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Region Aware Proactive Routing Approaches Exploiting Energy Efficient Paths for Void Hole Avoidance in Underwater WSNs

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ABSTRACT Nowadays, constrained battery life expectancy is an important issue for reliable data delivery in an Underwater Wireless Sensor Network (UWSN). Conventional transmission methodologies increase the transmission overhead, i.e., the collision of packets, which influence the data transmission. Replacement of the sensors' battery in brutal underwater environment is a difficult task. Therefore, to maintain a strategic distance from the unexpected failure of the network and to increase the life expectancy of the network, energy efficient routing protocols are required. At this end, in this paper, a proactive routing protocol with three different network types is proposed to solve the aforementioned issues. The proposed protocol adaptively changes its communication strategy depending on the type of the network, i.e., dense network, partially dense network and sparse network. This adaptive strategy helps the routing protocols to continue their transmission by avoiding the void holes. In the proposed protocol named Proactive routing Approach with Energy efficient Path Selection (PA-EPS-Case I), vertical inter-transmission layering concept is introduced (using shortest and fastest path) in the dense and partially dense region. In addition, cluster formation concept is also appended to make transmission successful in the sparse regions. The Packet Delivery Ratio (PDR) is improved by the proposed protocol with minimum End to End (E2E) delay and packet drop ratio. Scalability of the proposed routing protocols is also analyzed by varying the number of nodes from 100-500. A comparative analysis is performed with two cutting edge routing protocols namely: Weighting Depth and Forwarding Area Division Depth Based Routing (WDFAD-DBR) and Cluster-based WDFAD-DBR (C-DBR). Simulation results demonstrate that proposed protocol achieved 12.64% higher PDR with 20% decrease in E2E delay than C-DBR. Furthermore, the proposed routing protocol outperformed C-DBR in terms of packet drop ratio up to 14.29% with an increase of EC up to 30%.

INDEX TERMS Underwater wireless sensor networks, adaptive transmission, void hole, geographic and opportunistic routing, mobility prediction.

I. INTRODUCTION

Nowadays, advancement in Underwater Wireless Sensor Network (UWSN) roused researchers to improve different applications in the scientific era. For example, data collection and disaster's inhibition [1]–[4]. Moreover in UWSNs, during the long transmission, acoustic waves are favored rather than radio waves due to their low dispersion rate. In addition, dynamic environmental changes, the restricted life expectancy of the sensors and high End to End (E2E) delay are the unfavorable features in UWSN [5]–[7]. For this purpose, multi-hop routing protocols are preferred. These promising strategies limit the Energy Consumption (EC) with reasonable E2E delay. Furthermore, these protocols help in many other underwater applications, i.e., temperature and environmental data gathering. Therefore, researchers focused on Transmission Range Adjustment (TRA) to transmit the packet successfully with minimum EC [8]. Similarly,

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Balanced Energy Adaptive Routing (BEAR) convention is proposed to balance the EC of the sensor node [9]. However, constrained battery life expectancy is a difficult task in UWSN. At this end, it is extremely hard for sensors to use solar-powered chargers since daylight is unable to reach the bottom of the sea. In this way, these protocols still need to be improved as sensors are vulnerable against seawater erosion and marine creatures' activities. As a result, underwater environment faces some serious issues, i.e., high EC due to void hole occurrence and transmission overheads with limited bandwidth.

As in UWSN, deployment of sensor nodes is categorized in two ways: dense deployment and sparse deployment. Dense deployment of sensor nodes leads the network towards sudden failures, i.e., due to several collisions and high EC. Meanwhile, sparse deployment results in a void hole or energy hole creation (when current forwarder node has no potential forwarder node in its communication range). The void hole occurs because of two main reasons: no forwarder node in its transmission range and due to dead node occurrence. In this regard, the network's stability is an important metric to keep the transmission process continuous. As EC has a direct impact on network's stability, therefore it is expected that after the sensor nodes deployment, network remains stable for a particular period of time. In addition, optimal route selection is also an important parameter because high EC and void hole creation lead the network towards sudden degradation.

Therefore, energy efficient path selection is also considered as an important parameter to design a routing protocol. In this regards, many routing protocols are proposed for efficient path selection [10]–[18]. Although, researchers find some hot spots in the aforementioned protocols. These hot spots deplete the energy of the network at their earliest (due to void hole occurrence and inefficient data delivery). At this end, these routing protocols induce great impact on EC, Packet Delivery Ratio (PDR), packet drop ratio and E2E delay. Thus, these routing protocols still need to be improved.

Let us consider a routing protocol named Weighting Depth and Forwarding Area Division Depth Based Routing (WDFAD-DBR) [19]. In this routing protocol, the next forwarder node is selected using 2-hop neighbors information and depth of the nodes from the sea surface. The probability of void hole occurrence is efficiently reduced in WDFAD-DBR. However, the probability of void hole occurrence still exists as shown in Fig. 1. In this figure, the node C has three forwarder nodes: A, B and E. The node C selects the node E as its next forwarder node because the node E has a neighbor node at its first hop. However, the node E has no information regarding the first hop neighbors of the node D. Meanwhile, the node D has no forwarder node in its transmission range. Therefore, the node D designates as void node (with no forwarder node). Thus, it is concluded that void hole problem is reduced in the aforementioned paper. However, the extra power is required to overcome the void hole problem. Consequently, in this paper, the probability

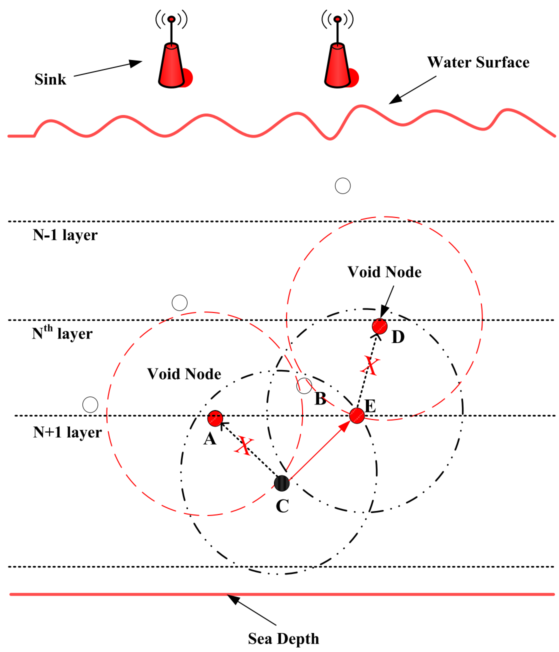

FIGURE 1. Problem of Void Hole Generation in WDFAD-DBR.

of void hole occurrence and E2E delay minimization with enhanced PDR are the key concerns. To overcome the aforementioned issues, a proactive routing protocol with three different network types is proposed to solve the aforementioned problems. The proposed protocol adaptively changes its communication strategy depending on type of the network, i.e., dense network, partially dense network and sparse network. This adaptive strategy helps the routing protocol to continue its transmission. Proposed clustering strategy makes clusters when the network becomes sparse as shown in Fig. 2 in [8]. In this figure, Cluster Heads (CHs) are selected using Dijkstra's algorithm and then cluster members pass the data packets to their respective CH. Afterwards, the CHs passe the data packet to their forwarder CHs and data reaches the destination. This strategy minimizes the E2E delay and packet drop ratio.

In the proposed routing protocol, the lifespan of nodes' battery is enhanced as compared to state-of-the-art routing protocols [8], i.e., WDFAD-DBR [19] and Cluster-based WDFAD-DBR (C-DBR) [8]. As a result, the overall performance of the system is enhanced.

In this paper, a proactive routing protocol with three different network types is proposed. So, the contributions of this work are:

1) the proposed protocol adaptively changes its communication strategy depending on the type of the network, i.e., dense network, partially dense network and sparse network,
2) the void hole occurrence is minimized using vertical layering concept for dense and partially dense network and cluster formation for the sparse network

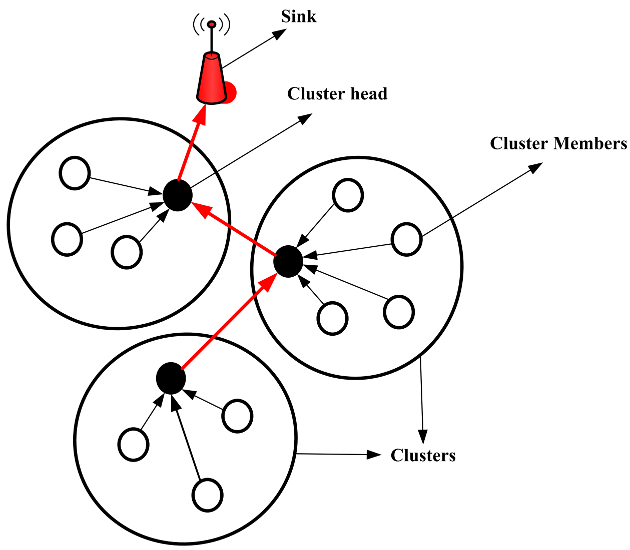

FIGURE 2. Cluster formation in proposed protocols.

