.g., Depth Based Routing DBR [4], Weighting Depth and Forwarding Area Division Depth Based Routing (WDFAD-DBR) [5], etc. DBR uses depth information of the sensor nodes for calculating holding time of a packet. It simply broadcasts the received packet and then all sensor nodes in the transmission range receive that packet. Each node knows its own depth by using depth sensors embedded in it. Before transmission, each node appends its depth information in the packet. A receiver node compares its own depth with the depth embedded in the received packet. Based on this comparison, if the receiver node happens to be shallower than the transmitter node, then it simply drops the packet, otherwise the node calculates its holding time based on its own depth and sets a timer. If the node does not hear any echo of the received packet before the timer expires, then it transmits the packet, otherwise it drops it. WDFAD-DBR uses the same forwarding mechanism as that of DBR but instead uses weighting depth difference of two hops to calculate the holding time of a packet.

In this paper, similar to WDFAD-DBR, a two-hop depth based routing mechanism is proposed for UWSNs. In addition to using weighting depth difference of two hops, the proposed scheme also takes PFNs and residual energy of the forwarder into account to improve the performance of WDFAD-DBR. For void hole avoidance, the proposed scheme considers PFNs of the forwarder. Checking depth and residual energy at the same time avoids duplicate packets. Residual energy also balances energy consumption among the neighbors in order to increase the lifetime of the network. Some additional features of the proposed protocol are as follows:

1) Two sinks are deployed under water at those areas of the network that have high traffic density, in order to decrease E2ED and the cost of delivery.
2) Adaptive transmission range is used by nodes near to the sink to decrease the energy consumption.

TABLE 1. Difference between UWSNs and TWSNs.

UWSNs	TWSNs
High E2ED due to Propagation speed of 1500m/s	E2ED due to Propagation speed of 3x10^8m/s
Communication using Acoustic signal	Communication using Radio signal
More power required	Less power required
Low bandwidth	High bandwidth
Low data rate	High data rate
Dynamic topology	Static topology
High deployment cost	Low deployment cost
Not accessible through GPS	Accessible through GPS
Node price is high	Node price is low
Sparse deployment due to high node price	Dense deployment due to low node price
Sinks are usually movable	Sinks are always fixed
High probability of link error due to longer E2ED	Probability of link error is low due to lower E2ED
Underwater devices are highly suffered by corrosion	Devices are not much suffered by corrosion
Node size is large	Node size is small
Path loss is high	Path loss is low

Table 2 shows a list of notations and symbols used in this manuscript.

The remainder of the paper is organized as follows: In section II, we present the related work on routing protocols for UWSNs. Section III presents the problem statement whereas section IV describes the proposed work in detail. The simulations and results are discussed in section V. Finally, section VI concludes the paper.

II. RELATED WORK

In this section, we briefly discuss some existing routing protocols for underwater as well as land-based sensor networks.

Routing mechanisms for land-based networks include Directed Diffusion [6], Rumor Routing [7], Gradient [8], COUGAR [9], Sensor Protocols for Information via Negotiation (SPIN) [10], and Two-tier Data Dissemination [11], etc. Due to water currents, underwater networks are dynamic in nature, so land-based routing protocols are not suitable for UWSNs. Some of the routing protocols for UWSNs are discussed as follows:

Routing protocols for UWSNs are divided into geographic-information based and geographic-information free routing. We will focus only on the geographic-information based routing because they are closely related to our proposed solution. Geographical routing uses location information of sensor nodes to find path between the source and the destination. It forwards packets to the node that is closest to the sink. The process is repeated until the packet reaches the sink node. In the existing literature, numerous routing protocols have been proposed that use position information of the sender and receiver nodes for forwarding data packets. Vector Based Forwarding (VBF) [3] uses a pipeline centred at a virtual vector drawn between source and destination pairs in which the packet is forwarded. Nodes lying beyond a specific distance from the virtual vector drop the packet. For high density networks, more numbers of nodes are qualified to forward packets, which results in large number of redundant packets and eventually increased total energy consumption of the network. To overcome such problems, authors have designed self-adaptation algorithms that use position information of the sender and receiver nodes with respect to the virtual vector in the virtual pipeline.

Geographic routing is again divided into receiver-based and sender-based routing, which are further divided based on the information type: it may be location information or depth information. The current protocols that use geographical information and are receiver based include Depth Based Routing (DBR), Delay Sensitive Depth Based Routing (DSDBR) [12], Hop by Hop Dynamic Addressing Based (H2-DAB) routing [13], etc. Following are a few of the sender based routing protocols that use geographical information: Relative Distance Based Forwarding, Routing and Multicast Tree Geocasting (RMTG), Adaptive Routing Protocol (ARP), Diagonal and Vertical Routing Protocol (DVRP) [14], Void-Aware Pressure Routing (VAPR) and Hydrocast.

In [4], authors proposed Depth Based Routing (DBR) protocol, which takes routing decisions based on the local depth of the sensor nodes. In DBR, a source node broadcasts its packet and all the nodes that come in its range receive the packet. Every packet has a portion, which contains depth information of the sender node. When a node receives a packet, it compares its own depth with that of the packet coming from the downstream. Nodes located in the lower hemisphere of the sender node simply drop the packet. If a receiver node is located in the upper hemisphere of the sender's transmission range, then it calculates the holding time of the packet based on it's local depth. Packet Forwarding Nodes (PFNs) add their own depth information to the depth field of the packet and set their timers based on the calculated holding time. During the holding time, if a node does not receive any duplicate packet of the received one, then it forwards it on expiry of the timer. DBR forwards the packet based on the depth of one hop. It does not check residual energy and PFNs of the forwarder, resulting in imbalanced node energy and void hole respectively. DBR is better for dense networks and does not work well for sparse networks because their Packet Delivery Ratio (PDR) is low as compared to that of dense networks. The performance of DBR is enhanced in RPR [15] by using encryption and decryption methods. The header and payload parts of the packet are encrypted in RPR. Two types of keys, namely public and private keys, are given to each node. Data exchange between the nodes is encrypted by using Network Security Key (NSK). During forwarding of packet, payload and header are encrypted with a Gateway Pubic Key (GPK) and NSK, respectively. The node decrypts the header after it receives a packet and also checks if the packet came from a valid node. Only packets with proper signatures are accepted for routing. In [5], authors proposed WDFAD-DBR, which is also a depth-based routing protocol. WDFAD-DBR is a two-hop mechanism, which takes routing

TABLE 2. Nomenclature.

Symbols	Description
E_{tax}	Energy tax
E_{tax}	Transmission energy
P_{tx}	Transmission power
P_{rcv}	Receiving power
N_o	Noise power density
W_{depth}	Weighting depth difference sum of two hops
h	Depth difference between the current node and last forwarding node
h_1	Depth difference between the current node and its PFNs
N_t(f)	Noise caused by turbulence
N_s(f)	Noise caused by shipping
N_w(f)	Noise caused by waves
N_{th}(f)	Noise caused by thermal noise
N	Set of nodes in network
α	Weighting coefficient
HT_p^i	Holding time
D_j^i	Euclidean Distance
N_n	Total nodes deployed
T_{proc}	Processing time at each node
$D_{i,j}$	Straight line distance from node i to node j
E_{consmp}	Energy consumption
DR	Data rate
E_{th}	Residual energy threshold
T_{hold}	Time required to hold a packet
Tp	Throughput
$T(FF_A)$	Time required to hold packet by node A
$T(FF_B)$	Time required to hold packet by node B
FF	Fitness function
R	Transmission range
v_o	Acoustic signal propagation speed
APD	Accumulated propagation distance
p	Number of packets

decisions on the current hop and next hop forwarding nodes. It checks the weighting depth sum of two hops to forward the packet, i.e., current PFN checks the most preferable PFN on the next hop, and compares multiple paths based on weighting depth sum. The path with maximum depth difference is then selected. WDFAD-DBR avoids void holes in advance, due to which the PDR is better as compared to DBR. Moreover, WDFAD-DBR is inefficient in void hole avoidance. There are two reasons for the occurrence of void holes. First, due to the sparse nature of underwater networks, the same node will be selected again and again, which will consume energy of the forwarder in a relatively small interval of time. Secondly, the mechanism can select a node that has no PFNs, because the forwarding criteria does not consider PFNs of the second hop forwarder node. In [16], Void-Aware Pressure Routing (VAPR) is proposed, which uses depth information like DBR to forward packets towards the destination. In VAPR, the complete information about the path towards the destination is predicted by exchanging beacon messages to discover the void region. The packet is forwarded through the low depth or high depth node in case of the void region. The selection criterion of next hop forwarder is based on the direction, i.e., Forwarding Set comprises all nodes that have the same (upward or downward) forwarding direction. DOW-PR [17] is a depth based routing protocol, which considers suppressed nodes in addition to PFNs in the forwarding process. DBR and WDFAD-DBR do not consider suppressed nodes in the forwarding process, due to which the probability of packet loss increases. DOW-PR is an improved version of WDFAD-DBR. DOW-PR consists of two mechanisms, the Dolphin and the Whale Pods routing protocols. In case of Dolphin Pods, all sinks are deployed at the water surface, while in Whale Pods, one sink is deployed under water and is known as embedded sink. In DOW-PR, if a node does not find any PFNs, then it uses suppressed nodes for the forwarding process. Besides, the transmission range is divided into a number of power levels by DOW-PR, thus reducing network energy consumption and a traffic control mechanism through hop count of the transmitted packet. However, it compromises end-to-end delay because involving suppressed nodes in the forwarding process increases average end-to-end delay.

