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# Towards Void Hole Alleviation: Enhanced GEographic and Opportunistic Routing Protocols in Harsh Underwater WSNs

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**ABSTRACT** Internet of Things enabled Underwater Wireless Sensor Networks (IoT-UWSNs) are quite useful in monitoring different tasks including: from instrument monitoring to the climate recording and from pollution control to the prediction of natural disasters. However, there are some challenges, which affect the performance of a network, i.e., void hole occurrence, high Energy Consumption (EC) and low Packet Delivery Ratio (PDR). Therefore, in this work, two energy efficient routing protocols are proposed to maximize the PDR by minimizing the ratio of void hole occurrence. Scalability analysis of the proposed routing protocols is also performed. Additionally, feasible regions are computed to check the optimality of the proposed protocol in terms of EC. Furthermore, proposed protocols are compared with benchmark routing protocols in counterparts. Simulation results clearly show that proposed routing protocols achieved 80-81% higher PDR than GEographic and opportunistic routing with Depth Adjustment based topology control for communication Recovery (GEDAR) and Transmission Adjustment Neighbor-node Approaching Distinct Energy Efficient Mates (TA-NADEEM). Moreover, the ratio of void hole occurrence is minimized upto 30% approximately.

**INDEX TERMS** Underwater wireless sensor networks, Internet of Things enabled harsh underwater WSNs, energy hole alleviation, enhanced geographic and opportunistic routing.

## I. INTRODUCTION

Internet of Things enabled Underwater Wireless Sensor Networks (IoT-UWSNs) help in monitoring natural disasters and the aquatic environment. Also, there are several applications in Underwater Wireless Sensor Networks (UWSNs), i.e., underwater vehicles, seaquakes, floods, mine recognition, military surveillance [1], etc. Due to the aforementioned applications, UWSN gains much attention of scientists and researchers.

In UWSNs, sensors are deployed to form an aquatic sea swarm architecture (where the nodes perform multi-hop acoustic communication by delivering the packets to the

nearest sink) [2]. They are equipped with different sensing devices and have limited bandwidth. In order to limit the mobility of the nodes due to underwater currents, each deployed node has a fish bladder like apparatus or winch based apparatus. Whereas, the drogue is used for their Depth Adjustment (DA) [3]. Furthermore, these sensor nodes are guided via sonobuoys and each sensor node has to report its respected sonobuoy. Then the retrieved data is delivered to onshore data centers.

Therefore, Geographic routing is considered as one of the most scalable and promising techniques in UWSNs [4]. For example, it does not require a complete route from source to destination. Moreover, there is no need to update the routing states during each transmission [5]. In geographic routing, the nodes are deployed closer to the destination are elected

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as next-hop forwarders. Whereas, in Opportunistic Routing (OR), the selection of the next-hop forwarder node is done randomly.

At this end, underwater communication faces a high bit error rate, multipath fading and void hole occurrence. In addition, low channel bandwidth and the probability of high packet drop increase the Energy Consumption (EC) of the network. However, the interconnection between network nodes becomes a difficult task. This problem arises due to the path loss, high attenuation and high bit error probability and it needs to be tackled efficiently.

Considering the aforementioned limitations, Geographic and opportunistic routing with DA based topology control for communication Recovery (GEDAR) is one of the useful UWSN routing protocols, which minimizes the EC with high Packet Delivery Ratio (PDR). However, it faces void hole [2]. It is defined as “a node with no next hop forwarder node in its transmission range (as shown in Figure 1)”. Due to the presence of a void node in the communication environment, the data forwarding towards the sonobuoy stops.

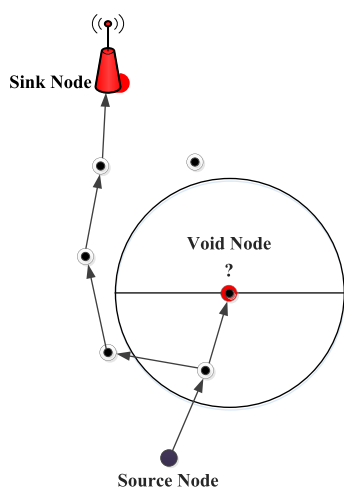


FIGURE 1. Void hole.

Different efforts have been done over the past few years for void node recovery, i.e., GEDAR, Neighbor-node Approaching Distinct Energy Efficient Mates (NADEEM), Fallback Approach NADEEM (FA-NADEEM) and Transmission Adjustment (TA-NADEEM) in [6] and [2], respectively. However, finding the location of a node is a difficult task to be solved. Therefore, aforementioned routing protocols failed to provide a feasible solution regarding the recovery of void node.

Motivating from the above consideration, two protocols are proposed, i.e., Improved GEographic DA Routing (Im-GEDAR) and Co-Improved GEographic DA Routing (Co-Im-GEDAR). At each layer, 9 fixed nodes are deployed at different strategic locations in the underwater network. These backup nodes (fixed nodes) play a dynamic role in route establishment (most importantly during sparse regions) and adjust their positions based on the topology of the sensors

(because they have high energy and assure the maximum monitoring of the network field). Firstly, they perform Transmission Range Adjustment (TRA) to minimize the fraction of the void nodes occurrence and overcome the dynamically changing network topology. Secondly, they perform DA in order to minimize the aforementioned issues with efficient data flow. The main contributions of the proposed work are:

- Two routing protocols namely: Im-GEDAR and Co-Im-GEDAR are proposed,
- the concept of backup or fixed nodes deployment at different strategic locations is implemented for efficient EC,
- in addition to fixed nodes deployment, the concept of horizontal mobility, TRA and DA are also implemented to reduce the issue of the void hole occurrence,
- the proposed protocols maximize the PDR with 10-15% efficient EC,
- the scalability analysis of the proposed protocols is also performed and
- feasible regions for the proposed protocols are also computed to check the optimality of the proposed protocols.

The proposed routing protocols are also compared against the baseline routing protocols to check the efficacy of proposed routing protocols.

The rest of the paper is organized as: section II covers the different routing protocols in terms of their operations, usefulness and their limitations. Section III covers the problem statement. Network architecture is discussed in section IV. Furthermore, section V presents the feasible regions of the proposed protocols. Section VI includes the performance comparison of the proposed and benchmark routing protocols. Finally, the paper is concluded in section VII.

## II. RELATED WORK

In this section, the related work of the benchmark routing protocols is discussed, i.e., DBR [8] is proposed by Yan *et al.* that considers the depth of nodes to find forwarder node. Low-pressure sensor nodes are elected as neighbor nodes. The proposed protocol minimizes the EC of the network. However, it fails to optimize network performance when a void node appears in the network. The node fails to elect forwarder node resulting in degradation of network throughput.

In [9], EEDBR is proposed to find the potential forwarder node using depth of the nodes and their remaining energy. The election of the forwarder node is based on a greedy approach. The source node finds the neighbor node in its transmission range having the lowest depth and the highest energy. The packet is delivered to nodes having low depth and high energy. EEDBR achieves high energy efficiency and throughput. However, it fails to cop with a void node in a sparse case which results in high EC and E2E delay.

The problem of void hole occurrence is minimized in [10]. It includes the protocols namely: Adaptive transmission range in Weighting Depth Forwarding Area Division (WDFAD) with DBR (A-DBR), Backward transmission-based WDFAD-DBR (B-DBR), Cluster-based

WDFAD-DBR (C-DBR) and Collision Avoidance-based WDFAD-DBR (CA-DBR). Proposed protocols enhance the throughput of the network and minimize the void hole occurrence. However, EC is minimized with E2E delay.