3) the scalability of the proposed routing protocols is also analyzed by varying the number of nodes from 100-500 and
4) linear programming is used to compute feasible regions for the optimal EC and to maximize the throughput of the network.

Comparative analysis is also performed with state-of-the-art routing protocols. Results validate that PA-EPS-Case I outperformed in the counterparts. Whereas, baseline UWSN routing protocols are shown in Fig. 3.

The difference between benchmark protocols (i.e., WDFAD and C-DBR) and proposed protocol is shown in Table 4. Whereas in this table, the term adaptive is alternatively used for scenario dependent functionality of the proposed routing protocol, i.e., in PA-EPS-Case I, term adaptive means proposed routing protocol dynamically operates the network. The abbreviations and acronyms used in this work are given in Table 1 and Table 2, respectively.

Rest of the paper is set as: section II presents the literature review of the benchmark protocols. Then the problem statement for the proposed work is elaborated in section III. Afterward, the proposed system model is described in section IV. Furthermore, the mathematical formulation for the proposed work is performed in section V. Section VI validates the proposed routing protocol against benchmark routing protocols. Finally, section VII ends up with a conclusion and future work.

II. LITERATURE REVIEW

In this section, comparative analysis of the state-of-the-art routing protocols is performed. The detail is given below.

In paper [11], long term data forwarding mechanism is proposed in UWSNs. The proposed mechanism is centralized and completely controlled. The proposed routing protocol enhances the throughput of network by using energy efficient forwarding. In addition, protocol minimizes the probability of void hole occurrence at minimum EC. The network throughput is enhanced with high E2E delay. In paper [12], E2E delay, maximum network throughput and load balancing of the nodes are efficiently handled. The proposed routing protocol outperforms the aforementioned parameters with minimum E2E delay. The proposed protocol uses the mechanism of adaptive routing with any-casting routing procedure to balance the load. However, the dynamic environmental changes effect on EC is ignored.

A secure and energy efficient routing protocol is proposed in [13]. The proposed routing protocol adopts chaotic compressive sensing to secure the data packets. Meanwhile, exploits the sparsity of data to forward the data efficiently.

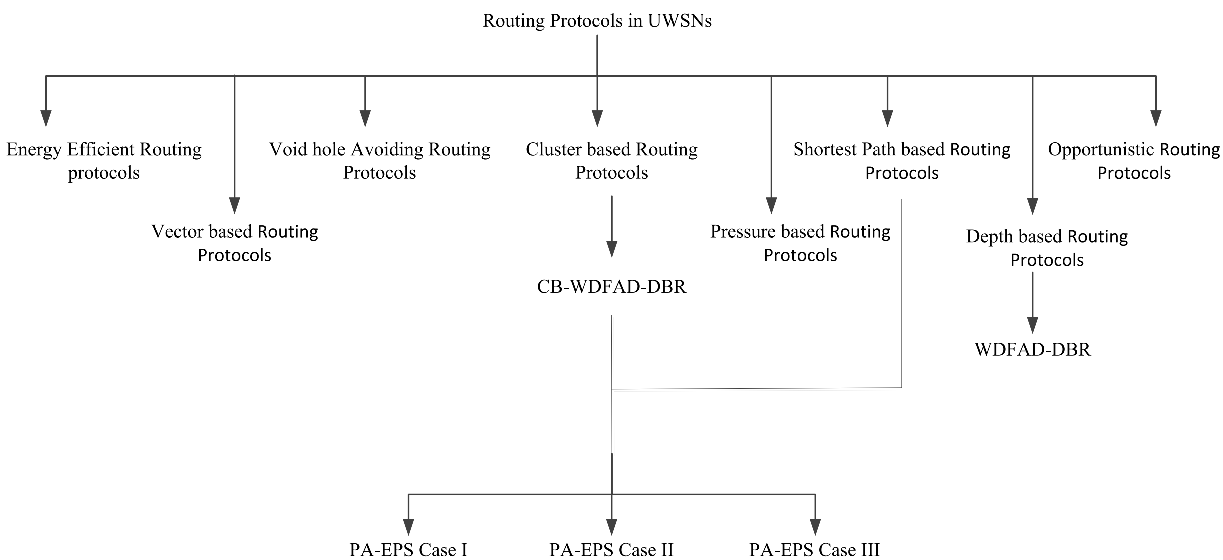

FIGURE 3. Routing protocols in UWSNs.

TABLE 1. Table of abbreviations.

Abbreviations	Descriptions
APD	Accumulated Propagation Distance
BEAR	Balanced Energy Adaptive Routing
BLOAD	Balanced LOAD
CH	Cluster Head
C-DBR	Cluster-based Weighting Depth and Forwarding Area Division Depth Based Routing
COA	Cuckoo Optimization Algorithm
DBR	Depth Base Routing
E2E	End to End
EC	Energy Consumption
EEL	Energy Efficient Location based geographic protocol
EULC	Energy balanced Unequal Layering Clustering
MRP	Multilayered Routing Protocol
PDR	Packet Delivery Ratio
PA-EPS	Proactive routing Approach with Energy efficient Path Selection
r	Rounds
SNR	Signal to Noise Ratio
TORA	Totally Opportunistic Routing Algorithm
TRA	Transmission range Adjustment
UWSN	Underwater Wireless Sensor Network
VBF	Vector Based Routing
WDFAD-DBR	Weighting Depth and Forwarding Area Division Depth Based Routing

TABLE 2. Table of acronyms.

Symbols	Definitions
δ	Amount of salt in water
$\alpha(f)$	Absorption coefficient
B_{Frwd}	Bandwidth for forwarding node
B_{NFrwd}	Bandwidth for non forwarding node
l	Distance
d	Depth of water
D_i	Directive index
DR	Data rate
E_{cons}	EC of the network
f	Frequency
H^n-PERP	Hop by hop power efficient routing protocol
$E_{initial}$	Initial energy of the nodes
$T_{rangemax}$	Maximum transmission range
r_{max}	Maximum Rounds
NL	Network lifespan
PS	Packet size
$R_p(f)$	Receiving power
$RSSI$	Received signal strength indicator
$RP-RSSI$	Received packet RSSI
E_{rec}	Receiving energy
$SS-RSSI$	RSSI of signals at sender
$E_{residual}$	Residual energy of the node
$N_s(f)$	Shipping noise
E_{trans}	Transmission energy
$N_{th}(f)$	Thermal noise
$T_p(f)$	Transmission power
τ	Temperature
η	Total transmission range of nodes in the network
D_p	Total range of data packets
T_{range}	Transmission range
$Total\ (Pkt_{sink})$	Total packets received at sink
$Total\ (Pkt_{source})$	Total number of packets generated by the source node
$Total\ Drop\ (Pkt_{sink})$	Total packets drop at sink
$Total\ (Pkt_{source})$	Total number of packets generated by the source node

The proposed routing protocol uses the shortest repeat strategy and random access method to handle the challenges in underwater complex environment. The network lifetime is prolonged by the proposed routing protocol. However, the network faces high EC. In [14], the cooperative and optimal relay selection protocol is proposed. The proposed routing protocol minimizes the EC and follows the acknowledgment message procedure after successful transmission. However, EC on dynamic topological changes is ignored. Similarly, in [15], the PDR and network throughput maximization are mainly focused. The proposed protocol uses the sink mobility information to increase the PDR. However, the network faces high E2E delay during sparse network field.

An energy efficient routing protocol is proposed in [16]. The proposed routing protocol is the combination of three techniques including: geo, multipath and duty cycle routing. The proposed protocol increases reliability in the data packets. However, topological changes in the network are not considered by the authors to provide energy efficient routing. In [17], an energy efficient routing protocol is proposed to avoid the void hole. The proposed protocol takes two important parameters into account: residual energy of the nodes and depth difference. In addition, 2-hop neighbors' information is used to avoid the void hole. As a result, PDR of the network is improved with minimum EC and enhanced throughput. However, effect of distance dependency on energy is not discussed.

Depth Base Routing (DBR) protocol is proposed in [18]. In this protocol, the local depth of the node is used to select the next forwarder node. The proposed routing protocol handles the dynamic topological changes efficiently without using localization services. Proposed routing protocol outperforms in minimizing the communication cost with high PDR. In [19], the DBR protocol is further enhanced to increase the PDR and EC. The proposed routing protocol selects the forwarder node using 2-hop neighbors' information. In addition, duplicate packets generation is minimized to reduce the EC of the nodes.