In location-based routing, first an optimal path is discovered towards the destination. Secondly, the packet is forwarded in the confined area towards the sink. This scheme can detect void holes by exchanging small packets. Therefore, location-based routing is efficient for void hole avoidance. However, due to dynamic topology of underwater networks, sometimes large communication overheads are produced. This can cause extra communication cost. To save network energy, routing protocols like AHH-VBF use variable transmission ranges. AHH-VBF scales transmission range according to the distance from the farthest forwarder. Network lifetime is improved in AHH-VBF by balancing the holding time between the nodes.

Considering the high mobility of UWSNs, the authors in [3] proposed a vector-based forwarding (VBF) routing protocol. In the VBF protocol, a virtual pipe center at a virtual vector from source to destination is used for data forwarding. Only nodes confined in the pipe are selected. Redundant and separate routes are used from source to destination, which help in making the protocol robust in terms of node movement. However, energy consumption is not balanced by selecting forwarders inside the pipe again and again. Due to the imbalanced energy consumption, network lifetime is reduced. To solve this problem and to improve the performance of VBF, in [18], a hop-by-hop vector-based forwarding protocol (HH-VBF) is proposed. In HH-VBF, the virtual pipe is made by every node due to which the direction of the vector changes according to the node position. The energy consumption becomes balanced as compared to VBF. However, large communication overhead is produced because of the hop-by-hop virtual pipe method. The overhead is higher as compared to that in VBF and it also does not have a strategy for void hole avoidance. In [19], the authors propose a technique called Avoiding Void Node with Adaptive Hop-by-Hop Vector Based Forwarding (AVN-AHH-VBF), which uses virtual routing pipeline having a predetermined radius for data processing. When a node receives a packet, it first checks its distance from the forwarder to see whether it is within a predefined threshold. To reduce unnecessary broadcasts, AVN-AHH-VBF uses the holding time. The node with a large number of neighbors will have a large value of the holding time and vice versa. Packet collision is reduced, which in turn improves PDR. However, it fails to improve the performance in terms of E2ED. Moreover, the strategy does not balance energy consumption between the nodes by using residual energy. In [20], the authors proposed Adaptive Hop by Hop Vector Based Forwarding (AHH-VBF) protocol. In AHH-VBF, the network lifetime is improved by using adaptive transmission range on every hop according to the node density of the local region. The direction of the virtual pipeline is changed if a node does not find PFNs, as a result of which low energy consumption and high network throughput is achieved. The limitation of AHH-VBF is the inefficient way of selecting the forwarder by not considering residual energy, which causes duplicate packets and imbalanced energy consumption. To balance the energy consumption, in [21], the authors proposed Energy Scaled and Expanded Vector Based Forwarding (ESEVBF) protocol. The selection criteria is based on the residual energy of all forwarding nodes in the potential forwarding zone. This protocol scales and increases the holding time difference with residual energy of the PFNs. The selection mechanism achieves reduced duplicate packets and energy consumption of the network, with lower end-to-end delay. The routing protocol does not show any improvement in PDR because the forwarding node suppresses large numbers of nodes in the potential forwarding zone with small difference in the residual energy. VBF fails to react when a communication void hole occurs. Considering this drawback, in [22], the authors integrate VBF with a void node recovery mode. It has two mechanisms namely back-pressure shift and forwarder shift for concave and convex void nodes respectively. In vector shifting, control packets are sent to the neighbor nodes in order to change the current virtual routing vector. If a node fails to recover from the void region after vector shifting technique, then the back pressure mechanism is used in which the packet is sent away from its destination where a node can apply vector shifting to transmit packet towards the destination. The proposed work successfully improves the PDR because packet loss due to void nodes is reduced. However, it fails to improve the performance in terms of end-to-end delay due to the recovery process in case of a void hole.

Underwater acoustic nodes are mostly deployed in harsh environments and are powered by batteries having limited energy. Therefore, energy efficiency is a main issue in designing underwater protocols. Many routing protocols have been proposed for improving efficiency of the existing work to prolong network lifetime. Considering this, many routing techniques use depth information rather than location information of the nodes to reduce energy consumption of the network. In [23], the authors proposed Energy Efficient Depth Based Routing (EEDBR) mechanism in which routing decisions take place on residual energy in addition to the depth of the nodes. In EEDBR, firstly all the nodes share depth and residual energy information with all the neighbours. Secondly, the packet is transmitted to the best forwarder (node with lowest depth and highest energy) in the transmission range. The achievement of EEDBR is low energy tax and end-to-end delay. However, the mechanism is inefficient for void hole avoidance. Moreover, due to control packets, a large communication overhead is produced. Considering EEDBR in which the transmission model is based on flooding, authors in [24] propose depth-based multi-hop routing (DBMR). Unlike EEDBR, DBMR utilizes a multi-hop transmission model to reduce energy consumption of the network. Like EEDBR and DBMR, in [25], authors proposed an energy-efficient routing protocol called EUROP, in which the whole network was divided into different layers. All nodes are equipped with pressure sensors, therefore, a node can easily find the particular layer in which it lies. Nodes of the same layer can communicate with each other. EUROP reduced energy consumption and propagation by utilizing depth-based routing techniques. Besides that, the packet loss and the number of control packets are successfully reduced. However, it requires extra cost to equip the nodes with pressure sensors.

Routing protocols proposed in [26] [27] use clustering techniques to reduce energy consumption and propagation delay. In cluster-based routing, the network consists of cluster heads and member nodes. These mechanisms consist of two phases, i.e., setup phase and communication phase. In the setup phase, cluster heads are selected either on the basis of residual energy or location. In the communication phase, the member nodes collect data and send it to their corresponding clustering heads. The clustering head, after collecting data from the member nodes, send it to the sinks. The data is sent to sinks only after all the clustering heads complete data collection from the corresponding member nodes, which results in high end-to-end delay. Therefore, cluster-based routing mechanisms are not good for time-sensitive applications in UWSNs. Due to water current, the position of sensor nodes is often changed and the cluster selection is frequently repeated, which creates extra burden on the network.

Considering the energy depletion problem in underwater network nodes, authors in [28] proposed a sink mobility based data collection mechanism. The sink moves through the network in a pre-defined path. This strategy prolongs network lifetime. However, high end-to-end delay is produced due to roaming of a single sink throughout the network. To reduce energy consumption and void hole problems, authors in [29] proposed a geo-cast technique in which autonomous underwater vehicle (AUV) moves in the network in a predefined pattern and gathers data from all the network nodes. It uses only one AUV for collecting data from the network. To improve the performance of routing mechanisms and data collection efficiency, in [22], mobile delay tolerant approach (DDD) is proposed. It uses dolphin nodes, which move in a random or a predefined pattern to collect data stored in fixed nodes. Sensor nodes detect the dolphin node once within a range of one-hop distance by using control packets. After the dolphin node has been detected, the nodes transmit data through one hop communication. In [30], an AUV-aided underwater routing protocol (AURP) is proposed in which multiple AUVs are used for collecting data. In AURP, gateway nodes are deployed to which all sensor nodes transmit their data. AUVs move through the network to collect data from the gateway nodes and carry it to the offshore stations. This reduces the propagation distance to transmit data to the surface station, as a result of which the energy consumption is reduced.

Next, we discuss some of the routing protocols that are location-based and do not utilize the concept of holding time. In Flooding Based Routing FBR [27], network energy consumption is reduced by using different power level ranges (P1 to PN). The potential forwarding area is reduced by confining the power to a conical region emerging from the source up to the sink. Two types of packets are used in the forwarding process; Request To Send (RTS) and Clear To Send (CTS). To select a forwarder, first the source broadcasts an RTS with a power level P1. On receiving RTS, the forwarder responds with a CTS. If the source node receives multiple CTS packets, then the PFN with lower depth is selected for forwarding. If no CTS is received in response to RTS, then the source node shifts the power level to P2 and the process is repeated up to PN until the node finds the PFN. If the power level reaches PN and the source does not receive any CTS, then the cone is shifted around the main cone and the packet is forwarded from the source node to the sink. In DFR [31], the flooding area is confined by the base angle of the cone determined by the source and the sink. Upon receiving a packet, the node first finds out whether it is within the base angle. If it is within the base angle, then it calculates the holding time and forwards the packet; otherwise it discards it. DFR limits the forwarding region due to which large amounts of network energy is saved. However, DFR consumes extra amount of energy due to the same power level for each transmission, whether the forwarder is near or far. Besides that, the forwarding mechanism is highly prone to void hole occurrence, because in sparse networks, it is quite hard to find PFNs. Routing protocols for UWSNs discussed in this section are summarized in Table 3.

III. PROBLEM STATEMENT

WDFAD-DBR is a two-hop routing mechanism that can avoid void hole successfully by considering the depth of the second forwarding node, in contrast to DBR, which takes routing decision based only on the depth of the current hop forwarding node. In other words, the routing mechanism of WDFAD-DBR is mainly focused on packet advancement. WDFAD-DBR, however, still has some problems regarding void hole and duplicate packets. Firstly, WDFAD-DBR is prone to void hole problem by not considering PFNs of the forwarder on the second hop. Due to this, the routing mechanism can select a node having no further PFNs, which results in a void hole and eventually decreased PDR. Secondly, WDFAD-DBR does not increase the holding time difference between the PFNs of the source node by considering residual energy of the PFNs. Due to this, the forwarder of the source node cannot supress its neighbors successfully. This results in increased number of duplicate packets, consuming large amount of extra network energy and eventually increased energy tax and packet collision. Thirdly, in WDFAD-DBR, the nodes near the sinks use full transmission power. With sinks so close to the nodes, where only half of the transmission power would be sufficient, transmitting packets with full power is simply wasteful. Fourthly, WDFAD-DBR assigns equal amount of initial energy to all the nodes, which decreases the lifetime of the network, due to the following reason: in UWSNs, the nodes (relay nodes) nearer to the sinks are greatly involved in the forwarding process because in addition to their own generated packets, nodes local and nearer to sinks also forward received packets from downstream. Therefore, nodes nearer to sinks die earlier than the other nodes in the network.