In [11], BEAR for UWSNs is implemented. It works in three phases: initialization (in this phase all nodes share information), tree construction (used for exploiting the location information for neighbors and successor selection on the basis of the cost function) and data transmission phase (source to destination delivery). The lifetime of the network is improved by this proposed strategy. However, EC on the tree construction is not discussed in BEAR protocol.

Noh *et al.* propose a Void Aware Pressure Routing (VAPR) protocol in [12]. It uses geographic and opportunistic routing for next-hop forwarder node selection. In VAPR, a beacon message disseminates across the network which contains information about void node such that nodes become aware of the situation. With the help of this information, each node establishes a directional route towards the sonobuoy. The selection of the forwarder node depends on forwarding direction of the neighbor node.

Hafeez *et al.* propose a technique named as Avoiding Void Node with Adaptive Hop by Hop Vector-Based Forwarding (AVN-AHH-VBF) [13]. The proposed routing protocol contains virtual routing pipelines having a predetermined radius for data processing. While receiving Data Packet (DP), the node checks its distance with the forwarder node whether the calculated distance is within the given threshold or not. Node chooses the best forwarder node to forward the DPs. Moreover, it also involves time holding factor. Nodes having less number of neighbors have less holding time and vice versa. It minimizes the number of redundant DPs resulting in enhanced PDR. However, it increases the E2E delay in large area network.

To extend the idea of DBR [8], RPR [14] uses encryption and decryption mechanism. In RPR, payload and packet header are encrypted. A pair of keys (public and secret keys) are given to each node and a generated pair of key certificate is issued to nodes by a trusted party. Information shared between nodes is encrypted using the Network-wide Security Key (NSK). During the data forwarding phase, the packet payload is encrypted with a Gateway Public Key (GPK) and encryption of packet header at each forwarder node is done using NSK. After a successful DP reception, the header is decrypted and validated. DP with a proper signature is forwarded. TORA is proposed in [15] to avoid the problem of the energy hole. The proposed work uses the idea of multi-hop to minimize the aforementioned problem. However, reliability and complexity of the protocol is not catered.

In [16], void node recovery mode is proposed to improve communication. This routing strategy is similar to Vector Based Forwarding (VBF) protocol and it uses two mechanisms namely back-pressure shift and forwarder shift for concave and convex void nodes, respectively. During vector shifting mechanism, the information is sent to neighbor nodes in order to change their current routing vector. After vector

shifting, if a node is still void then the back pressure mechanism is adopted by moving the packet away from its destination. Afterward, a suitable routing path is selected to transmit the DP. The proposed strategy improves the PDR; however, the protocol faces high E2E delay during a concave hole. The E2E delay increases due to the process of recovering void holes, which maximizes the E2E delay.

In [17], Hydrocast routing protocol is proposed, which is a pressure based routing protocol. The proposed routing protocol recovers the void node using depth-first recovery method. The forwarder node selection is based on the status of the packet and the link cost towards the sonobuoy. Hydrocast decreases the void node probability on the expense of high overhead, which incurs while constructing a recovery path. In [7], a Weighting Depth and Forwarding Area Division DBR routing protocol (WDFAD-DBR) is proposed that considers the depth difference between 2-hops. A Reuleaux triangle is introduced in WDFAD-DBR such that each node overhears the transmission of high priority node to avoid redundant transmission. The priority is based on its depth from its sonobuoy. If a high priority node starts its data transmission, the nodes with lower priority suppress their transmission. This protocol achieves high PDR in sparse network, less EC and minimum delay level. However, the protocol fails to improve network performance in dense area network.

A multi-modal communication is proposed by O'Rourke *et al.* [18]. The proposed algorithm helps in determining the set of surface nodes for data forwarding. The major limitation of the proposed mechanism is high E2E delay due to the movement of the node at new depth until it reaches to the surface in order to transmit the data towards the sink.

A distributed algorithm Hop by Hop Dynamic Addressing based Routing Protocol for Pipeline Monitoring (H2-DARP-PM) of long-range underwater pipelines is proposed by Abbas *et al.* [19] which assigns dynamic hop address to each node that participates in the data forwarding process. It enhances the PDR on the cost of high EC.

In [20], a Localization Free Interference and Energy Holes Minimization (LF-IEHM) routing protocol is proposed. The protocol is featured with packet holding time. LF-IEHM overcomes the problem of interference during DPs forwarding. Energy hole formation is mitigated by the proposed protocol. The proposed protocol is compared with state-of-the-art protocols. Simulation results validate that the proposed protocol outperformed in terms of E2E delay and packet received ratio. However, the EC on packets holding is ignored by the authors, resulting in high EC.

In [21], two routing protocols using layered multipath approach are proposed. Tree-based topology is exploited in both proposed protocols to generate multiple copies from the cross-node. The generation of multiple copies ensures reliable data delivery. Proposed protocols succeed in minimum energy dissipation and maximum packets received ratio. However, the energy dissipation on binary tree generation is ignored by the authors, resulting in high EC.

In [22], geospatial division based opportunistic routing protocols are proposed. The proposed protocol avoids interference. To ensure the minimum interference, network is divided into a number of subcubes. These cubes help to make informed decisions during the packet forwarding. An optimal number of forwarder nodes are selected from the cube to avoid the void holes. Proposed protocol outperformed in terms of maximum network lifespan and PDR.

To control the node's mobility and to prolong the network lifespan, a Cluster-Based Energy Efficient Routing (CBE2R) is proposed in [23]. CBE2R controls node's mobility and enhances the network lifespan by minimizing the EC on the node's mobility. A multilayered approach is used in the proposed work. Therefore, forwarder nodes are selected on the bases of their assigned weights. Proposed protocol outperformed in terms of minimum energy dissipation and maximum PDR.

In [24], a sender-based approach is proposed for opportunistic routing. In this approach, based on current network conditions, the sender node finds a candidate set dynamically. However, whenever a sender forwards the DPs, it may have to handle different routing paths. Conventional routing protocols overlook this property during opportunistic routing. Therefore, to minimize the E2E delay, the optimal candidate selection for each node is determined in [24]. The proposed routing protocol considers global and local optimization jointly, which help the protocol to find original candidate set. In addition, the protocol can be further optimized considering real-time link and duty cycle information. However, the network faces affordable computational time and maintenance overhead.

An energy-efficient, reliable and opportunistic routing protocol for dense networks is proposed in [25]. In addition, the two most critical issues namely: reliable data delivery and power conservation are jointly considered to design the routing protocol. As a result, network lifespan and reliability in data is improved. The proposed routing protocol selects the optimal transmitting power and forwarder set to increase the network lifetime. Results validate that using the proposed idea, reliability and energy conservation is improved up to 50% and 30%, significantly.

In [26], a link model is proposed to predict the link availability. Proposed routing protocol observes the behavior of vehicles and considers two types of states namely: stable and unstable state to maximize the network throughput. Network resource consumption is minimized in the proposed model providing next street selection at each intersection. Results validate that the proposed model has improved the PDR and average E2E delay of the network, significantly. The comparison of benchmark protocols is shown in Table 1.