A cluster-based routing protocol is proposed in [20]. In this paper, CHs are elected using Dijkstra and breadth-first search routing algorithms. In both proposed routing protocols, all cluster members send their information to their respective CHs. As a result, data is transmitted towards the respective sink. PDR of the network is improved using high energy. In [21], two routing protocols are proposed to avoid the void hole. In its first routing protocol, 3-hop neighbors' information is used to avoid the void hole. In the second routing protocol, to minimize the EC using the shortest path, the efficient path is elected using 'Bellman-Ford' routing algorithm. Multilayered Routing Protocol (MRP) is proposed in [22]. MRP finds the efficient routing path and handles the EC efficiently by enhancing the network lifetime. Likewise, splice method is introduced in [22] for efficient data delivery. Energy effective transmission is performed using MRP; however, selection of single shortest path deplete that node's energy at its earliest, which is not discussed in [22].

A void hole avoidance based routing protocol is proposed in [23]. The proposed routing protocol is energy aware with layering and data collection phase. The proposed routing protocol uses opportunistic directional forwarding strategy to transmit the data from concentric layers. This strategy avoids the void hole using the residual energy information of the nodes. In addition, it avoids the cyclic flow of data packets. The proposed protocol minimizes the EC and E2E delay effectively. However, the sparse region affects network performance, significantly. In [24], cluster based energy efficient routing protocol is proposed. The proposed routing protocol prolongs the network lifetime using an event-driven energy efficient routing. Proposed protocol finds the shortest path to transmit the data packets with uniform EC. As a result, PDR of the network is improved. However, sparsity effect on EC is not addressed [24].

An energy efficient localization based geographic location based routing protocol is proposed in [25]. The residual energy of the nodes is considered to perform greedy forwarding of data towards the sink. The proposed protocol is adaptive with respect to dynamic topological changes (because it updates its location information periodically). Therefore, EC of the network is reduced by the proposed routing protocol with enhanced PDR. However, communication overhead is not discussed by the authors. Energy balanced and lifetime extended routing protocol is proposed in [26]. The proposed routing protocol balances the network load and optimizes the EC during data transmission. The network lifetime is also improved by the proposed routing protocol. Whereas, in [27], the layering and cluster-based routing protocol are proposed to balance the EC and to prolong the network lifetime. However, the EC on collision overhead is not discussed.

A reliable and energy efficient routing protocol is proposed [28]. The transmission phase of the protocol is based on local flooding with optimal nodes selection (using adaptive selection mechanism). The proposed protocol performs efficient in shallow water with minimum EC. Meanwhile, provides reliable data delivery. However, the distance dependency on energy is not focused. In [29], a cluster based energy efficient routing protocol is proposed. The proposed routing protocol adopts the fixed nodes deployment to perform reliable data delivery. It uses the bottom-to-top strategy to transmit the data towards the sink. In [31], Energy Efficient Location based geographic protocol (EEL) and Totally Opportunistic Routing Algorithm (TORA) are proposed. EEL and TORA achieve the high PDR with minimum EC [31]. Meanwhile, in [31], time of arrival and range based equations are used to locate the nodes in the network. TORA outperformed than the existing algorithms, i.e., VBF, HHVBF, VAPR and H2DAB. However, communication overhead and EC on potential node selection is not discussed [31].

A hybrid solution based on spherical division and vector-based forwarding is proposed in [30]. The scheme reduces the number of routing paths using basic routing algorithms. Similarly, Vector-Based Routing (VBR) protocol is enhanced in [32] which depends on the radius of the routing pipe. At this end, to control the EC of nodes, there exists a function; if receiving node's energy is less than the sender's node then VBR reduces the radius of the pipe. Therefore, priority for the selection of that respective node as a forwarder node reduces. Both protocols show efficacy with an increase in PDR with minimum EC [30], [32]. However, authors in [30] have not considered dynamic topology environment effect on EC [32]. Additionally, EC on adjusting the diameter of the pipe is not discussed.

In Balanced LOAD (BLOAD) distribution scheme, sensed data of the sensor nodes are subdivided [33]. The transmission range of every node is logically adjusted to balance the data among forwarder nodes. Moreover, each node sends evenly distributed data directly to the sink node, even if an energy hole occurs. The main difference between BLOAD and proposed protocol (PA-EPS-Case I) is shown in Table 5.

The author in [34] discusses the special issues regarding the development of routing protocols in UWSN along with sensor nodes deployment. In this paper, the author highlights that during the development and deployment of routing protocols, following important metrics should keep in mind, i.e., positioning of the sensor nodes, location of the sensor nodes, protocol's architecture, communication transceivers of protocols on lower level layers such as layer 1 and 2. According to the author's point of view, without having strong knowledge of lower level layers (including their physical sensors information and nodes hardware knowledge) this level has no sense. In [35], authors explain different procedures regarding how nodes have acoustic communication. Authors discuss that underwater acoustic environment behaves variable because of different environmental factors, i.e., salinity, temperature and pressure. The awareness of these parameters helps the network to achieve high data rates at maximum distance. In addition, the authors highlight some important issues regarding acoustic modems, e.g., unstable underwater

TABLE 3. Summary of literature review.

Categorization	Features	Achievements	Limitations
Energy efficient	Depth based and Energy Aware: DEA [12]	Throughput maximization, load balancing and minimum delay	Security and dynamic environmental changes are not considered
	Chaotic compression: in [13]	Reduces the number of retransmissions, prolongs the network life time and minimum EC	EC on compression is not considered
	Hop by Hop Routing Protocol: H^n-PERP [11]	Throughput maximization, minimum EC and prolongs the network lifetime	EC, delay in data packets during selection of next hop selection
	Cooperative and Optimal Relay-Selection Protocol: Co-EEORS [14]	Minimum EC and acknowledgement after successful transmission	Dynamic changes in UWSNs environment is not focused
	Mobility sink utility ratio: in [15]	High PDR, throughput maximization and prolonged network lifetime	Sparse region deployment and delay in packet transmission
	Combination of geo-routing, duty-cyclic routing and multi-path routing Algorithm: COA [16]	Energy efficient	Dynamic environmental changes in the network are not considered
Void hole avoidance	Dynamic depth adjustment for avoiding energy hole: E2RV [17]	High PDR, less EC and prolongs the network lifetime	Communication overhead due to distance
	Energy-aware and void avoidable routing protocol: EAVARP [23]	Void hole avoidance and minimum EC	Sparse regions effect and processing time of network increase
Clustering based	Clustered-based energy efficient routing protocol: CBEER [24]	High PDR and minimum EC	Sparse regions overhead is not tackled
	Layering and clustering: EULC [27]	Energy balancing and prolonged network lifetime	Communication overhead is not discussed
	Clustered-based energy efficient routing protocol: CBEER [29]	Prolongs the network lifetime and control the mobility of the nodes effectively	No
Pressure based	Energy balancing routing protocol: RE-PBR [28]	Energy balancing and prolongs the network lifetime	Distance dependency on energy is not considered
Shortest path	Multilayered routing protocol: MRP and splice method is introduced [22]	Efficient data delivery	Selection of single shortest path with number of collisions
Opportunistic routing	Energy efficient location based geographic protocol: EEL [25]	Energy efficient and good PDR	Communication overhead
	An anycast, geographical and totally opportunistic routing algorithm: TORA [31]	Minimum EC, minimum E2E delay and maximum PDR	Potential node selection is not considered
Vector based	Spherical divisions and vector based forwarding routing: in [30]	Minimum EC, maximum PDR and increases the lifetime of the network	Dynamic topology environment is not focused
	Vector-Based Routing: VBR [32]	Increase the PDR and minimum EC	EC on adjusting the diameter of the pipe is not discussed

environment because of the aforementioned reasons, even at lower depth area. The main reasons for attenuation at lower depth are shipping noises and water density. In this paper, authors focus is on the careful selection of technology, which ensures the capability to tackle the issues regarding long term communication.

In [36], rModem is presented. The proposed model is based on the daughter card interference board. This interference card is used to add an amplifier phase in the designed model. Authors present Simulink environment based software application and real-time workshop toolbox. Further, four nodes are used to run the application on the testbed. Authors claim that proposed modem provides high throughput. In [37], practical implementation of joint sensor deployment in a small network area is focused. Additionally, link scheduling and routing are also focused. A mathematical model is also proposed by the authors to validate the acoustic wave model as well as interference conditions in the network. However,

TABLE 4. Comparison of WDFAD-DBR, C-DBR and PA-EPS-Case I.

Protocols and Features	Achievements	EC	Adaptive	Avoid Voids	Feasible Regions	Scalability
C-DBR is cluster, collision avoidance based protocol [8]	Performance of the network is increased through void hole avoidance	Low	✓	✓	×	✓
WDFAD-DBR uses proactive approach (two hop neighbor nodes information) for forwarder nodes selection [19]	Handle the energy hole problem	High	×	✓	×	✓
PA-EPS-Case I adaptively changes its communication strategy depending on the type of the network, i.e., dense network, partially dense network and sparse network	Adaptive strategy selection results in minimum void holes	High	✓	✓	✓	✓

TABLE 5. Comparison of BLOAD and PA-EPS-Case I.