IV. PROPOSED WORK

This section presents a detailed description of our proposed work. At the end, we will compare the performance of our proposed protocol with WDFAD-DBR routing protocol.

TABLE 3. Summary of routing protocols for UWSNs.

Protocol	Feature	Achievements	Limitations
FBR [32]	Flooding Based Routing	Reduced unnecessary delay Flooding	Increased E2ED
DFR [33]	Flooding based Routing	Limit the E_{consmp}	No strategy for void hole in sparse network
DBR [4]	Depth Based Routing	Increasing the PDR in dense area network	Performance of the network is degrade in sparse area network
EEDBR [23]	Depth and Energy Based Routing	Network lifetime is via energy balancing maximized	Redundant packets are generated thus increase the E_{consmp} in dense area network
WDFAD-DBR [5]	Depth Based Routing	Network lifetime increases with less E_{consmp}	E2ED is increased
DOW-PR [17]	Depth Based Routing	PDR is increased	E2ED is increased
VAPR [16]	Depth based routing	Void hole avoidance	High E_{consmp}
DBMR [24]	Depth based routing	Reduced communication cost	Not addressed the void hole problem
DSDBR [34]	Depth based routing	Minimum E2ED	Not addressed high E_{consmp} due to duplicate packets
EUROP [25]	Depth based routing	Reduced propagation delay and E_{consmp}	Extra cost on pressure sensors
VBF [3]	Vector Based Routing	Limiting the direction and forwarding range	Cause duplicate packets in dense and void holes in sparse network
HH-VBF [18]	Vector Based Routing	Improved PDR	Fails to provide energy fairness and void hole avoidness
AHH-VBF [20]	Vector Based Routing	Energy efficiency is achieved due to transmission power adjustment	Imbalanced energy consumption
ESE-VBF [21]	Vector Based Routing	Reduced the E_{consmp}	PDR does not improve
DDD [22]	AUVs based data collecting	Decreased E_{consmp}	High E2ED
AURP [36]	AUVs based data collecting	E_{consmp}	High E2ED
MCCP [27]	Cluster Based Routing	Improved energy efficiency	High E2ED
H2-DAB [13]	Beacon based routing	Improved reliability	High network overhead
RMTG [37]	Location information based routing	Reduced void hole	Increased E2ED

A. PRELIMINARIES

1) HOLDING TIME

When a node receives a packet, it holds the packet for some time (depending upon the conditions), which is known as holding time of the packet.

2) POTENTIAL FORWARDING NODES (PFNs)

The nodes that lie in the upper hemisphere of the transmission range of the source node are called PFNs of the source node.

Mathematically, we represent the PFNs as:

$$Z_{PFNs} \geq Z_{Source}$$

3) EUCLIDEAN DISTANCE

The distance that separates two nodes in a three-dimensional space is called the Euclidean distance (Ed). Mathematically, Ed can be written as:

$$E_d = \sqrt{\left(x_i\text{-}x_j\right)^2 + \left(y_i\text{-}y_j\right)^2 + \left(z_i\text{-}z_j\right)^2}$$

4) SUPPRESSED NODES

The nodes that lie in the lower hemisphere of the transmission range of the source node are called Suppressed Nodes (SNs).

Mathematically, we can show the suppressed nodes as follows:

$$Z_{Supp} \leq Z_{Source}$$

5) TRANSMISSION RANGE

The three-dimensional space surrounding a node in which other nodes can hear the transmission from the node is called transmission range of the node. It depends on the transmission power of the node; greater the transmission power, greater will be the transmission range and vice versa. However, the attenuation and noise reduce the signal power when travelling through the distance d, as presented in equation (4). At the receiver, if the Signal to Noise Ratio (SNR) is equal to or greater than the threshold power, then the receiver can decode the received signal correctly. The graphical representation of the transmission loss versus distance travelled by the acoustic signal is shown in Figure 2.

B. NETWORK ARCHITECTURE OF UWSN

The network architecture of our protocol consists of sink nodes, anchored nodes and relay nodes, as shown in Fig. 3. Sink nodes are deployed on the surface of water, while relay nodes are deployed at different positions in water, which are used for forwarding and sensing purposes. Relay nodes are movable with the water current, while anchored nodes are fixed at the bottom of water, which collect data from the underwater environment. Sink nodes use radio links to communicate with one another and with the outside base station. Relay and anchored nodes use acoustic links to communicate with one another and with the sink nodes. Sink nodes have embedded radio and acoustic modems. Radio modem is

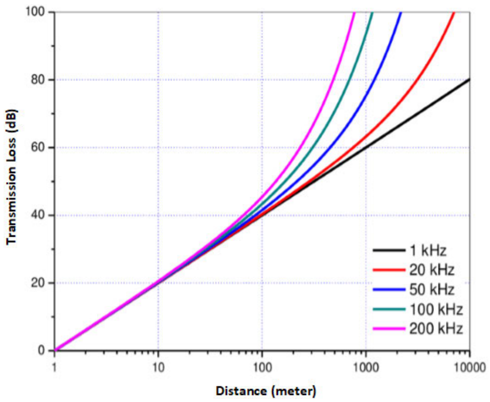


FIGURE 2. Effect of propagation distance travelled on acoustic signal.

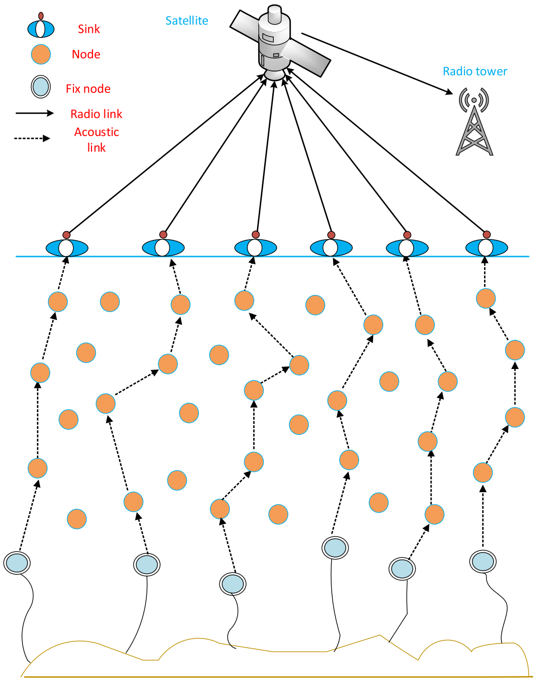


FIGURE 3. Network architecture.

used by the sink nodes to communicate with one another and with the outside environment, while acoustic modem is used to communicate with relay and anchored nodes. A successful packet is the one that is received by one of the sink nodes, which is further transmitted to the outside base station.

C. SPEED OF ACOUSTIC CHANNEL

Acoustic communication is affected by different factors, i.e., salinity, temperature, pressure and depth of water, etc. The mathematical expression for the speed of acoustic signal is expressed as [34]:

$$\begin{aligned} c = {} & 1448.96 + 4.591T - 5.304 \times 10^{-2}T^2 \\ & +2.374 \times 10^{-4}T^3 + 1.340(S-35) + 1.63 \\ & \times 10^{-2}D + 1.675 \times 10^{-7}D^2 - 1.025 \times 10^{-2} \\ & T(S-35) - 7.139 \times 10^{-13}D^3 \end{aligned} \tag{1}$$

where c represents the speed or velocity of acoustic signals in m/s in sea water, and T denotes the temperature in degree Celsius. The speed of the acoustic signal is directly proportional to the temperature and it increases with the increase in temperature. S represents the salinity in parts per thousand and D denotes the depth of water in meters. The above equation is valid when the conditions are satisfied for each factor, as follows: $0°C \leq T \leq 30°C$, $30 \leq S \leq 40\ PPT$, $0 \leq D \leq 8000\ m$.

D. ENERGY PROPAGATION MODEL

Acoustic channel is attenuated in UWSNs over distance d and is expressed as follows [35]:

$$10logA(d,f) = k.10logd + d.10log\alpha(f) \tag{2}$$

The above equation consists of two terms, the spreading loss and the absorption loss. The spreading coefficient is denoted by k and has values 1, 1.5 and 2. It defines the geometry of propagation. For k = 1, spreading is cylindrical in shallow water region, for k = 1.5, the spreading is practical, and for k = 2, the spreading is spherical in deep water region. α(f) represents the absorption coefficient. The underwater noise can be expressed by the given formula [36]:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \tag{3}$$

where N_t(f) denotes noise caused by turbulence, N_s(f) denotes noise caused by shipping, N_w(f) denotes noise caused by waves and N_{th}(f) denotes thermal noise.

For frequency f of an acoustic signal and distance travelled d in the underwater environment, the Signal to Noise Ratio (SNR) can be expressed as:

$$SNR(f,d) = P(f) - A(d,f) - N(f) + DI \tag{4}$$

where *p(f)* is the transmission power, *A(d,f)* is the attenuation and *N(f)* is the noise. DI is the directivity index, which is the ability of a node to avoid unwanted noise by directing its hydrophone.