### A. SUMMARIZED RELATED WORK

In the aforementioned benchmark routing protocols, the main focus of the researchers is to avoid void hole and minimize EC. However, the features of the existing protocols vary with respect to the scenario, i.e., geographic OR, DBR,

vector-based routing, pressure based routing, interference and nodes mobility management for minimum EC and void hole avoidance. All aforementioned protocols work on energy minimization and successful data delivery; however, they still face some challenges, i.e., high EC, low PDR and high E2E delay.

### III. PROBLEM STATEMENT

In GEDAR [2], immutable forwarder nodes selection is performed (depending on the depth and energy of the nodes). This immutable forwarder node selection leads the network towards a void hole. Therefore, GEDAR implements the concept of DA to minimize the void hole occurrence. At this end, the void hole is moved to new depth to continue the data forwarding (using greedy forwarding) among the sensor nodes. However, this movement of void node results in excessive topology changes with additional energy dissipation problem. Although the void hole is recovered via DA in a vertical direction; however, this strategy dissipates the network energy even more quicker (due to excessive DAs). Moreover, reconfiguration of the network also becomes a challenging task. If the cost of moving the node is reduced in GEDAR, the high E2E delay decreases the network performance.

In the current work, two protocols namely: Im-GEDAR and Co-Im-GEDAR are implemented to solve the aforementioned problem. The proposed protocols avoid the void hole occurrence and minimize the EC using fixed nodes deployment at different strategic locations in UWSN. The detail of the proposed protocols is explained in the following subsection.

### IV. ARCHITECTURE OF THE PROPOSED PROTOCOLS

The proposed network model is adopted from GEDAR [2]. The nodes are distributed in the network as in Figure 2. They are capable of sensing and transmitting the sensed data towards the sink nodes or sonobuoys. Sonobuoys are special nodes that are deployed at the ocean surface. They collect the DPs from sensor nodes and deliver them to the onshore data center. The network architecture consists of  $N$  number of nodes. Where,  $N = N_n \cup N_s \cup N_f$ .  $N_n$  denotes the set of sensor nodes,  $N_s$  denotes the set of sink nodes and  $N_f$  represents the set of fixed nodes. A 3D model is considered involving space and time as well. Nodes are equipped with sensing devices to sense the data and deliver it to sonobuoys. Sensor nodes move freely due to water currents. Sonobuoys are equipped with a GPS system which enables them to determine their location. Furthermore, radio signals do not propagate well in the water because of their high absorbing rate. Thus, sonobuoys use acoustic signals for communication between sensor nodes in an underwater environment. Meanwhile, they use the radio signals for communication with other sonobuoys at the ocean's surface. A packet that arrives at respective sonobuoy is delivered to the monitoring center [8] and [12]. Whereas, sensor nodes move with the velocity  $v = 2.4$  m/min. whereas, the energy cost  $E_m$  spent on the node's movement

TABLE 1. Related work of the benchmark routing protocols.

Protocols	Features	Achievements	Limitations
DBR [8]	Depth based routing	Increases the PDR in dense area network	Performance of the network is degraded in sparse area network due to low PDR and high EC
EEDBR [9]	Depth and energy based routing	Network lifetime is maximized via energy balancing	Redundant packets are generated thus increases the EC in dense area network
A-DBR, B-DBR, C-DBR and CA-DBR [10]	Adoptive, back transmission based, cluster based and collision avoidance based Routing	Performance of the network is increased through void hole avoidance	Minimum EC and high E2E delay
BEAR [11]	Geographic routing	Performance of the network is increased by minimizing the E2E delay	High EC
VAPR [12]	Geographic and opportunistic routing	Void hole alleviation with increased PDR	High packet loss
AVN-AHH-VBF [13]	Vector based routing	Network performance is improved	Redundant packets and high E2E delay degrade the network performance
RPR [14]	Encryption and decryption mechanism	Secure data transmission	High energy consumption
TORA [15]	Multi-hop routing	Energy hole alleviation	Complexity of the system increases
VBVA [16]	Vector based routing, Backward-pressure and forward shift	Successful transmission of data towards sonobuoy increases through void node recovery	High EC and E2E delay
Hydrocast [17]	Pressure based routing, forwarder node selected by checking the status of DP and the link cost	Decreases void node probability	Increases the overhead
WDFAD-DBR [18]	Depth Based Routing, forwarder Node selection is based on depth difference between 2-hops	Network lifetime increases with less EC	E2E delay is increased
Multi-model communication [19]	Energy hole alleviation with enhanced PDR	High energy consumption and E2E delay	
H2-DARP-PM [20]	Selection of forwarder node is based on hop counts	PDR is increased	High EC
LF-IEHM [21]	Interference free route	E2E delay is minimized with high packet received ratio	EC on packets holding is ignored
FLMPC-One and FLMPC-Two [22]	Reliable data delivery	PDR is increased with minimum EC and maximum network timespan	EC on binary tree generation is ignored
GDGOR-1A and GRMCSM [23]	Geographic based routing	PDR is increased with enhanced network lifespan	High interference
CBE2R [24]	Nodes mobility management	PDR is increased with minimum EC	High Interference
Shortest Latency Opportunistic Routing (SLOR) [25]	Opportunistic routing	E2E delay is minimized with maximum network time	High computational time with maintenance overhead
Reliable and Energy-efficient Opportunistic Routing (REOR) [26]	Reliable, energy-efficient and opportunistic routing	PDR is increased with 30% energy conservation	Maintenance overhead
Expected Transmission cost over a multi-hop Path (ETCoP) [27]	Street centric opportunistic routing	PDR is increased with minimum network resources	High computational time

is kept 1500 mJ/m. At this end, the propulsion mechanism is not considered like [2].

### A. UNDERWATER PROPAGATION MODEL

In this subsection, underwater propagation model is used to estimate the PDR probability. We use underwater acoustic channel model by getting motivation from [27]. The path loss for a signal having frequency  $f$  with distance  $d$  is computed as:

$$A(d, f) = d^k u(f)^d, \tag{1}$$

where,  $k$  denotes the spreading factor. For cylindrical spreading,  $k = 1$ . The value of  $k$  for practical scenario is 1.5 and

for spherical spreading, the value of  $k$  is 2. Whereas,  $u(f)$  denotes the absorption coefficient (computed in dB/km) for frequency  $f$  (computed in KHz). The absorption coefficient  $u(f)$ , is described by the Thorp's formula [2], [13], [17] as:

$$10 \log u(f) = 0.11 \times \frac{f^2}{1 + f^2} + 44 \times \frac{f^2}{4100 + f} + 2.75 \times f^2 + 0.003. \tag{2}$$

The average Signal to Noise Ratio (SNR) [2] is computed as:

$$\Upsilon(d) = \frac{E_b/A(d, f)}{N_o} = \frac{E_b}{N_o d^k u(f)^d}. \tag{3}$$

whereas,  $E_b$  represents the energy transmitted per bit and  $N_o$  denotes the noise power density [2]. Rayleigh fading is