Protocols	Features	Achievements	Limitations
BLOAD [33]	Data is divided in to fractions and transmission range is logically adjusted	Network lifetime, energy balancing, stability period and reduce energy holes	EC increases
Proactive routing Approach with energy efficient Path Selection (PA-EPS-Case I)	Adaptively changes its communication strategy depending on the type of the network, i.e., dense network, partially dense network and sparse network	Adaptive strategy selection results in minimum void holes	Increase in EC with minimum delay

authors have not discussed the issue of packet drop when the distance exceeds 350 m.

The paper [38] includes the survey of the existing routing protocols in underwater acoustic communication. In this paper, authors highlight the important issues and discuss how different researchers overcome these issues, i.e., battery lifetime, low bandwidth, high E2E delay which restrict the efficiency of underwater acoustic network's throughput and high rate reliable data transmission. The summary of the literature review is also presented in Table 3.

III. PROBLEM STATEMENT

In DBR, next hop forwarder nodes are elected on the base of depth difference (between the current node and previous hop forwarder node). The higher the depth difference is, higher will be the priority of that node to be selected as forwarder [18]. DBR selects the forwarder node within one hop neighbor nodes. Here, an issue of local optimal solution arises (in which every sensor node considers the depth difference in its local region instead of the next forwarding sensor node). Therefore, to reduce the probability of local optimal solution, WDFAD-DBR is introduced [19]. It considers two metrics for reliable data delivery, i.e., the depth difference of the nodes and next forwarder node selection criteria (including 2-hop neighbors information). The void hole occurrence is minimized to some extent; however, the probability of void hole occurrence still exists in the network as shown in Fig. 1. This discussion validates that forwarder node selection criteria can be further optimized.

Therefore, in this paper, a proactive routing protocol is proposed which adaptively changes its communication strategy depending on the type of the network, i.e., dense network, partially dense network and sparse network to solve the aforementioned problems. This adaptive strategy selection helps the routing protocol to continue its transmission using predefined route from source to destination sink (without any void hole generation).

IV. SYSTEM MODEL AND DESCRIPTION

In this section, system model of the proposed and existing protocols is discussed. Afterwards, the EC model is discussed in detail.

A. DETAILED DESCRIPTION OF THE EXISTING PROTOCOLS

Firstly, WDFAD-DBR and C-DBR are implemented to compare the proposed protocol with baseline protocols. The WDFAD-DBR considers depth adjustment of the nodes and 2-hop neighbors information for the selection of next forwarder node [19]. However, the probability of void hole occurrence still exists in the network, e.g., in Fig. 1, the node C has three forwarder nodes A, B and E. The node C selects the node E as its next forwarder node because the node E has a neighbor node at its first hop. However, the node E has no information regarding one hop neighbor nodes of the node D. In addition, the node D has no forwarder node in its vicinity. Therefore, the node D designates as a void node (with no forwarder node). In contrary, average propagation distance in C-DBR is reduced by minimizing the packets collision. However, it performs TRA to keep maximum nodes in its vicinity. which requires extra power. In addition, this adjustment helps the CHs to retain maximum cluster members in its transmission range, which helps the protocol to increase its

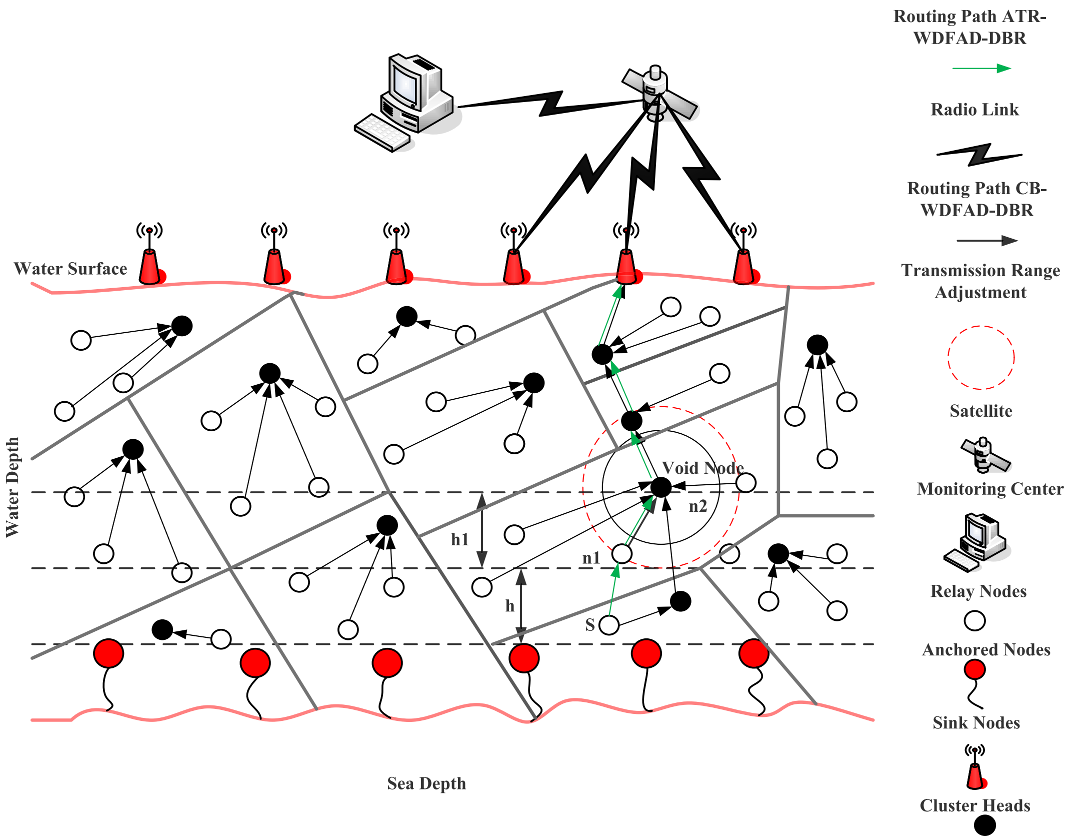

FIGURE 4. System model of C-DBR.

PDR as shown in Fig. 4. This discussion shows that criteria for the forwarder node selection should be further optimized.

B. DETAILED DESCRIPTION OF THE PROPOSED PROTOCOL

To tackle the aforementioned problem, a proactive routing protocol PA-EPS-Case I including the features of PA-EPS-Case II (for partially dense network) and PA-EPS-Case III (for sparse network) is proposed. The proposed protocol adaptively changes its communication strategy depending on type of the network. The types are:

1) dense network,
2) partially dense network and
3) sparse network.

Adaptivity: The adaptive strategy helps the routing protocol to continue its transmission process by avoiding the void node problem in the underwater environment. In the current work, to minimize the void node occurrence, the vertical layering concept is implemented for dense and partially dense network. Meanwhile for the sparse network, the concept of cluster formation is implemented. In this regard, CHs are selected using Dijkstra's algorithm. Then cluster members residing in the vicinity of that CHs pass the data packets to their forwarder CH. Afterward, CHs passes the data packet to forwarder CHs and data reaches the destination. This strategy maximizes the PDR and minimizes the E2E delay with reduced packet drop ratio. The detailed description is given below.

Network Architecture: In the proposed protocol, 3D network with multiple sinks is supposed [8]. The network includes sensor nodes varying from 100-500 (where every sensor node is a source node) and 9 sinks (see Fig. 5-7). The nodes are randomly distributed in 9 vertical layers. The distance between each layer is kept equal to cover the whole area by the given number of sensor nodes. Whereas, the responsibility of each node includes: receiving and forwarding of the data packets towards the sink, simultaneously. The sinks are distributed at the sea surface (housed with both radio and acoustic modems). It is assumed that:

- sinks have high energy and
- every sink knows the coordinates of all other nodes.