E. SELECTION OF FORWARDER

For the selection criteria of the next forwarder, we consider three parameters, which are as follows: weighting depth difference similar to WDFAD-DBR, PFNs and residual energy of the forwarder. In the remaining section, we discuss each of these parameters in detail. Furthermore, we also discuss the way these parameters contribute to eliminating the above-mentioned problems.

Firstly, like WDFAD-DBR, we see the weighting depth difference of two hops. This parameter checks depth of the first hop as well as the second hop forwarding node due to which the void hole can be removed to some extent. The mathematical expression for weighting depth is as follows [5]:

$$W_{depth} = \alpha h + (1-\alpha)h_1 \tag{5}$$

W_{depth} represents the weighting depth difference sum of two hops. Let h be the depth difference between the current and the last forwarding node S, and h1 be the depth difference between the current node and its PFN with lowest depth. α is the weighting coefficient, which lies in the interval [0 1]. To further differentiate PFNs in the forwarding process in terms of holding time, we consider residual energy on each hop. Residual energy is used to avoid duplicate packets by increasing the holding time difference among the forwarders, which saves large amount of network energy by minimizing unwanted transmissions. Furthermore, it also contributes to increased PDR, because limiting duplicate packets minimizes packet collision. Residual energy also balances energy consumption among the forwarders due to which the lifetime of the network increases. Normally, residual energy has a high value. So the proposed scheme normalizes it by dividing it into initial energy, as shown in equation (6). After this treatment of the residual energy, we can use it in our mathematical model.

$$Energy = 1 - \frac{Node\ energy}{Initial\ energy} \tag{6}$$

where *Initial energy* shows the initial energy and *Node energy* shows the current residual energy of the node.

When a sensor node broadcasts a packet, it requires PFNs to forward it. If no PFN is present in the range of the sensor node, then the packet is lost. To increase the reliability and to minimize the chance of void hole occurrence, the proposed protocol considers PFNs of each forwarder on the coming hop. Like energy, the value of PFNs of a node is also high, so the proposed model normalizes it with the number of neighbor nodes, as shown in equation 6. The normalized value, i.e., pfns, is always between 0 and 1.

$$pfns = 1 - \frac{PFN}{Neighbor\ nodes} \tag{7}$$

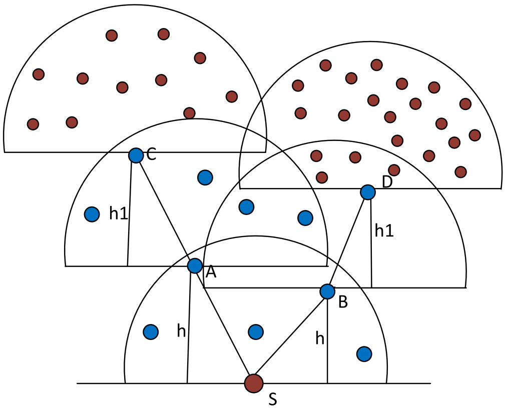


FIGURE 4. Selection of forwarder.

In Fig. 4, node S has two optimum paths, i.e., SAC and SBD. According to WDFAD-DBR, path SAC will be selected because it has a larger value of weighting depth as compared to path SBD. However, node C has lesser number of PFNs as compared to node D. This means that the probability of packet loss after some packet transmissions increases because lesser number of PFNs of node C will die (lacking enough energy to continue further transmission) in relatively small time interval, as compared to node D, which has larger number of PFNs. In our proposed scheme, we select path SBD, although it has lesser value of weighting depth as compared to path SAC. However, in path SBD, the probability of packet loss is lesser due to larger number of PFNs of node D.

F. SINK DEPLOYMENT

The proposed scheme also deploys two sinks at those positions in the network area that have high traffic density. Packets that arrive at any sink are considered successful packets because sinks can communicate with each other as well as the outside station through high speed radio links. The nodes located in high traffic area do not need to further forward the packet, instead they will transmit the received packet to the nearest sink. In this way, we can achieve high delivery ratio at relatively low cost. Fig. 5 shows two embedded sinks ES1 and ES2 deployed at 4000m and 5000m of the network height respectively.

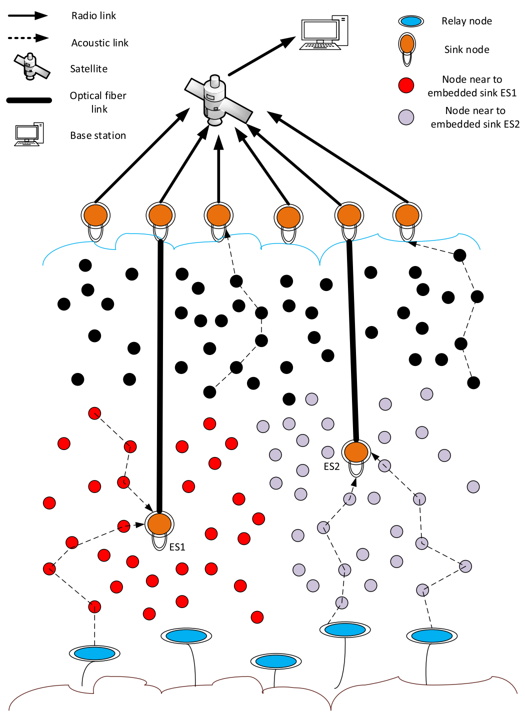


FIGURE 5. Network with two embedded sinks.

G. TRANSMISSION ENERGY ADAPTABILITY BY NODES IN AREA LOCAL TO SINKS

In UWSNs, nodes near to the sink suffer from high traffic, as shown in Fig. 6. This area is highly energy sensitive, because these nodes forward all network traffic to sinks. The nodes near to the sink transmit the whole network packets and die more quickly as compared to other nodes in the network. These nodes are more important for the whole network because they are like bridges between the sinks

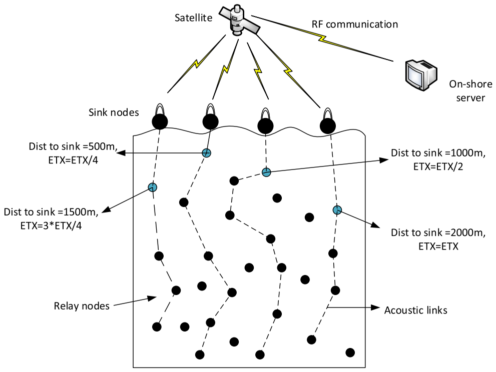


FIGURE 6. **Transmission energy adaptability by nodes near to sinks.**

and the rest of the network. In order to increase the energy efficiency, the nodes first find distance to the nearest sink. After calculating the distance, these nodes set their transmission power accordingly, as shown in Fig. 6. This strategy saves total energy consumption of the network. Furthermore, the network will survive for relatively longer intervals of time.

H. HOLDING TIME COMPUTATION

When a source node broadcasts a packet, all the nodes within its transmission range receive the packet. All the receiving nodes retrieve the depth information of the transmitter node from the packet and compare it with their own depths. If the depth of a receiving node is less than that of the source node, then the receiving node calculates its holding time, otherwise the packet is dropped. For holding time calculation, the proposed work creates a fitness function, which consists of depth difference sum of two hops H, PFNs of the nodes of the second hop, and the residual energy E of each PFN in the second hop. The fitness function is calculated as:

$$FF = \frac{W_{depth}}{1 + Energy * pfns} \tag{8}$$

where

$$Energy = 1 - \frac{Node\ energy}{Initial\ energy}$$

and

$$pfns = 1 - \frac{PFN}{Neighbor\ nodes}$$

The equation of holding time is a function of the following values:

$$T(FF) = k(FF) + \beta \tag{9}$$

When the source node S broadcasts the packet, nodes A, B, C, D and E receive the packet, as shown in Fig. 7. The nodes A, B and C are in the potential forwarding region of the node S; and the nodes D, E are in the suppressed region of the node S, therefore, they drop the packet, and nodes A, B, and C calculate their holding time and set the timer because they are in the potential forwarding region. Before expiry of the timer, if any duplicate packet is received by the PFN, then the packet is dropped, otherwise it is forwarded after expiry of the timer.

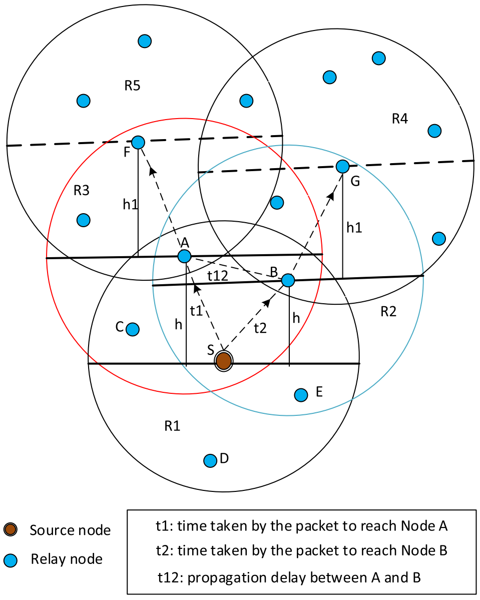


FIGURE 7. **Holding time computation.**

Let node A and node B be the best PFNs of the source node S. Let nodes A and B receive a packet from the source node S in time t1 and time t2 respectively and time t1-t2 be the propagation time between nodes A and B.