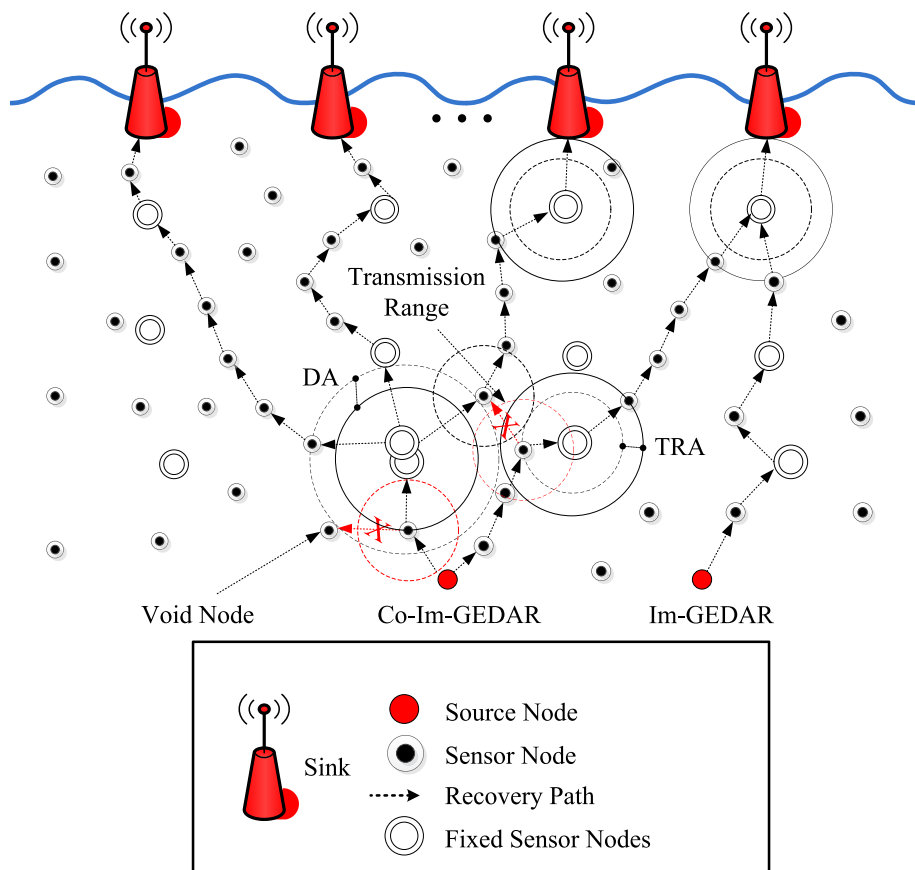


FIGURE 2. Network architecture: Im-GEDAR and Co-Im-GEDAR.

used for small-scale modeling. The purpose of using Rayleigh fading is to find out the dominant signal in case of multipath fading. Like [28], the probability distribution of SNR is given by:

$$p_d(\beta) = \int_0^\infty \frac{e^{-\frac{\beta}{\gamma(d)}}}{\Upsilon(d)} \cdot \quad (4)$$

Also, the probability of the error [2] is given as:

$$p_e(d) = \int_0^\infty p_e(\beta)p_d(\beta)d\beta. \quad (5)$$

where,  $p_e(\beta)$  is used to represent the error probability for a random modulation using a specific value of SNR  $\beta$ . BPSK modulation is widely adopted in [29], [30]. In BPSK, a bit is carried by each symbol. The bit error probability with distance  $d$  is calculated as [30]:

$$p_e(d) = \frac{1}{2} \left( 1 - \sqrt{\frac{\Upsilon(d)}{1 + \Upsilon(d)}} \right). \quad (6)$$

The PDR probability for  $m$  bits data transmitted is given by:

$$p(d, m) = (1 - p_e(d))^m. \quad (7)$$

The proposed work forwards the data in two phases. In first phase, periodic beaconing is used for localization. In second

phase, the neighbors selection strategy is used to find neighbor nodes in order to deliver the data towards sonobuoys. Afterwards, each protocol follows void node recovery phenomenon which is described in sections below.

### B. PERIODIC BEACONING

This section deals with periodic beaconing, as in [2]. Each sonobuoy at the water surface is equipped with Global Positioning System (GPS) and uses the periodic beaconing (beacon after a specific time interval) to know the location information of underwater sensors. A beacon message is transmitted by sonobuoys to inform the unique sequence number, their identity and their X, Y, Z location to every other sonobuoy. A beacon message transmitted by the sensor nodes contains information about their sequence number, ID and X, Y, Z location. We suppose that each underwater sensor node identifies its location. The location of the neighbors is known via periodic beaconing. As GPS is negligible in underwater due to high-frequency signal absorption. Therefore, each node locates its information using localization services [2]. Avoiding the long size of the beacon message a sensor node only includes the position information of the known sonobuoy [2]. Whenever a new beacon message is received by a node from the sonobuoy then that node updates

its entry in the neighboring table of sonobuoy set  $S_s$ . Beaconing algorithm is already discussed in [2], where each node broadcasts a beacon message to communicates with other nodes to advise its location. This information helps neighbor nodes to select possible forwarder nodes of all reachable sonobuoys.

### C. NEIGHBOR NODES SET SELECTION STRATEGY

Neighbor candidate selection in Im-GEDAR and Co-Im-GEDAR is based on the previously adopted mechanism [2]. Let  $n_i$  is the node that wants to transmit the DP. The selection of neighbors is based on packet ADVancement (ADV) value [2] and [31]. For given set of neighbor nodes  $N_s$  and the known sonobuoys set  $S_s$ , the ADV is used to find neighbors that are capable to forward the DP towards the nearest sink. ADV is defined as the difference in distance between the source  $n_s$  and destination node  $n_d$  and the distance between the neighbor node  $n_n$  and destination node  $n_d$ . Neighbor candidate set can be written as [2]:

$$C_i = \{n_k \in N_s : \exists s_v \in S_s \mid D(n_i, s_i^*) - D(n_k, s_v) > 0\}, \quad (8)$$

whereas,  $n_k$  is the neighbor set node,  $s_i$  belongs to set of closest sonobuoy of node  $n_i$  which is given as:

$$s_i^* = \operatorname{argmin}_{s_j \in S_s} \{D(n_i, s_j)\}. \quad (9)$$

### D. HOW TO DISCOVER THE VOID HOLE?

A void hole is a zone inside the network vicinity, where a node is unable to locate its forwarder neighbor node to whom it can pass the received packet. The reasons for void hole occurrence are: no potential forwarder node found (with higher depth than the current source node) and dead node occurrence. Therefore in this work, two routing protocols are proposed to minimize the void node occurrence through TRA and DA.

### E. GREEDY FORWARDING STRATEGY FOR NEIGHBOR SELECTION IN Im-GEDAR AND Co-Im-GEDAR

In both proposed routing protocols, void holes are minimized using fixed nodes deployment at different strategic locations in the UWSN (using backup nodes concept). At this end, following steps are performed to minimize the EC and probability of void hole occurrence.

- Firstly, Im-GEDAR tries to alleviate the void hole using these fixed nodes. If void node still exists then small horizontal mobility of the current node is performed to remove the void hole,
- in contrary, when Im-GEDAR fails to find the next forwarder node (maybe a simple sensor node or fixed node) then Co-Im-GEDAR introduces the concept of TRA
- the TRA of the void node helps the routing protocol to find the forwarded node to resume the greedy forwarding among the nodes,
- afterward, Co-Im-GEDAR checks immediate forwarder nodes for the next forwarder,

- if void node still not finds the next forwarder node then fixed nodes first performs their TRA to receive a DP from the current source node and
- in the end, if a void node still exists, then fixed nodes adjust their depth to remove the void node (because of their high energy).