Beaconing: In the proposed protocol, each node finds its neighbor nodes and hop counts by broadcasting a beacon message [21]. The aforementioned parameters are computed through the beacon generated by the sink nodes destined at the sea surface. The implemented beaconing procedure is named as reactive beaconing. It keeps the sensor nodes synchronized with their routing tables. In addition, to share the computed information, the concept of hello packet is taken into account (see Table 6). At this end, every sensor

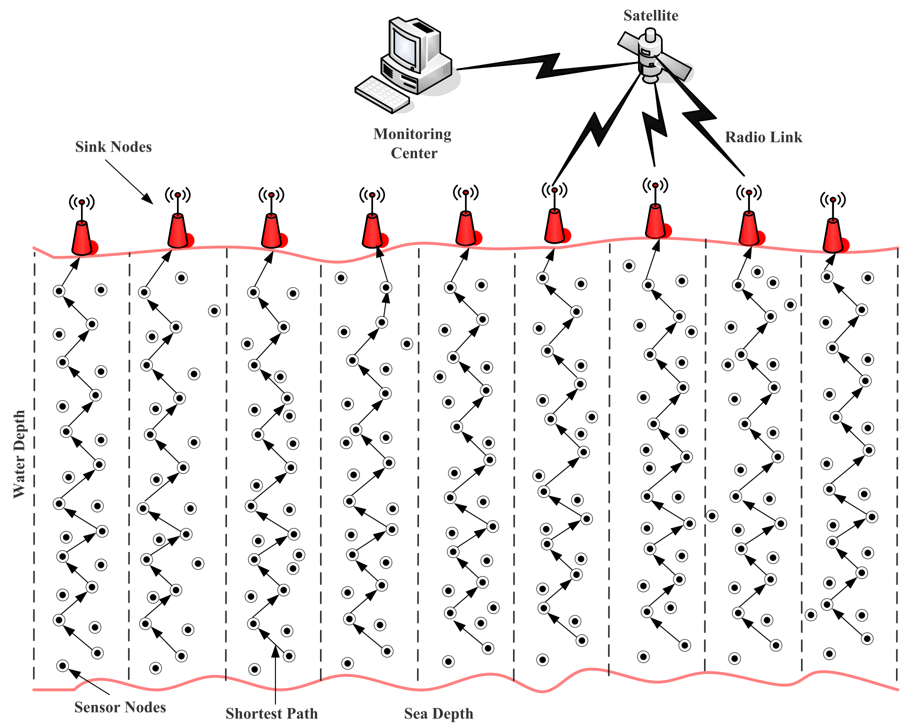

FIGURE 5. System model for the dense network.

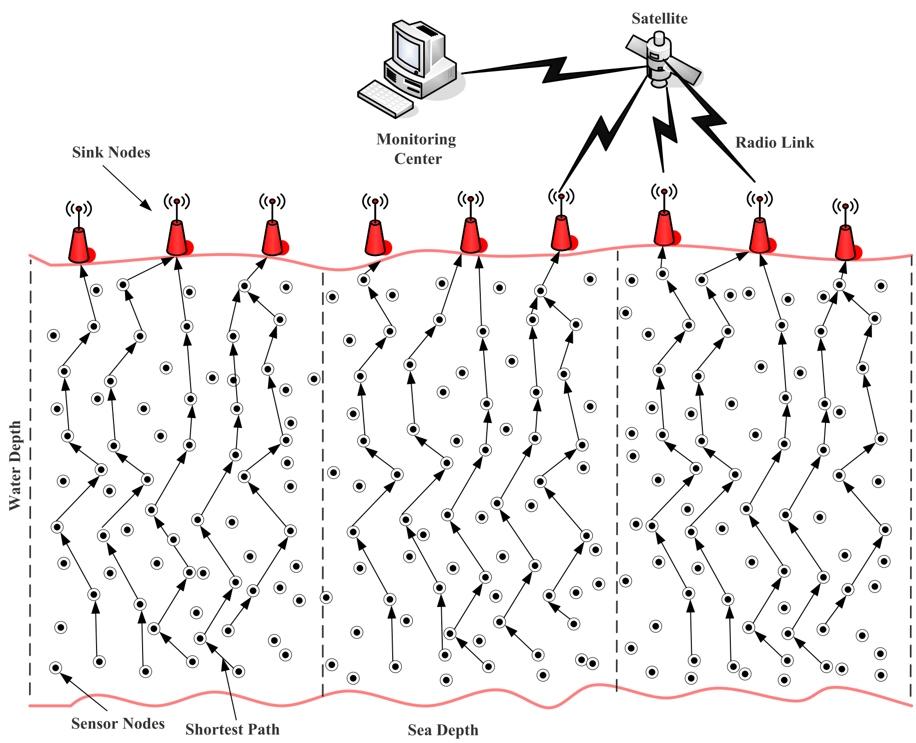

FIGURE 6. System model for the partially dense network.

nodes update their routing table (see Table 7) when it receives a hello packet from their neighbor nodes. Whereas, the hello packet is a part of the data packet generated from a source node. After the successful packet reception, the receiver node also upgrades its routing table. Fig. 8 shows the protocol message flow diagram.

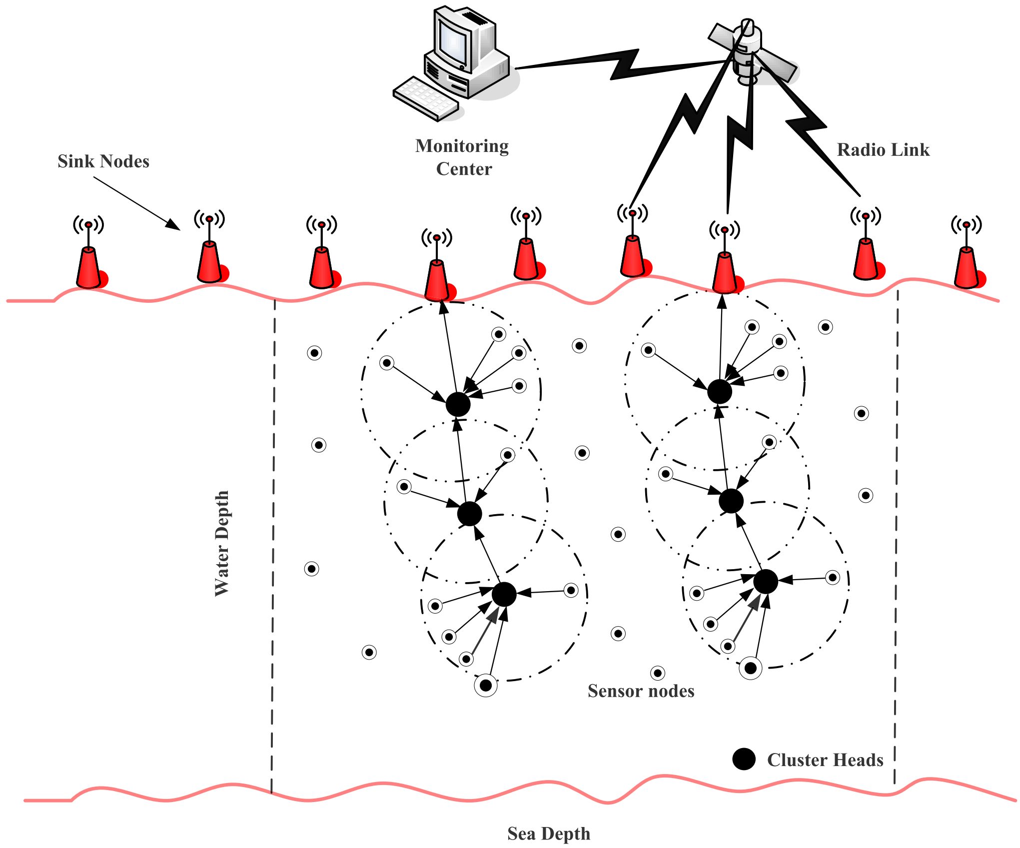

FIGURE 7. System model for the sparse network.

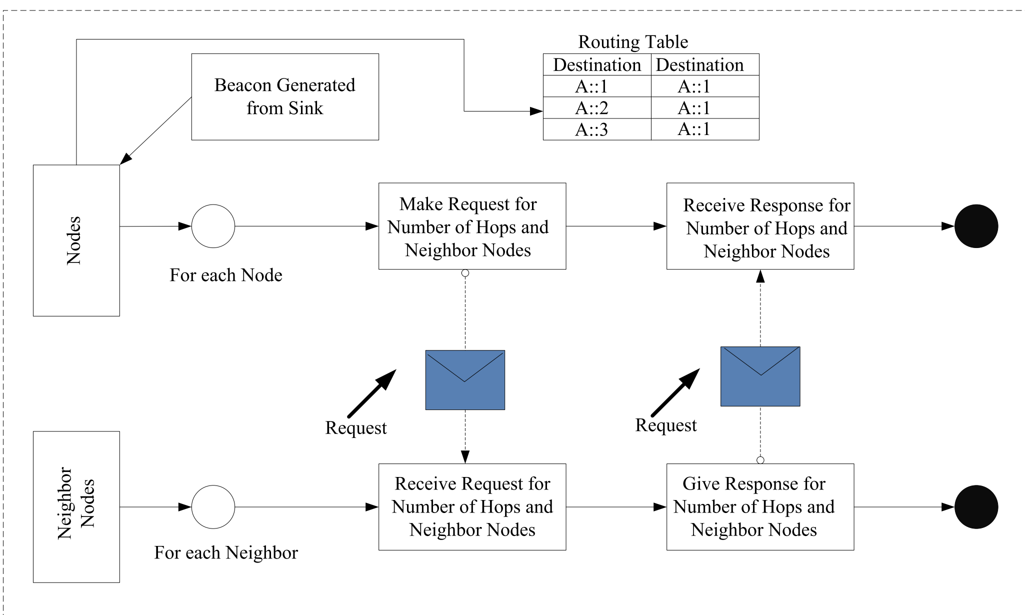

FIGURE 8. Message flow diagram for proposed protocol.