If the fitness function value of node A is greater than that of node B, then the condition in equation (9) is satisfied:

$$T[FF_A] < T[FF_B] \tag{10}$$

The holding time between node A and node B should be different. The node with greater fitness function value will be the best forwarder for node S. Amongst node A and node B, the prior has greater fitness function value than the later. Therefore, the packet will be transmitted by node A while node B simply drops the packet. To avoid duplicate packets, the following condition must be satisfied:

$$t1 + T[FF_A] < t2 + T[FF_B] + t12 \tag{11}$$

Substituting equation (8) into equation (10) results in the following equation:

$$k \le \frac{(t2 - t1) - t12}{FF_A - FF_B} \tag{12}$$

In mathematics, there is an inequality theorem of a triangle, which states that the sum of two sides of a triangle is greater than one side and the length of each side in the triangle is greater than the difference of the two sides, and (t2-t1)-t12 is always less than zero. k is always a negative value as T[FFA] < T[FFB]. The above two inequalities can hold true if:

$$|k| \ge \frac{(t_2 - t_1) - t_{12}}{FF_A - FF_B} \tag{13}$$

In case of worst condition, the value of k for nodes A and B will be:

$$|k| = \frac{\frac{2R}{vo}}{FF_A - FF_B} \tag{14}$$

where R is the transmission range of the node and v_o is the acoustic signal's propagation speed in water.

$$k = \frac{\frac{-2R}{V_0}}{\delta} \tag{15}$$

It guarantees that the packet will be forwarded by node A before node B. The node will have holding time equal to zero if the value of weighting depth difference is minimal. To calculate b, we use the following equation:

$$\frac{\frac{-2R}{V_0}}{\delta} + \beta = 0 \tag{16}$$

Putting the values of equation (15) and equation (16) in equation (9), we get:

$$T(FF) = \frac{\frac{2R}{V_0}}{\delta}(R - FF) \tag{17}$$

A node will be the next forwarder if its fitness function value is larger than others in the range of the source node. The larger the value of the fitness function, the smaller will be the holding time of a particular node and vice versa. The holding time is inversely proportional to δ, therefore, for larger δ, the holding time will decrease.

The forwarding technique of the proposed protocol is given in Algorithm 1.

V. SIMULATIONS AND RESULTS

In this section, we perform a detailed simulation analysis of our proposed protocol in comparison to WDFAD-DBR. We used Matlab as a simulation software for the verification of our proposed model. We used all the parameters of the underwater environment to check the performance of our proposed protocol.

A. SIMULATION SETUP

In our proposed model, we deployed 500 sensor nodes in a three dimensional space of 1000 km^3 volume (i.e., length = 10 km, width = 10 km, height = 10 km), as shown in Fig. 8. Simulations are carried out under different node densities (from 100 to 500 nodes), therefore, the average volume covered by each node can vary from 2 km^3 to 10 km^3. We also deployed eleven sinks, which are distributed as follows: two sinks are deployed underwater in the areas where network traffic is most likely to flow, and the rest of the nine sinks are deployed at the water surface. Our proposed architecture uses three types of packets, namely data packet, neighbour request, and acknowledge packet. The size of the data packet is 83 bytes, which consist of 11 bytes of header and 72 bytes of payload. The neighbor request and acknowledge packets both have the size of 50 bits. We find PFNs by checking the following condition:

$$Z_{receiver} \leq Z_{transmitter}$$

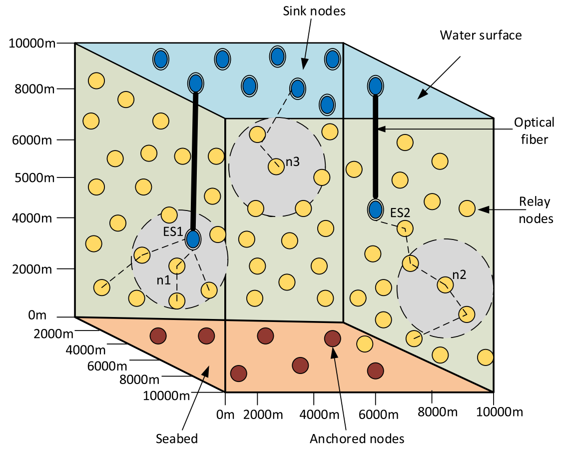


FIGURE 8. **Network deployment.**

TABLE 4. **Experimental settings.**

Variable	Value
Nodes deployed	100:50:500
Sinks deployed on water surface	9
Sinks deployed under water	2
Node transmission range	2 km
Total network area (3D region)	10 km × 10 km × 10 km
P_{tx}	50 W
P_{rx}	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 $N_{request}$	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 µPa
Minimum power for receiving	10 dB re µPa

If a particular node satisfies the above condition, then the node ID is added to the PFNs vector table. Otherwise, it is added to the suppressed nodes vector table. We use equation (8) to compute our fitness function value for calculating the holding time of a packet.

Generally, the values of energy and number of PFNs of a sensor node are high, and if we feed these values into our fitness function, then the holding time difference between the nodes will decrease, hence causing duplicate packets. For this purpose, we normalize the energy and PFNs using equation (6) and equation (9) respectively, so that the values lie between 0 and 1. The parameters used in our simulation experiments are listed in Table 4.

B. PERFORMANCE METRICS

Energy tax: It is denoted by E_{tax}, and is one of the main performance factors in underwater networking protocols. E_{tax} is defined as the average energy consumption

Algorithm 1 Forwarding Technique of the Proposed Work

```
for $k \leftarrow 1$ to $numberofnodes$ by 1 do
    $bcast\_id = N(k).ID$
    f=1
    while $f$ do
        for $l \leftarrow 1$ to $numberofsinks$ by 1 do
            calculate distance $D_l^k$ with sink(l)
            if $D_l^k$<$t\_range$ then
                $T\_energy = ((t\_range - dist\_to\_sink)/dist\_to\_sink) * T\_energy$
                Packet successfully delivered
                $S(bcast\_id).E = S(bcast\_id).E - Tr\_Energy$
                f=0
                break
        $P_{forwarders} = N(bcast\_id).PFN$
        if $P_{forwarders} == 0$ then
            $pkt\_drop$
            f=0
            break
        if $P_{forwarders} == 1$ then
            $N(bcast\_id).E = N(bcast\_id).E - Tr\_Energy$
            $bcast\_id = PFN\_ID$
        if $P_{forwarders} > 1$ then
            for $l \leftarrow 1$ to $Sink\_Nodes$ by 1 do
                find distance $D_l^k$ with sink(l)
                if $D_l^k$<$t\_range$ then
                    $T\_energy$=$((t\_range - dist\_to\_sink)/dist\_to\_sink) * T\_energy$
                    Pkt successfully delivered
                    $N(bcast\_id).E$= $N(bcast\_id).E - Tr\_Energy$
                    f=0
                    t=1
                    Break
            t=0
            $Suitable\_FF = \infty$
            for $m \leftarrow 1$ to $P_{forwarders}$ by 1 do
                Calculte Fitness Function ($FF_k^m$) value for m$_{th}$ $P_{forwarder}$
                $N(bcast\_id).E = N(bcast\_id).E - Tr\_Energy$
                if $FF_k^m < Suitable\_FF$ then
                    $Selected\_next\_forwarder = N(N(N(i).ID).PFN(s)).ID$
                    $Suitable\_FF = FF_k^m$
                    t=1;
            if $t == 1$ then
                $bcast\_id = qualified\_forwarder\_ID$
                find $H_{time}$ for $Suitable\_FF$
```

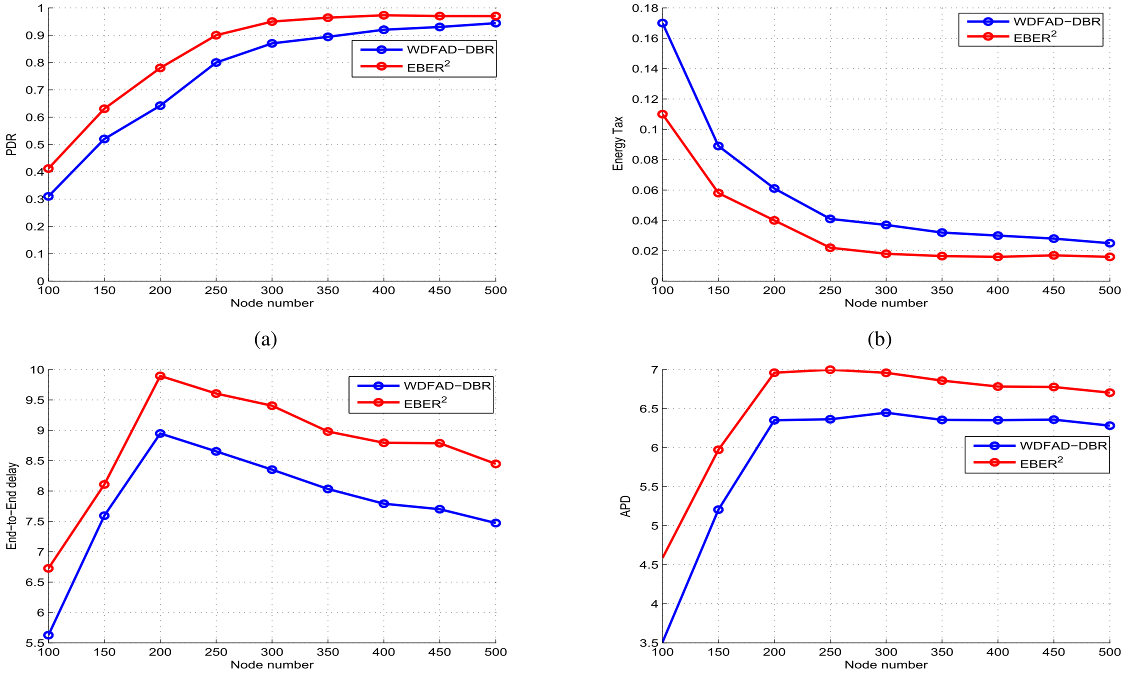
per node on successful delivery of packets from source to destination. It includes transmission, receiving and computational energy, etc.