### F. FEASIBILITY OF THE FIXED NODES

The mechanism of DA in GEDAR avoids the void region; however, it performs immutable forwarder nodes selection resulting in high EC. Therefore, the strategic deployment of fixed nodes is adopted in the proposed protocols to minimize number of transmissions and to cover the whole network field.

In the proposed methodology, the backup nodes (fixed nodes) play a dynamic role in route establishment (most importantly during sparse regions) and dynamically adjust their positions based on the topology of the sensors. Firstly, TRA is performed to reduce the probability of the void node and to overcome the dynamically changing network topology. Secondly, DA is performed in order to minimize the aforementioned issues and to provide efficient data delivery. Thirdly, fixed nodes assure the maximum monitoring of the network field.

we consider that, as in [32], sensor nodes are static (no movement due to currents or water waves). In our harsh UWSN, the fixed nodes are conveyed for the following reasons.

- To cover the maximum range of the UWSN,
- to minimize the retransmissions in UWSN and
- to increase the PDR with affordable E2E delay.

Furthermore, paper [32] shows the feasibility of the fixed nodes in terms of high number of transmitted data packets with increased PDR. By getting motivation from aforementioned literature, we deployed 9 fixed nodes at each layer.

### G. STRATEGY FOR FIXED NODES DEPLOYMENT IN Im-GEDAR AND Co-Im-GEDAR

In this subsection, the strategy for fixed nodes deployment for the proposed protocols is discussed. Firstly, we divide the network into 6 equal hidden layers. Then at each layer, after a specific interval (usually of 150 m), 9 fixed nodes are deployed. These fixed nodes have higher energy than other ordinary sensor nodes. The reason for fixed nodes deployment is to reduce the probability of void hole occurrence in the network. Further, the E2E delay of the packet per node is minimized and PDR of the network is enhanced (using minimum EC).

### H. FORWARDING ALGORITHM FOR THE PROPOSED PROTOCOLS

In this algorithm, firstly, sensors, fixed and sink nodes are deployed in the network vicinity. Then neighbors selection is performed. Afterward, in range sink nodes are selected. Further, void nodes in the network are checked. If the sink

TABLE 2. Difference between Im-GEDAR and Co-Im-GEDAR.

GEDAR	Im-GEDAR	Co-Im-GEDAR
GEographic and opportunistic routing with DA based topology control for communication recovery	Improved geographic and opportunistic routing for communication recovery	Co-Improved geographic and opportunistic routing for communication recovery
No backup or fixed nodes concept at different strategic locations	Backup or fixed nodes at different strategic locations with only DA capabilities to receive the DPs	Backup or fixed nodes at different strategic locations with both DA and TRA capabilities to receive the DPs
<b>Methodology:</b>	<b>Methodology:</b>	<b>Methodology:</b>
<ul style="list-style-type: none"> <li>Several DAs to avoid void node</li> </ul>	<ul style="list-style-type: none"> <li>Alleviation of void node via DA of the ordinary sensor node to forward the DPs and</li> <li>afterwards, DA of the fixed nodes, if needed</li> </ul>	<ul style="list-style-type: none"> <li>Alleviation of void node via DA of the ordinary sensor node to forward the DPs,</li> <li>afterwards, DA of the fixed nodes is performed, if needed,</li> <li>check for the immediate forwarder node, if void node still exists,</li> <li>firstly, TRA of the ordinary sensor node takes place to resume the greedy forwarding,</li> <li>afterwards, the TRA of the fixed nodes take place to receive DP from the current forwarder and</li> <li>if still no forwarder found, then DA of the fixed node is opted to alleviate the void node, as it consumes high energy than TRA</li> </ul>
Immutable forwarder nodes selection	Less immutable forwarder nodes selection than GEDAR	No immutable forwarder nodes selection than GEDAR and Im-GEDAR
No concept of layers	Layering concept for positioning of fixed nodes	Layering concept for positioning of fixed nodes
High probability of void nodes occurrence	Almost 45.95% decrease in probability of void nodes occurrence than GEDAR	Almost 60% decrease in probability of void nodes occurrence than Im-GEDAR
Low PDR	Almost 74.19% increase in PDR than GEDAR	Almost 22.58% increase in PDR than Im-GEDAR
High EC	Efficient EC than GEDAR	Efficient EC than Im-GEDAR
Greater number of void nodes	Less than GEDAR	Less than Im-GEDAR
E2E Delay	Higher than GEDAR	Higher than GEDAR; however, less than Im-GEDAR

is found in the vicinity of the current forwarder node then the packet is delivered to the sink. Otherwise, the current forwarder checks the fixed node in its vicinity. If no fixed node found in its vicinity then small horizontal mobility of node is performed to remove the void hole and then next forwarder node is elected to continue the greedy forwarding.

In contrary, when Im-GEDAR fails to find the next forwarder node (maybe a simple sensor node or fixed node) then Co-Im-GEDAR introduces the concept of TRA. Afterwards, Co-Im-GEDAR checks immediate forwarder nodes for the next forwarder. If void node still not finds the next forwarder node then fixed nodes first performs their TRA to receive a DP from the current source node. In the end, if a void node still exists, then fixed nodes adjust their depth to remove the void node. The difference between GEDAR, Im-GEDAR and Co-Im-GEDAR is given in Table 2.

### V. FEASIBLE REGIONS OF PROPOSED PROTOCOLS FOR ENERGY MINIMIZATION

We define feasible region as a set of all the possible solutions to an objective function regarding defined constrains, i.e., maximize  $(a^2 + b^2)$  concerning (a, b), where, variable a and b must satisfy the following limits:  $1 \leq a \leq 9$  and  $5 \leq b \leq 10$ . In this section, a linear programming based mathematical formulation is performed to check the feasibility of the proposed protocols. Therefore, to achieve the objective function, we define some constraints. Using these constraints, the coordinates of the feasible regions for the proposed protocols are calculated. The objective function for minimizing the EC is defined as:

$$\text{minimize } \sum_{r=1}^{r_{max}} EC(r) \quad \forall r \in r_{max}, \tag{10}$$



where,

$$EC(r, N) = \frac{E_{total}(r, N)}{N \times Energy} \quad \forall r \in r_{max}. \quad (11)$$

Considering Im-GEDAR, where nodes are capable to receive the data from other nodes and transmit it towards sink. From Eq. (11),  $N$  denotes the number of nodes,  $E_{total}$  is the total energy dissipated by nodes in a round  $r$  as in Eq. (12), i.e.,

$$E_{total}(r) = E_o - sum(E_{consumed}), \quad (12)$$

where,  $E_{consumed}$  denotes the consumed energy and it is calculated as:

$$E_{consumed} = \sum_{r=1}^{r=r_{max}} \sum_{n=1}^{n=N} E_{tx}^n(r) + E_{rcv}^n(r) \quad \forall r \in r_{max}, \quad (13)$$

In the above mentioned equation  $r_{max}$  shows the maximum number of rounds. Also from Eq. (13),

$$E_{tx}^n(r) = \left( P_{tx}^n \frac{Packet_{size}}{Data_{rate}} \right) \times N. \quad (14)$$

From Eq. (14),  $E_{tx}$  is the EC during data transmission,  $P_{tx}$  denotes the transmission power and  $N$  is total number of nodes in UWSN.

$$E_{rcv}^n(r) = \sum_{n=1}^{n=N} \left( P_{rcv}^n \frac{Packet_{size}}{Data_{rate}} \right) \times N. \quad (15)$$

From Eq. (15),  $E_{rcv}$  and  $P_{rcv}$  denote the receiving energy and power, respectively. The objective is to minimize  $E_{consumed}$ , i.e., the total energy dissipation is minimized in order to reduce EC. Restrictions followed by the objective function are given in the following constraints.