Transmission Phase: The transmission process of the proposed protocol adaptively changes its communication strategy depending on the type of the network, i.e., dense, partially dense and sparse network. If the network is dense, then the transmission is followed by 9 vertical layers and network firstly computes the following information, i.e., the number

TABLE 6. Hello packet format.

ID (Nodes)	Neighbour nodes	Distance from destined sink	Number of hops from destined sink

TABLE 7. Routing table format.

ID (Neighbors)	Neighbors in range	Distance from neighbors	Number of hops from destined sink

of sensor nodes, their depth and their coordinates. The proposed protocol uses a proactive approach and finds the shortest and fastest path from every source node to the destined sink of the respective layer (using Dijkstra's algorithm). By using the energy efficient path, the reliable delivery of the data packets towards the sink node starts (see Fig. 5). Additionally, it is assumed that:

1) all sinks ARE connected to keep the packets flow balanced and
2) successfully packet delivery to destined sink means that it is successfully delivered at the control station.

When protocol finds the network partially dense, then the transmission is followed by reducing the vertical layers. In each layer, the number of sensor nodes, their depth and their coordinates are calculated first. Then the proposed protocol uses a proactive approach and finds the shortest and fastest path from every sensor node to the destined sink of the respective layer (using Dijkstra's algorithm). By using this energy efficient path, every node transmit the data packets to the nearest sink node (see Fig. 6).

At the end, when the network becomes sparse, the cluster formation strategy is adapted to keep the communication continuous. CHs are elected on the basis of the residual energy of the sensor nodes. These CHs collect data from the cluster members and pass the data packets to the next CHs (in its transmission range). Then CH to CH communication leads the data to destined the sink node (by following the aforementioned assumptions). The process remains continuous until all data packets reach the sink node (see Fig. 7).

C. EC MODEL

Now, the EC and propagation model of the proposed protocol are discussed. Therefore, attenuation in UWSN over distance l is calculated as [10]:

$$10\ logA\ (l, f) = c * 10 * logl + log * \alpha(f) * l * 10 * . \quad (1)$$

Here, absorption coefficient ($\alpha(f)$) is used to find the absorption loss during transmission and c is the spreading coefficient which defines the geometry of propagation.

In the proposed work, network faces transmission are shipping and thermal noise [10]. These noises are expressed as ($N_s(f)$, $N_{th}(f)$) and calculated as,

$$N(f) = N_s(f) + N_{th}(f). \quad (2)$$

Meanwhile, Signal to Noise Ratio (SNR) for acoustic signals is calculated as,

$$SNR\ (f, l) = T_p(f) - A(l, f) - N(f) + D_i, \quad (3)$$

whereas, $T_p(f)$ denotes the transmission power and frequency is denoted as f. In addition, D_i is the directive index used in the above mentioned equation. The propagation model is the same as used in [8].

D. ALGORITHM AND FLOW CHART FOR THE PROPOSED PROTOCOL

In this subsection, algorithm of the proposed protocol is presented (Algorithm 1). First of all, input parameters are initialized then ordinary sensor nodes and sink nodes are deployed in the network. Afterward, the proposed protocol finds the neighbor nodes of each node and checks the void hole in the network. Then inputs for the Dijkstra's algorithm are formulated. Furthermore, protocol checks the network type and adaptively changes its communication strategy depending on the type. The void hole occurrence is minimized using vertical layering concept for dense and partially dense network and clustering concept for the sparse network. This adaptive strategy minimizes the void hole occurrence from the network. After that, CHs are selected using Dijkstra's algorithm and the cluster members pass the data packets to their respective CH. Then the CHs pass the data packet to their forwarder CHs and data reaches the destination. This strategy maximizes the PDR and minimizes the E2E delay with reduced packet drop ratio. Whereas, the flow chart describing the proposed protocol is shown in Fig. 9.

V. MATHEMATICAL FORMULATION BASED ON LINEAR PROGRAMMING

A feasible region is defined as the set of all possible solutions to a problem that satisfy all defined constraints. Let us consider a problem, i.e., minimize $(x^2 + y^2)$ with respect to variable x and y. Whereas, $1 \leq x \leq 10$ and $6 \leq y \leq 10$. Therefore, the feasible region contains the set of pairs (x, y) which must satisfy the aforementioned constraints [39]. In the current scenario, linear programming is adopted to check the optimality of the proposed protocol. Therefore, feasible regions for the proposed protocol are computed by using the defined constraints. In this regard, mathematical formulation to compute the network throughput and EC is given below.

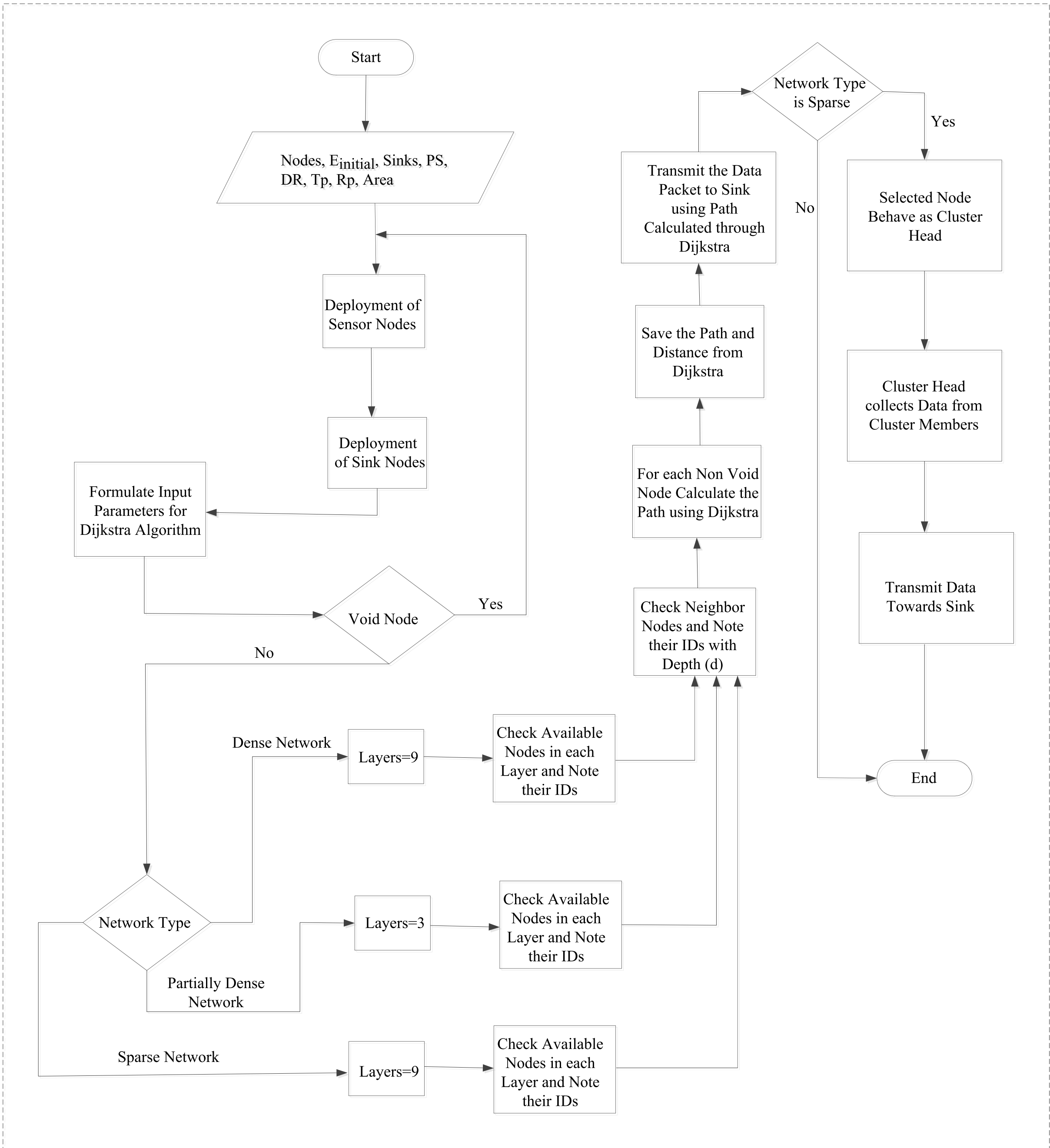

FIGURE 9. Flow chart explaining the protocol procedure.

A. FEASIBLE REGION FOR ENERGY MINIMIZATION

To minimize the EC, our first objective function is defined in Eq. (4).

$$Min\ \Sigma_{r=1}^{r_{max}} E_{cons}(r) \quad \forall r \in r_{max}. \tag{4}$$

Here, EC is denoted by E_{cons}, r denotes the number of rounds and r_{max} presents the number of maximum rounds. Whereas, round is defined as: single iteration in which a packet reaches the destination successfully. Furthermore, the constrains for the Eq. (4) are as follows:

1) transmitting and receiving energy (E_{trans}, E_{rec}) should not exceed the residual energy (E_{re}) of the node, i.e., $(E_{trans}, E_{rec}) \geq E_{re}$,
2) transmission and residual energy must be less than the initial energy of the node, i.e., $(E_{trans}, E_{rec}) \leq E_{initial}$ and
3) data packets should be transmitted within the transmission range of the node (T_{range}), i.e., $(T_{range}) \leq T_{rangemax}$. Here, $T_{rangemax}$ denotes the maximum transmission range of a node.