Mathematically,

$$E_{tax} = \frac{Total\ energy}{N * packets} \tag{18}$$

where N denotes number of nodes deployed in the network.

Packet delivery ratio: It is abbreviated as PDR, and is related to successful packet delivery from source to destination. PDR is a factor in underwater networking protocol performance and is defined as the ratio of the total number of packets successfully received by the sink nodes to the total packets generated in a network.



(a)

(b)

(c) E2ED vs number of nodes

(d) APD vs number of nodes

FIGURE 9. (a) PDR vs number of nodes; (b) E_{tax} vs number of nodes; (c) E2ED vs number of nodes; (d) APD vs number of nodes. Comparison of our protocol with WDFAD-DBR.

Mathematically,

$$PDR = \frac{Packets\ successfully\ received}{Packets\ sent} \tag{19}$$

End-to-end delay: It is abbreviated as E2ED, and is the average time elapsed between the instances when a node starts transmission and when the packet is received at the sink. In a multiple sink scenario, several sinks may receive the packet. In this case, the shortest one is selected. E2ED is the combination of propagation delay, transmission delay, holding time, and processing time.

Accumulated Propagation Distance: It is abbreviated as APD, and is one of the performance parameters in underwater networking protocols. APD is defined as the average distance covered by successful packets from source to destination. Due to multiple sinks and multiple paths, more than one copy of the same packet is received. So, the shortest path is considered in APD calculation.

Mathematically, APD can be calculated as follows:

$$APD = \frac{1}{p}\sum_{j=1}^{p}\sum_{i=1}^{hops} dist_{\mathrm{j}}^{\mathrm{i}} \tag{20}$$

where p represents the number of packets, $hops$ represents the number of hops traversed by a packet, and $d_{\mathrm{j}}^{\mathrm{i}}$ is the distance covered by ith packet in jth hop.

Packet loss: It occurs due to multiple reasons, e.g., a node having no PFNs, a node not having enough energy to perform packet forwarding, and packet collision, which occurs due to network congestion.

Void hole: If a particular forwarder has no energy or PFNs, then it is said to be a void hole for the node. The hole that occurs due to energy is called energy hole and the one due to lack of PFNs is called coverage hole.

C. PERFORMANCE COMPARISON AND ANALYSIS

After mathematical modelling, we proceed to the simulation phase and compare our results with those of WDFAD-DBR. Simulation results show that our proposed protocol outperforms WDFAD-DBR in terms of E_{tax}, PDR and packet loss. The simulations are performed under different node densities of the network. After each round, we increase the number of nodes by 50, and extract results for different numbers of nodes.

Fig. 9 shows that PDR increases with the increase in the number of nodes because the number of qualified forwarders increases with the number of nodes. However, when the node density is increased above a certain value, then PDR gradually starts decreasing due to increase in packet collision at the receiver. Our proposed model provides better results compared to WDFAD-DBR in terms of PDR, because WDFAD-DBR does not consider PFNs and the source node can select the next forwarder having no further forwarders. This phenomenon causes a great deal of packet loss and eventually decreases PDR. Our proposed model selects the node that has larger number of PFNs than all other nodes in the range of the source node. So, we get large numbers of forwarders, which result in improved PDR. At the same time, we reduce duplicate packets by considering residual energy of the PFNs. Due to this choice, extra network energy consumption is reduced, resulting in decreased E_{tax}. Residual energy in forwarding process also increases network lifetime by balancing energy consumption among the nodes. So, a large number of packets will be delivered. Besides, energy tax is improved due to intelligent energy consumption adopted by the nodes near the sinks.

This is because E_{tax} is directly proportional to the network energy consumption. We decreased network energy consumption by making different levels of transmission energy in the area near to the sink. This is due to the fact that once a sink is found at a distance half of the transmission radius, then the node decreases the transmission power accordingly, as shown in Fig. 6.

In this way, network lifetime is increased and large numbers of packets can be delivered to the sinks. The proposed protocol performs better than WDFAD-DBR with respect to all the performance metrics except E2ED because WDFAD-DBR only works on packet advancement, as shown in Table 5. WDFAD-DBR always selects a node, which is near to the sink, so the average APD and E2ED are decreased.

TABLE 5. Overall comparison between EBER^2 and WDFAD-DBR with respect to E_{tax}, PDR, and E2ED.

No. of nodes	100	200	300	400	500	Average
E_{tax} %age improvement	35.29%	34.42%	51.35%	46.66%	36%	11.82%
PDR %age improvement	24.75%	17.69%	8.42%	5.15%	3.09%	40.74%
E2ED %age increased	16.36%	9.60%	8.51%	11.49%	11.50%	11.50%

D. PERFORMANCE COMPARISON USING EMBEDDED SINKS

In the last section, we discussed the deployment of all sinks at the surface of water and then compared the performance results. Details of simulation analysis are described in this section and the results of our proposed solution are compared with those of WDPAD-DBR when two embedded sinks are deployed. Our proposed model deployed eleven sinks: two sinks are deployed underwater and are called embedded sinks, while the rest are deployed at the surface of water. In this scenario, we got three network regions. One region is occupied by nodes that are within the closest proximity to embedded sink1 (ES1). The second region is occupied by nodes that are in the closest proximity to embedded sink2 (ES2). In the third region, the sensor nodes are in the closest proximity to surface sinks, as shown in Fig. 8. Embedded sinks are connected to surface sinks through high speed radio links. When a node receives a packet, it first finds its distance to all the sinks and then transmits the packet to the nearest sink. So a packet received by any of the sinks is considered as a successful packet. In this way, we get decreased network latency, and as a result, E_{tax} is decreased and PDR is increased, as shown in Fig. 10. E_{tax} is the energy consumed per node per packet, which means that under increasing or constant node density, if the number of successful packets increases, then E_{tax} will decrease. Our performance results show 52.63% improvement in terms of E_{tax} as compared to WDFAD-DBR, as shown in Table 6. This is because we deployed two sinks under water and instead of further forwarding, nodes transmit their packets to the embedded sinks that are nearer to them, resulting in decreased network latency. The main benefit of the embedded sinks is that successful transmission of packets incurs relatively low cost.

TABLE 6. Overall comparison between EBER^2 and WDFAD-DBR with respect to E_{tax}, PDR, and E2ED in case of two embedded sinks.

No. of nodes	100	200	300	400	500	Average
E_{tax} %age improvement	56.52%	42.30%	53.48%	55%	55.88%	52.63%
PDR %age improvement	43.63%	16.47%	7.29%	6.18%	6.12%	15.93%
E2ED %age improvement	16.09%	5.78%	7.66%	6.49%	6.87%	8.57%

We further analyzed the phenomena and found a considerable decrease in packet loss. Since the energy is consumed per packet and the probability that a forwarder contains no energy decreases, packet loss and void holes also decrease. E2ED is reduced in comparison to the scenario in which all sinks are deployed at the surface of water. The reason is that large numbers of packets are transmitted to the embedded sinks instead of surface sinks, for which the average APD is relatively larger.

E. PERFORMANCE COMPARISON WITH WDFAD-DBR USING DIFFERENT TRANSMISSION RANGES

To verify the performance of our protocol, we further analyze our results under different transmission ranges. The results show that the proposed solution performs better under varied transmission range compared to WDFAD-DBR.

Normally, if there is no strategy to limit the number of forwarding nodes, as in the flooding-based routing, then E_{tax} increases with increase in the number of nodes. This is due to the fact that when node density increases, packet collision at the receiver also increases, which leads to decreased E_{tax}. In DBR and WDPAD-DBR, there is a proper mechanism for limiting forwarding nodes, i.e., by taking only the nodes in the upper hemisphere as qualified forwarders, which decreases packet collision at the receiver's end and increases the number of successful packets. This is the reason why E_{tax} decreases with the increase in node density. The phenomenon is more optimized in our proposed work even at different transmission ranges. We performed further simulations on 1200m, 1600m and 2000m transmission ranges and compared the results with those of WDFAD-DBR to verify the validity of our proposed protocol. We found that our protocol shows