**Constraints:**

$$C_1 : E_{tx}^n, E_{rcv}^n \leq Initial\ energy\ (E_o) \quad \forall n \in N, \quad (16)$$

$$C_2 : E_{tx}^n + E_{rcv}^n \leq E_o \quad \forall n \in N, \quad (17)$$

$$C_3 : Trx_n \leq Trx_n^{max} \quad \forall n \in N. \quad (18)$$

The purpose of Eq. (16) is to limit the energy dissipation within the available energy provided to a node. Constraint regarding the selection of the forwarder node in Eq. (17) shows that the total EC during DP transmission and reception must be less than the initial energy of the node. In the end, to receive a quality signal, the data should be delivered within its transmission range as given in Eq. (18). Whereas,  $Trx_n$  denotes required transmission rate and  $Trx_n^{max}$  denotes maximum transmission range.

**A. GRAPHICAL ANALYSIS (Im-GEDAR)**

To give a reasonable perception of the problem, graphical analysis of Im-GEDAR is presented to compute the feasible region. Assuming  $Packet_{size} = 100$  bytes,  $Data_{rate} = 16$  kbps,  $P_{tx} = \{0.4, 0.8, \dots, 2\}$ ,  $P_{rcv} = \{0.2, 0.4, \dots, 1\}$  and  $N = \{150, 200, \dots, 450\}$ , we compute feasible solution for energy minimization. From the aforementioned parameters, the following values are extracted:

$$0.026 \leq E_{tx} \leq 0.13 \quad (19)$$

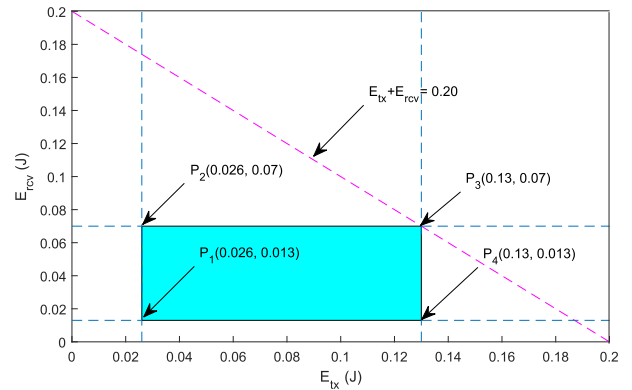


FIGURE 3. Feasible region: EC (Im-GEDAR).

$$0.013 \leq E_{rcv} \leq 0.07 \quad (20)$$

$$0.13 \leq E_{tx} + E_{rcv} \leq 0.20 \quad (21)$$

A feasible region is plotted as shown in Figure 3, keeping in mind the constraints from Eq. (16-18) and the points from Eq. (19-21). An optimal solution is approved from the given points:

$$P_1(0.026, 0.013) = 0.039\ J,$$

$$P_2(0.026, 0.07) = 0.096\ J,$$

$$P_3(0.13, 0.07) = 0.20\ J \quad \text{and}$$

$$P_4(0.13, 0.013) = 0.143\ J.$$

Hence, the above points validate an optimal solution and the EC within the bounded region in order to enhance the performance of the network. Whereas, the energy consumed during the data transmission towards static sonobuoy at time  $t_s$  is given in Eq. (22) as:

$$E_{tx} = P_{tx} t_s, \quad (22)$$

where, from Eq. (22),  $P_{tx}$  is the transmission power,  $t_s$  is the moving time of a mobile sonobuoy. We can find  $t_s$  as:

$$t_s = \frac{TS_{range}}{v}, \quad (23)$$

where,  $v$  denotes the speed of acoustic link and  $TS_{range}$  is the transmission range of sink. Receiving energy for sonobuoy set is denoted as:

$$E_{rcv} = P_{rcv} t_s, \quad (24)$$

$P_{rcv}$  is the receiving power.

**B. GRAPHICAL ANALYSIS (Co-Im-GEDAR)**

Considering  $v = 1500$  m/s,  $P_{tx} = \{0.4, 0.8, \dots, 2\}$ ,  $P_{rcv} = \{0.2, 0.4, \dots, 1\}$ , the calculated energy points are given as:

$$0.026 \leq E_{tx} \leq 0.13 \quad (25)$$

$$0.013 \leq E_{rcv} \leq 0.10 \quad (26)$$

$$0.13 \leq E_{tx} + E_{rcv} \leq 0.23 \quad (27)$$

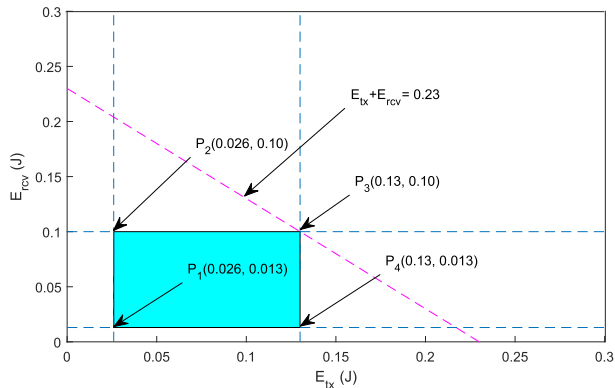


FIGURE 4. Feasible region: EC (Co-Im-GEDAR).

Feasible region is given in Figure 4 via points computed by using Eq. (25-27) and the points are:

$$\begin{aligned}
 P_1(0.026, 0.013) &= 0.039 \text{ J,} \\
 P_2(0.026, 0.10) &= 0.126 \text{ J,} \\
 P_3(0.13, 0.10) &= 0.23 \text{ J and} \\
 P_4(0.13, 0.013) &= 0.143 \text{ J.}
 \end{aligned}$$

An optimal solution is validated from these feasible points. The values on the boundary of the bounded region results in minimum EC of the network.

## VI. SIMULATION AND RESULTS

In this section, Im-GEDAR and Co-Im-GEDAR are evaluated by performing extensive simulations for benchmark routing protocols (GEDAR, WDFAD-DBR, NADEEM, FA-NADEEM and TA-NADEEM). In this work, our main focus is to maximize the network lifespan, efficient energy utilization, void hole avoidance and maximization of PDR. These performance parameters are computed using the average percentage difference with existing routing protocols.

### A. SIMULATION PARAMETERS

Proposed protocols are implemented in Matlab. The transmission area of the network is kept  $1500 \text{ m} \times 1500 \text{ m} \times 1500 \text{ m}$  and the transmission range of each node is kept 250 m. The number of sensor nodes varies from 150 to 450. The number of static sonobuoys is 45. Furthermore, the data rate and the payload are kept 16 kbps and 100 bytes, respectively. The values for idle, reception and transmission energies are 0.01 W, 0.1 W and 2 W, respectively [2]. Table. 3 also lists the simulation parameters for the proposed routing protocols.