Algorithm 1 PA-EPS-Case I Data Forwarding

Input Parameters: (nodes, $E_{initial}$, sinks, PS, DR, $T_p(f)$, $R_p(f)$, area)

```
ξ = 0;
for υ =1 ϵ 9 do
    ξ = 150 + ξ
    for υ = 1 ϵ nodes do
        S(υ).xd = randi ([0,1500],1,1);
        S(υ).yd = randi ([0,1500],1,1);
        S(υ).id = υ;
        S(υ).Re = Eo; // Initial energy
        S(υ).Type = 'N'; // Node type
        Deployment of sensor nodes
    end for
    for υ = nodes ϵ nodes+9 do
        S(υ).xd = sink(t).xd;
        S(υ).yd = sink(t).yd;
        S(υ).Re = Eo; // Initial energy
        S(υ).Type = 'SN'; // Node type
        S(υ).id = υ;
        Deployment of sink nodes
    end for
    for ℜ = 1 ϵ nodes+9 do
        neighbor_count = 0;
        neighbors_distances = [];
        neighbors_id = [];
        for ℑ = 1 ϵ nodes+9 do
            if ℜ ≠ ℑ then
                Check neighbor nodes for each node
                S(ℜ).Neighbors_Distances =
                neighbors_distances;
                S(ℜ).Neighbors_ID = neighbors_id;
            end if
        end for
    end for
    arr = [];
    arr1 = [];
    for ℜ = 1 ϵ nodes do
        if numel(S(ℜ).Neighbors_ID) == 0 then
            S(ℜ).arr = ℜ;
        else
            S(ℜ).arr = 0;
        end if
    end for
end for
Formulate the input parameters for Dijkstra's algorithm
nodes_inpp = [(1:size(A,2))' A' B'];
SINK_Nodes = [(nodes+1:nodes+25)' ([sink.xd])' ([sink.yd])'];
nodes_inp = [nodes_inpp];
segments = [(1:numel(A_B))' A_B' All_Neighbours'];
Check the network type
```

Algorithm 1 *(Continued.)* PA-EPS-Case I Data Forwarding

```
if Network type==Dense then
    Layers = 9
    for υ = 1 ϵ nodes do
        Check the nodes in every vertical
        layer of the network
        S(υ).Neighbors_ID =_id;
    end for
    for ℜ = 1 ϵ nodes+9 do
        neighbor_count = 0;
        neighbors_distances = [];
        neighbors_id = [];
        for ℑ = 1 ϵ nodes+9 do
            if ℜ ≠ ℑ then
                Check neighbors for each node
                S(ℜ).Neighbors_Distances=
                neighbors_distances;
                S(ℜ).Neighbors_ID = neighbors_id;
            end if
        end for
    end for
    for ℏ = 1 ϵ numel(Non void nodes) do
        if Neighbor (Neighbor (ℏ))≥1 then
            [Distance, Path]= Dijkstra's (nodes,
            segments, starting ID, finishing ID);
            S(start_id).Path_A = [S(start_id).Path];
            S(start_id).Distance_A =
            [S(start_id).Distance];
            Transmit the data packets
        end if
    end for
end if
if Network type == Partially dense then
    Layers = 3
    for υ = 1 ϵ nodes do
        Check the nodes in every
        vertical layer of the network
        S(υ).Neighbors_ID =_id;
    end for
    for ℜ = 1 ϵ nodes+9 do
        neighbor_count = 0;
        neighbors_distances = [];
        neighbors_id = [];
        for ℑ = 1 ϵ nodes+9 do
            if ℜ ≠ ℑ then
                Check neighbors for each node
                S(ℜ).Neighbors_Distances =
                neighbors_distances;
                S(ℜ).Neighbors_ID = neighbors_id;
            end if
        end for
    end for
    For non void nodes
    Find the route using Dijkstra algorithm
    Save the path and distance
end if
```

Algorithm 1 *(Continued.)* PA-EPS-Case I Data Forwarding

```
if Network type == Sparse then
    Layers = 9
    for ℏ = 1 ϵ numel(Non void nodes) do
        if Neighbor (Neighbor (ℏ)≥1 then
            [Distance, Path] = Dijkstra's (nodes,
            segments, starting ID, finishing ID);
            S(ℏ).CH = S(ℏ).path;
            Transmission using clustering
            Cluster member transmit data to CHs
            CH transfer the data to next CH
            Ultimately data reaches at sink node
            While (packet to sink == 0)
            if CH exists in Sink range then
                Forward the data to sink
                Packet reaches the destination sink
                Transmit to respective base station
            else
                CH finds next CH in its vicinity
                Transmit data to the next CH
            end if
            end While
            Unicast the data packets
        end if
    end for
end if
Output: (EC, Minimum E2E delay, enhanced PDR, low
packet drop ratio)
```

Whereas, total consumed energy is the sum of transmission and receiving energy of the nodes, i.e.,

$$\Sigma_{r=1}^{r_{max}} E_{cons}(r) \; = E_{trans} + E_{rec} \quad \forall r \in r_{max}. \tag{5}$$

where,

$$E_{trans} = T_p(f)\left(\frac{PS}{DR}\right). \tag{6}$$

E_{trans} is the transmission energy (ranges from 0.7-2.77) and $T_p(f)$ is the transmission power. In addition, PS represents the packet size and DP denotes data rate.

$$E_{rec} = R_p(f)\left(\frac{PS}{DR}\right). \tag{7}$$

E_{rec} is the receiving energy (ranges from 0.2-0.8) and $R_p(f)$ is the receiving power.

B. GRAPHICAL ANALYSIS

In this subsection, graphical analysis is performed for the defined objective function. According to the assumptions defined, we kept PS = 72 bytes, DR = 16 kbps, $T_p(f) = 15, 25, \ldots, 50$ and $R_p(f) = 0.0390, 0.080, \ldots, 0.150$. Whereas, the sum of both transmitting and receiving energy should be in-between 0.690-2.85. Feasible region for minimum EC is shown in Fig. 10. Using the aforementioned

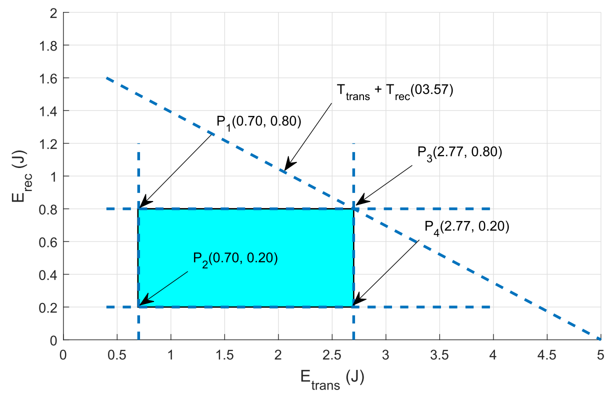

FIGURE 10. Feasible region of EC minimization.

constrains, the points on the feasible region's boundary are as follows:

$$P_1\,(0.70, 0.80) = 1.5\,J,$$
$$P_2\,(0.70, 0.20) = 0.90\,J,$$
$$P_3\,(2.77, 0.80) = 3.57\,J \text{ and}$$
$$P_4\,(2.77, 0.20) = 2.97\,J.$$

If we choose any value from the aforementioned points value, it results in minimum EC during the packets transmission.

C. FEASIBLE REGION FOR THROUGHPUT MAXIMIZATION

In this subsection, our second objective is to maximize throughput. It is calculated using Eq. (8) as follows:

$$Max \; \Sigma_{r=1}^{r_{max}} Throughput(r) \quad \forall r \in r_{max}. \tag{8}$$

whereas, constraints for the Eq. (8) are as follows:

1) transmitting and receiving energy must not exceed the initial energy of the node, i.e., $(E_{trans}, E_{rec}) \leq E_{initial}$,
2) transmission energy must be less than residual energy of the node ($E_{residual}$), i.e., $(E_{trans} \leq E_{residual})$,
3) data packets should be transmitted within the transmission range of the node, i.e., $(T_{range}) \leq T_{rangemax}$ and
4) threshold between source and destination node should be maintained. It should not exceed the maximum distance.

D. GRAPHICAL ANALYSIS

For pictorial representation of maximum throughput, bandwidth range is taken as 4000 Hz. Bandwidth for forwarding node is represented as B_{Frwd} (ranges from 200-1000) and B_{NFrwd} (ranges from 2000-3000) denotes bandwidth for non forwarding nodes. The sum of both B_{Frwd} and B_{NFrwd} should be in-between 2200-4000.