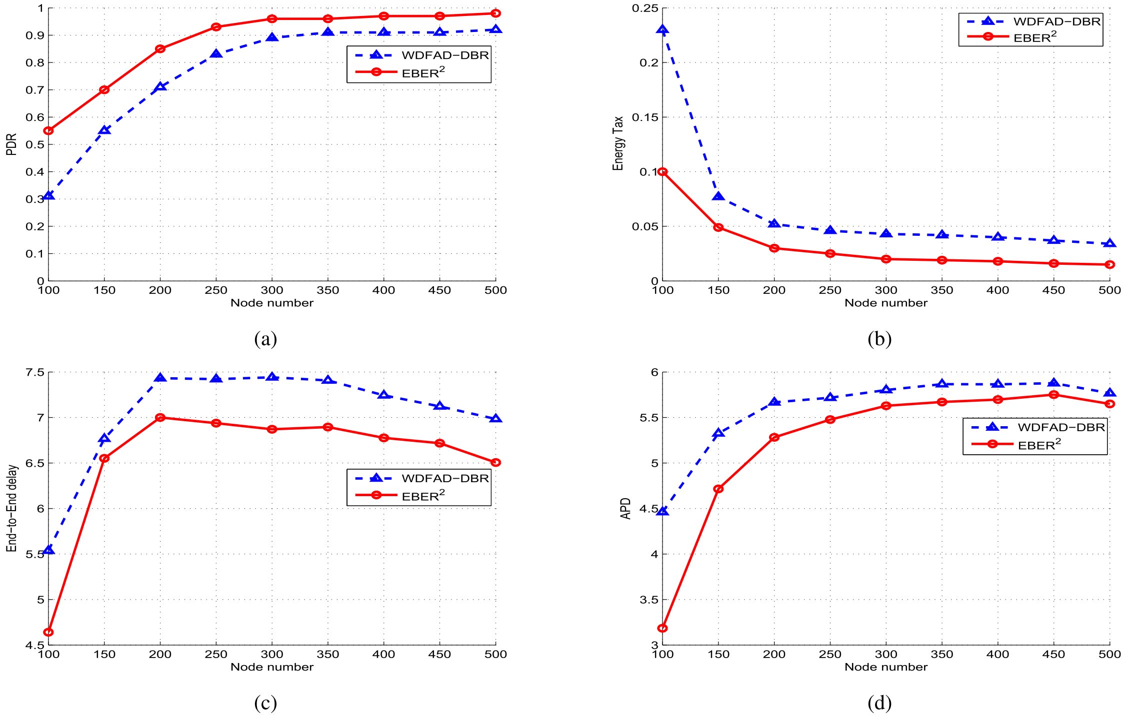


FIGURE 10. (a) PDR vs Node number; (b) E_{tax} vs Node number; (c) E2ED vs Node number; (d) APD vs Node number. Comparison of our protocol with WDFAD-DBR using two embedded sinks.

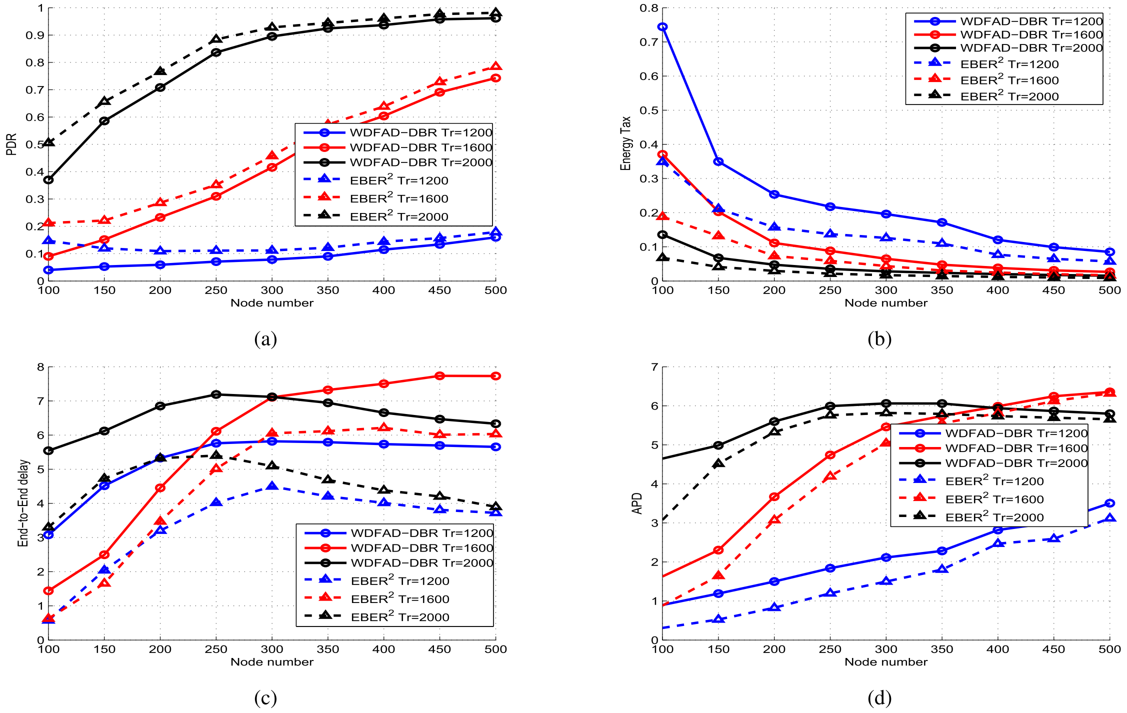


FIGURE 11. (a) PDR vs Node number; (b) E_{tax} vs Node number; (c) E2ED vs Node number; (d) APD vs Node number. Comparison of our protocol with WDFAD-DBR using different transmission ranges.

better results compared to WDFAD-DBR on all of the above mentioned transmission ranges, as shown in Tables 7, 8 and 9. The percentage improvement gradually increases when we go from a short transmission range towards the large one, as shown in Fig. 11, because most underwater networks have sparse nature due to high cost of the acoustic nodes. For short transmission ranges, the source node cannot find PFNs most of the time, which causes high packet loss.

From the below simulation analysis, we observe that E_{tax} is inversely proportional to the transmission range, i.e., by decreasing transmission range, E_{tax} increases and vice versa. The same observation is noticed in case of PDR because nodes with short transmission range have less probability to find the next forwarder due to sparse deployment of the nodes, and as a result, the number of successful packets decreases. E_{tax} improvement becomes more dominant when we go from large transmission range towards the short one because WDFAD-DBR only considers advancement of packets.

WDFAD-DBR has no mechanism for checking PFNs of the forwarder due to which high packet loss occurs, especially in case of short transmission ranges. E_{tax} improvement gradually decreases with increase in transmission range. For large transmission ranges, a forwarder has higher probability of finding PFNs, which consequently causes relatively small improvement in E_{tax}. Furthermore, we found that with varying transmission range, the overall percentage improvement in each performance metric decreases with increase in node density, as shown in Tables 7, 8 and 9. For every UWSN protocol, there are optimized values of the parameters for which we obtain best results. For example in DOW-PR, the performance is better in case of 200 nodes and 1000m transmission range. Likewise, our proposed protocol performs better in case of 100 nodes and 1200m transmission range, as presented in the below tables. This is because our proposed protocol mainly focuses on successful delivery of data. In case of 1200m transmission range, the forwarding area is minimum, which consequently decreases the number of duplicate packets, due to which E_{tax} becomes minimum and provides maximum improvement, as shown in Table 8.

TABLE 7. Overall comparison of PDR with WDFAD-DBR using different transmission ranges.

T-range	100 nodes	200 nodes	300 nodes	400 nodes	500 nodes
1200(m)	72.7%	45.8%	29.7%	20.8%	11.1%
1600(m)	57.5%	18.8%	8.9%	5.4%	5.3%
2000(m)	26.7%	7.4%	3.5%	2.5%	2.1%
Average Improvement	52.3%	24%	14.03%	9.5%	6.1%

TABLE 8. Overall comparison of E_{tax} with WDFAD-DBR using different transmission ranges.

T-range	100 nodes	200 nodes	300 nodes	400 nodes	500 nodes
1200(m)	53.2%	37.9%	35.38%	35.8%	32.14%
1600(m)	49.1%	34.2%	33.8%	36.8%	38.4%
2000(m)	50.3%	38.2%	42.8%	40%	46.7%
Average Improvement	50.8%	36.7%	37.3%	37.5%	39%

TABLE 9. Overall comparison of E2ED with WDFAD-DBR using different transmission ranges.

T-range	100 nodes	200 nodes	300 nodes	400 nodes	500 nodes
1200(m)	49.38%	25.53%	26.31%	17.32%	5.98%
1600(m)	18.07%	5.81%	3.37%	3.49%	6.71%
2000(m)	9.56%	2.83%	2.10%	2.77%	2.60%
Average Improvement	25.07%	11.39%	10.6%	7.9%	5.09%

The improvement in PDR is maximum in case of 100 nodes and 1200m transmission range, as shown in Table 7, because the packet collision is minimum for less dense networks. Moreover, the forwarding region is small and minimum numbers of redundant packets are generated.

F. PERFORMANCE COMPARISON ON DIFFERENT DATA RATES

To observe the output of our protocol on different data rates, we perform the analysis on 16 kbps, 32 kbps and 64kbps.

Fig. 12a shows that PDR increases when we move from low data rate to high data rate, i.e., from 8 kbps to 32 kbps in the simulations. This is because under lower data rate, the time from sending to receiving a packet is large, and so the collision probability is high. As data rate increases, the time taken by a packet to reach the destination reduces due to decrease in collision probability, and consequently, the number of successful packets increases. But the case is not true for every increasing data rate because acoustic signals offer limited bandwidth and PDR cannot increase further when it reaches a value of 0.92. Fig. 12b shows that E_{tax} decreases as the data rate increases from 8 kbps to 32 kbps. The reasons are as follows: Extra network energy consumption is reduced by decreasing packet loss while going from 8 kbps to 32 kbps. On the other hand, under constant packet size and transmission power, the cost of sending a packet reduces, which also decreases the total energy consumption. Furthermore, the phenomenon is more obvious for sparse networks due to low probability of successful packets. Fig. 12c shows that E2ED decreases with increase in the data rate. With such increase in the data rate, the time taken by a packet from transmission to reception decreases, i.e., E2ED also decreases. Moreover, the percentage improvement between 16 kbps and 32 kbps is more as compared to the one between 8 kbps and 32 kbps due to the following reason: at low data rate, the collision probability is high and some packets avoid the best path from source to destination, due to which the average APD increases and causes high E2ED.