### B. EC

The EC of the baseline and proposed routing protocols is shown in Figure 5. It is clearly shown in the figure that TA-NADEEM and Co-Im-GEDAR perform efficient EC than proposed and baseline routing protocols. The reason for efficient EC in TA-NADEEM is that it only requires energy in power adjustment and factors like message exchange and DA

TABLE 3. Simulation parameters.

Simulation Parameters	Values
Network volume ( $\text{m}^3$ )	$1500 \times 1500 \times 1500$
Transmission range of nodes (m)	250
Nodes	150-450
Fixed nodes	54
Static sonobuoys	45
V (m/s)	1500
Data rate (kbps)	16
Payload (bytes)	100
Frequency (kHz)	10
Idle power (W)	0.01
Receiving power (W)	0.1
Transmission power (W)	2

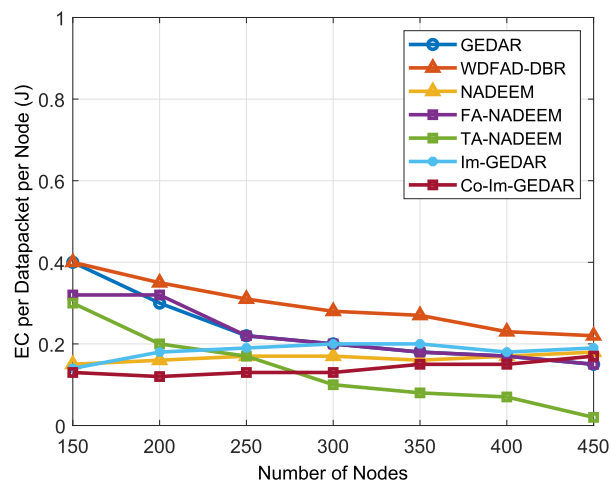


FIGURE 5. EC.

are not involved. The key reason for higher EC in Co-Im-GEDAR than TA-NADEEM is its strategy to alleviate the void hole using fixed nodes. For example, when Im-GEDAR fails to find the next forwarder node then Co-Im-GEDAR introduces the concept of TRA of the void node to find the forwarded node to resume the greedy forwarding among the nodes. Afterward, Co-Im-GEDAR checks immediate forwarder nodes for the next potential forwarder. If void node still not finds the next potential forwarder node then fixed node first performs its TRA to receive a DP from the current source node. In the end, if a void node still exists, then fixed node performs DA to remove the void node. While the reasons for high EC in baseline protocols (i.e., GEDAR, WDFAD-DBR, NADEEM and FA-NADEEM) are: successive DAs and the energy wastage in alternative routes selection. Moreover, in GEDAR, the EC on immutable forwarder nodes create a great impact on energy dissipation. Meanwhile, the void node moves from one location to another location resulting in several DAs, which increases the EC of the nodes. Furthermore, in WDFAD-DBR, the EC on 2-hop neighbors information, depth of the current node and next expected forwarder node

consume high energy. Comparative analysis shows that proposed routing protocol (Co-Im-GEDAR) minimizes EC than GEDAR, WDFAD-DBR, NADEEM and FA-NADEEM.

C. PDR

Figure 6 illustrates the PDR of baseline and proposed routing protocols. It can be observed from the figure that proposed routing protocols (Im-GEDAR and Co-Im-GEDAR) have high PDR than baseline routing protocols. The reasons for high PDR is the fixed nodes deployment. These fixed nodes provide alternative paths to the DPs by avoiding the void hole problem. Due to which these packets are successfully transmitted towards the destined sink. Additionally, the fraction of packet drop in the void region reduces.

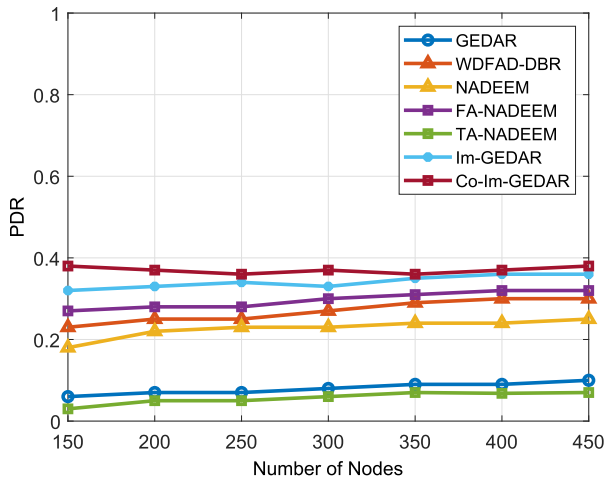


FIGURE 6. PDR.

In contrary, the PDR of the GEDAR is lower than NADEEM, FA-NADEEM and proposed routing protocols because in GEDAR, immutable forwarder node selection leads the network towards the void hole. Therefore, GEDAR implements the concept of DA. At this end, the void hole is moved to new depth to continue the data forwarding. However, this movement of void node results in excessive DAs. The strategy dissipates the network energy even more quicker resulting in a void hole at a new location. Whereas, FA-NADEEM has higher PDR than NADEEM and TA-NADEEM because FA-NADEEM has the ability to provide alternative paths in its vicinity.

On the other hand, the PDR of TA-NADEEM is lower than all aforementioned routing protocols because TA-NADEEM performs TRA. Moreover, TRA needs power adjustment and power adjustment requires high EC. Whereas, the EC depends on distance (from the current source node to the next potential forwarder node in its vicinity). Therefore, the network faces the problems of attenuation and channel fading which ultimately reduce the PDR. Similarly, the PDR of WDFAD-DBR is lower than FA-NADEEM because it only considers the data transmission up to 2-hop neighbor nodes, which is not sufficient to eliminate the void hole occurrence from the network. In WDFAD-DBR, after the 2-hops,

a void node may occur that may result in packet drop, which decreases the PDR. On the other side, PDR is higher than NADEEM because of its better neighbors selection strategy and holding time to avoid the redundant transmissions, which enables the WDFAD-DBR towards better network lifetime and improved PDR than NADEEM.

It is clear from the figure that when the network is sparse, i.e., varies from 150 to 350 number of nodes, PDR shows a decreasing trend. The reason for this decreasing trend is the limited number of nodes in each layer (this limitation is due to random deployment of nodes in each layer). As the number of nodes increases, i.e., from 350 to 450, so each layer possesses enough number of nodes to forward the data packets, which increase the performance of the network. Comparative analysis shows that proposed routing protocols achieved 80-81% higher PDR than benchmark routing protocol (GEDAR) and on average 30-40% compared to other benchmark routing protocols.

D. FRACTION OF VOID NODES

Figure 7 presents the fraction of void node for the proposed routing protocols against GEDAR, WDFAD-DBR, NADEEM and its variants. It is obvious from the figure that all the routing protocols behave in the same manner and the fraction of the void node decreases with increase in nodes' density.

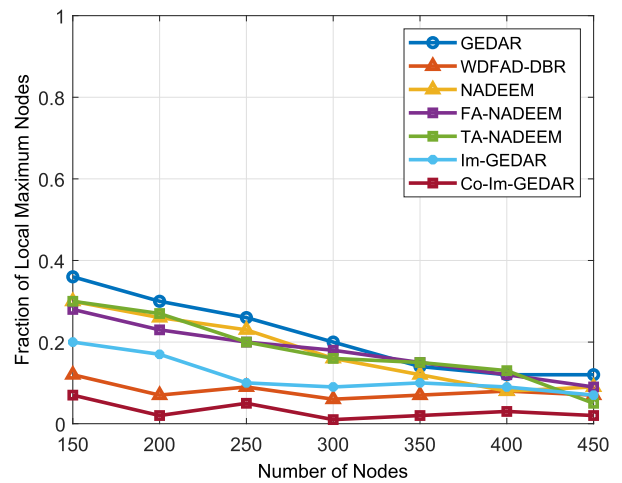


FIGURE 7. Fraction of void nodes.

At the start of transmission, the FA-NADEEM has the highest failure ratio which continuously degrades until the node density becomes equal to 250. Then after a small increase, it degrades again. Whereas, TA-NADEEM and GEDAR show similar behavior during communication. As GEDAR does not consider the availability of the neighbor nodes in its vicinity to elect the forwarder node. In return, it has a high fraction of void nodes.

Where, WDFAD-DBR has low probability of void nodes occurrence than all benchmark routing protocols namely: GEDAR, WDFAD-DBR, NADEEM and its variants; however, higher than Co-Im-GEDAR because of its better

TABLE 4. Performance trade off.

Protocols	Features	Achieved Parameters	Compromised Parameters
GEDAR [2]	Geographic routing with DA to avoid the void holes	Network performance is enhanced in terms of PDR	High EC and void hole occurrence with low E2E delay
NADEEM [6]	Geographic and opportunistic routing using backward transmission	Performance of the network is enhanced with enhanced PDR	High propagation distance
FA-NADEEM [6]	Geographic and opportunistic routing using collision avoidance	Performance of the network is increased in terms of PDR	Low throughput
TA-NADEEM [6]	Geographic and opportunistic routing with TRAs	PDR of the network is increased	High EC when the network becomes sparse
DBR [7]	DAs to avoid the void holes	Network performance is enhanced in terms of PDR	High EC and void holes occurrence with high E2E delay
Im-GEDAR	Improved geographic and opportunistic routing to avoid the probability of void holes occurrence	Fraction of void node is decreased with enhanced PDR	High E2E delay and PDR with minimum probability of void hole occurrence
Co-Im-GEDAR	Improved geographic and opportunistic routing to avoid the probability of void holes occurrence	Fraction of void node is decreased with enhanced PDR	High E2E delay and PDR with minimum probability of void hole occurrence

neighbors selection strategy and holding time. This strategy helps the WDFAD-DBR to avoid the redundant transmissions and enables the WDFAD-DBR for better network lifetime than Co-Im-GEDAR.

The fraction of void node occurrence of the proposed routing protocols (Im-GEDAR and Co-Im-GEDAR) is minimum than all baseline routing protocols. The main reason of minimum void hole occurrence is fixed nodes deployment at different strategic locations. These nodes provide the network with alternative paths. Due to which the probability of void hole occurrence decreases and overall performance of the network increases. Figure 7 clearly validates that proposed routing protocols minimized the void hole occurrence upto 30% approximately.

E. E2E DELAY

The E2E delay of the proposed routing protocols against baseline routing protocols is shown in Figure 8. It is observed that the proposed routing protocols (Im-GEDAR and Co-Im-GEDAR) have less E2E delay than NADEEM; however, high E2E delay than GEDAR, FA-NADEEM and TA-NADEEM. The main reason for this high E2E delay is high nodes density. As number of nodes increases the collision between the packets increases which results in number of retransmission. In addition, protocol faces several DAs.

In contrary, the E2E delay of GEDAR, FA-NADEEM and TA-NADEEM is less than NADEEM, WDFAD-DBR, Im-GEDAR and Co-Im-GEDAR. The reason for this minimum E2E delay in GEDAR is due to the following two reasons: its opportunistic routing and its DA strategy. These strategies minimize the void hole occurrence. However, the network

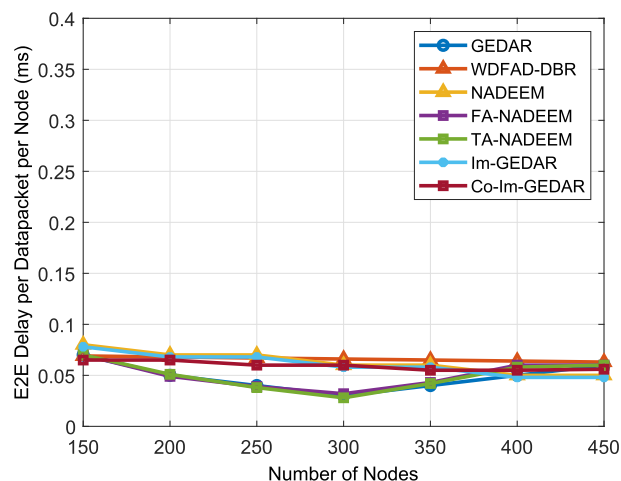


FIGURE 8. E2E delay.

causes high energy dissipation (on these DAs). Meanwhile, in FA-NADEEM and TA-NADEEM, only fallback and TRA based routing strategies are implemented. These aforementioned strategies take less computational time as compared to the proposed ones. As a result, proposed routing protocols face a bit higher E2E delay. Furthermore, in WDFAD-DBR, the E2E delay is almost higher than all benchmark routing protocols because of its holding time to avoid the redundant transmissions, which enables the WDFAD-DBR towards better network lifetime and improved PDR.

F. PERFORMANCE TRADE-OFF

In this subsection, trade off between proposed protocols and existing baseline protocols is discussed. The proposed

protocols overcome the problem of void node occurrence with enhanced PDR and high E2E delay. Here, the probability of void node occurrence is minimized by deploying the fixed backup nodes. However, the baseline routing protocol GEDAR minimizes the void hole occurrence with high EC and E2E delay.

In contrary, the baseline protocols (including NADEEM, FA-NADEEM and TA-NADEEM) minimize the void hole occurrence with enhanced PDR. FA-NADEEM selects the neighbors with minimum neighbor nodes and low throughput. Further, TA-NADEEM minimizes the void hole occurrence using TRAs; however, causes high energy dissipation. Performance trade off between the compromised parameters is shown in Table 4.

## VII. CONCLUSION AND FUTURE WORK

In this paper, Im-GEDAR and Co-Im-GEDAR routing protocols are proposed. Meanwhile, comparative analysis is performed with the baseline protocols namely: GEDAR, WDFAD-DBR, NADEEM, FA-NADEEM and TA-NADEEM. At this end, proposed routing protocols achieved almost 80-81% higher PDR than benchmark routing protocols (GEDAR and TA-NADEEM). In addition, probability of void hole occurrence is minimized upto 30% approximately (by avoiding the immutable nodes selection). Moreover, a mathematical formulation is performed using linear programming, which checks the feasibility of the proposed routing protocols. Furthermore, the scalability of the proposed routing protocols is also analyzed by varying the number of nodes from 150-450. Simulation results clearly show that proposed routing protocols outperformed the baseline routing protocols are compared to its counterpart schemes.

In the future, some metaheuristic techniques will be implemented to minimize the E2E delay and to maximize the network throughput.

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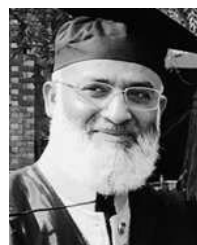
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