G. PERFORMANCE COMPARISON ON DIFFERENT PAYLOAD SIZES

To verify the impact of the payload size on the performance metrics, we analyze our protocol on 44 bytes, 72 bytes and 144 bytes. Fig. 13 shows that the network performance in terms of PDR, E_{tax}, E2ED and APD decreases with increase of payload from 36 bytes to 144 bytes. At constant data rate, increase in payload correspondingly increases sending and receiving time. Thus, E2ED increases with increase in

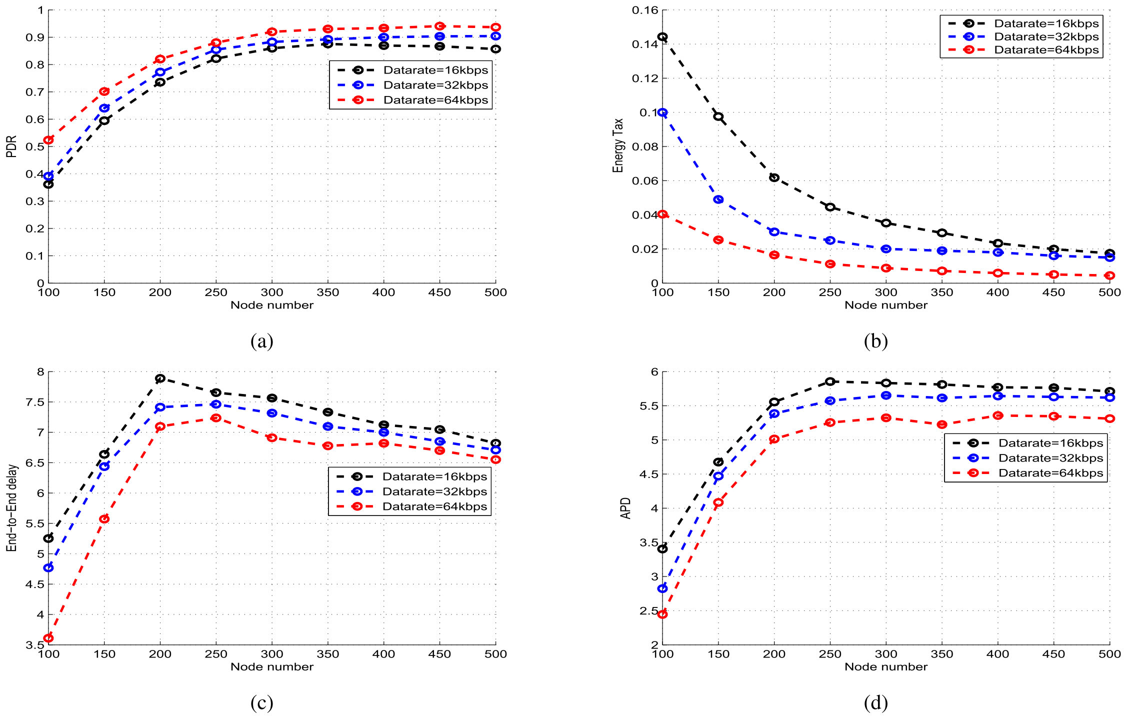


FIGURE 12. (a) PDR vs Node number; (b) E_{tax} vs Node number; (c) E2ED vs Node number; (d) APD vs Node number. Comparison of our protocol with WDFAD-DBR on different data rates.

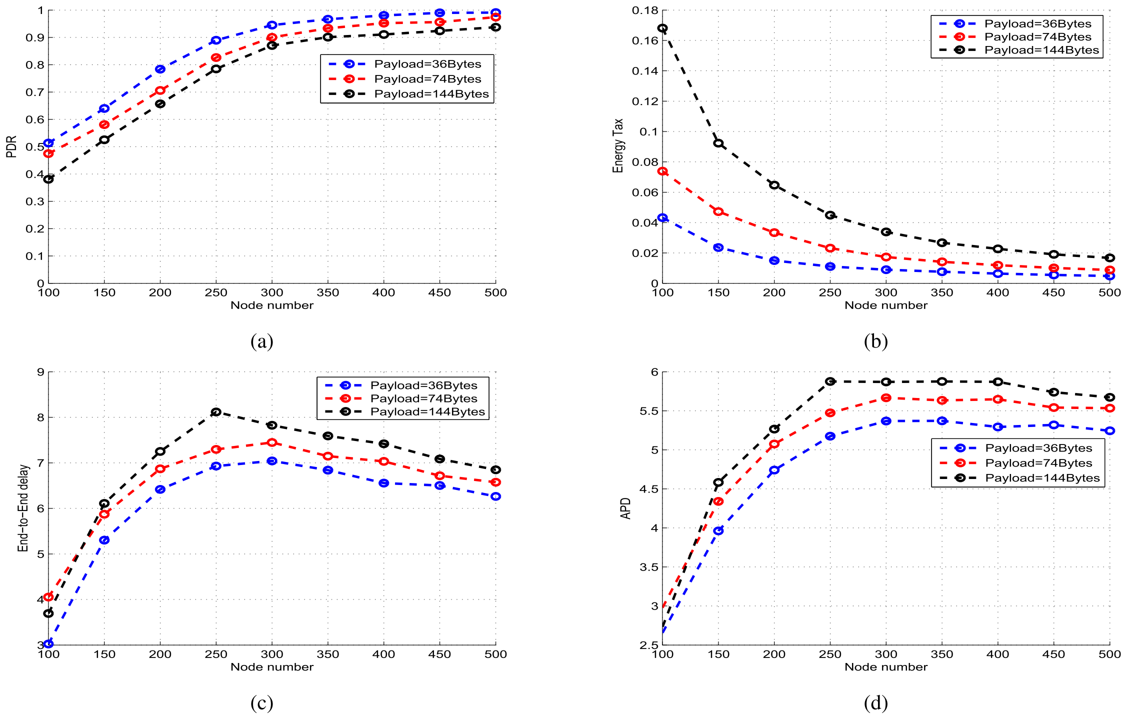


FIGURE 13. (a) PDR vs Node number; (b) E_{tax} vs Node number; (c) E2ED vs Node number; (d) APD vs Node number. Comparison of our protocol with WDFAD-DBR on different payloads.

the payload. Due to increase in sending and receiving time, the probability of packet collision increases due to which the number of successful packets decreases. Since PDR is the ratio of successful packets and generated packets, so PDR is reduced by increase in the payload. According to the definition, E_{tax} is inversely proportional to the successful packets, so E_{tax} increases with increase in the payload, as shown in Fig. 13b. Increase in payload actually increases the time slot for packet collision, due to which the packet loss increases with payload. Packet loss consumes extra amount of network energy, which leads to increasing E_{tax}.

H. FEATURE TRADE-OFFS OF EBER^2

According to the above results, we can conclude that EBER^2 offers various advantages and also suffers from some shortcomings. In case of considering PFNs, void holes are avoided and PDR is improved. On the other hand, more duplicate packets are generated. When the residual energy feature is considered, the network lifetime is increased but this comes at the expense of increasing E2ED. Prioritizing PFNs helps in reducing duplicate packets but longer E2ED is incurred. The embedded sinks feature allows high delivery ratio and low E2ED. However, high communication with the surface sinks is recorded. Control transmission power near to the sink permits decreased E_{tax} but at the cost of more duplicate packets that are sent to surface sinks. The advantages and shortcomings of EBER^2 with respect to each feature are shown in Table 10.

TABLE 10. **Achievements and trade-offs.**

Feature	Advantages	Shortcomings
PFNs consideration	Void hole avoidance and improved PDR	Duplicate packets
Residual energy consideration	Increased network lifetime	Increased E2ED
Prioritizing PFNs by holding time	Reduced duplicate packets	Increased E2ED
Embedded sinks	High delivery ratio and decreased E2ED	High cost on physical connection to surface sinks
Control transmission power near to sink	Decreased E_{tax}	Duplicate packets to surface sinks

VI. CONCLUSION

In this paper, we proposed Energy Balanced Efficient and Reliable Routing (EBER^2) protocol for Underwater Wireless Sensor Networks (UWSNs). The proposed protocol is basically the improved version of WDFAD-DBR. The tasks achieved in this protocol are reduced energy tax, improved PDR, and decreased packet drop at the cost of E2ED. E_{tax} is reduced by the increased number of successful packets and controlled transmission power. Packet drop is decreased and consequently, PDR is improved by selecting high node density path for forwarding. In the high node density path, duplicate packets are reduced by checking more information about the neighbors like depth and residual energy. Results show that EBER^2 improved E_{tax} and PDR by 40.7% and 11.82% respectively, at the cost of 11.5% increase in E2ED, for the case when all sinks are deployed at the surface of water. Furthermore, we tested the performance on different node densities, transmission ranges, data rates and payloads to validate EBER^2.

We further analyzed that EBER^2 showed average improvement of 40.26% in E_{tax}, 21.18% in PDR and 12.93% in E2ED, in case of embedded sinks.

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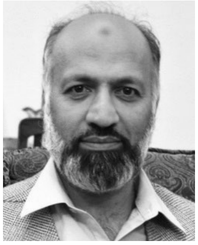

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