Feasible region for maximum throughput is shown in Fig. 11. Using the aforementioned constraints, the points on the feasible region's boundary are as follows:

$$P_1\,(200, 2000) = 2200\,kHz,$$
$$P_2\,(1000, 2000) = 3000\,kHz \text{ and}$$
$$P_3\,(200, 3000) = 3200\;\;kHz.$$

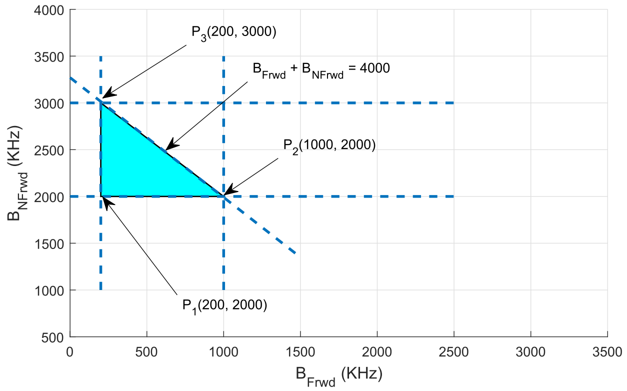

FIGURE 11. Feasible region for throughput maximization.

Therefore, if we choose any value from these points, it results in maximum network throughput during the transmission of data packets.

VI. SIMULATIONS RESULTS AND DISCUSSION

In this section, we evaluated the proposed protocol against benchmark protocols.

A. SIMULATIONS SETUP

Simulations setup includes sensor nodes (randomly deployed) in UWSN (10 km^3). Whereas 9 sinks are placed at the sea surface. The transmission range for each sensor node is kept 2 Km, DR as 16 kbps and payload as 72 bytes [8]. The $E_{initial}$ of the sensor nodes is initialized with 100 J; where the consumption rate during the reception of data packets is kept 158 mW and during transmission, it is kept 50 W. During the execution of the UWSN operations, the number of sensor nodes varies from 100-500.

To deal with the versatility of nodes, the node speed is kept 2 m/s (in the horizontal direction). In addition, the propagation rate of the acoustic wave is kept 1500 m/s along with a bandwidth of 4 kHz. The header size of the data packet is kept 15 bytes. Whereas, performance metric is calculated in rounds and a single round is defined as a single iteration in which all the packets are transmitted towards the sink from the respective source node. Additionally, the Poisson distribution model is opted to generates one packet in every 5 Second (s). The above mentioned parameters are taken from [8] and listed in Table 8.

B. PERFORMANCE METRICS

The performance metrics of the protocols are defined. These are:

1) **EC:** The EC is the energy consumed during the successful packets transmission towards the sink. It is calculated in (J) using Eq. (9) as in [19].

$$EC = \frac{Econs}{\eta \times D_p}, \tag{9}$$

whereas, $Econs$ is the overall EC of the network. η denotes the transmission range of nodes in the network and D_p denotes the total data packets effectively received at the sink node.

2) **PDR:** It is the ratio of total packets received at the sink over the packets generated from source. It is calculated using Eq. (10) as in [19].

$$Average\ PDR = \frac{Total\ (Pkt_{sink})}{Total\ (Pkt_{source})}, \tag{10}$$

where, $Total\ (Pkt_{sink})$ is the total packets received at sink and $Total\ (Pkt_{source})$ denotes the total number of packets generated from source.

3) **Packet Drop Ratio:** It is the ratio of packets dropped during the transmission over the total packets generated from source. It is calculated using Eq. (11) as in [19].

$$Pkt\ Drop\ Ratio = \frac{Total\ Drop\ (Pkt_{sink})}{Total\ (Pkt_{source})}, \tag{11}$$

where, $Total\ Drop\ (Pkt_{sink})$ is the total dropped packets at sink and $Total\ (Pkt_{source})$ denotes the total number of packets generated from the source.

4) **E2E Delay:** The E2E delay is the time consumed during the packet transmission from source to destination sink. It is measured in (s).

TABLE 8. Parameters for simulations.

Parameters	Value
Bandwidth	4000 (Hz)
Consumption rate during transmission of data packet	50 (W)
Consumption rate during reception of data packet	158 (mW)
Center frequency	12000 (Hz)
Dimensions of the network	3D region of (10 km^3)
DR	16 (kbps)
Header size of packet	11 (bytes)
Initial energy	100 (J)
Idle power consumption	158 (mW)
Number of sinks	9
Number of nodes	100-500
Nodes mobility speed	2 (m/s)
Payload	72 (bytes)
Propagation speed	1500 (m/s)
Running rounds	100
Size of acknowledge	50 (bits)
Simulation time for one round	1000 (s)
Transmission range	2 (km)
Transmission power	90 (dB)
Packet generation model	Poisson distribution, generate one packet in every 5 (s)

C. PERFORMANCE COMPARISON

In this section, the comparative analysis of the proposed routing protocol is performed with benchmark routing protocols.

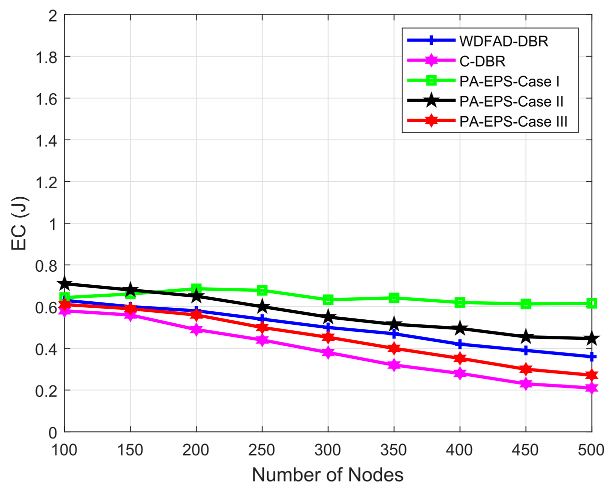

FIGURE 12. EC (J).

The detailed discussion for simulation results and discussion is given below.

1) EC

The EC of the proposed and baseline routing protocols is shown in Fig. 12. The figure demonstrates that the EC of C-DBR is less than WDFAD-DBR. The high EC in WDFAD-DBR is due to its strategy of forwarder nodes selection, e.g., depth difference during forwarding. Meanwhile, in C-DBR, the excess energy is disseminated on versatile transmission range change. Further, in C-DBR, clustering and cooperation of each node also results in high EC of the sensor nodes.

In the proposed protocol, a proactive routing protocol with three different network types is implemented. The proposed protocol adaptively adjusts its communication strategy depending on the type of the network, i.e., dense network, partially dense network and sparse network. This adaptiveness helps the protocol to keep its transmission continuous. During the dense network, the proposed protocol divides the network into 9 equally distributed vertical layers. In these layers, the transmission phase starts using the shortest and fastest path (using Dijkstra's algorithm). When the network becomes partially dense, the number of layers is reduced and transmission continues. At the end, when the network becomes sparse, the cluster formation helps the protocol to transmit the data packet towards sink. These three phases of transmission make the network reliable for successful data delivery.

The EC of the proposed protocol with three different strategies is also shown in Fig. 12. It is demonstrated from the figure that EC of PA-EPS-Case I is high. The reason behind this is that the proposed protocol uses Dijkstra's algorithm to find the shortest and fastest path using two approaches namely: layering and clustering approach. Firstly, the path selection using Dijkstra's results in the collision and retransmission of several packets. Secondly, the EC on the clustering phase results in the high energy dissipation.

Until the number of nodes up to 200, the EC of PA-EPS-Case I is low. However, PA-EPS-Case I has high EC after increasing the density of the nodes. It is obvious that energy efficiency is a key problem in avoiding the void hole; however, this little bit high EC of PA-EPS-Case I is justifiable as it enhances the PDR by avoiding the void hole, minimizes the E2E delay and packet drop ratio. Furthermore, packet's collision has no effect on the performance of the network because of affordable E2E delay. As, in the proposed routing protocol, there exists a trade off between some parameters which are explained below (see subsection VI: Performance Trade off). Thus, limitation of the high EC due to several retransmissions is justifiable with minimum E2E delay.

Afterward, the EC of PA-EPS-Case II is shown. In this case, the EC is bit low because of less number of vertical layers. Additionally, the increase in the node's density in the layers provides several alternative paths to the proposed protocol resulting minimum EC. Similarly, the EC during clustering in sparse regions is shown in PA-EPS-Case III, which is a bit lower than WDFAD-DBR and bit higher than C-DBR. The reason for this behavior of PA-EPS-Case III is that it selects the CHs, computed through Dijkstra's algorithm (nodes elected during route selection via Dijkstra's algorithm are considered as CH). Meanwhile in C-DBR, the CH is elected on the basis of the highest residual energy of the nodes. In addition, it consumes some energy on TRA too.

2) PDR

The PDR of (baseline and existing) protocols is shown in Fig. 13. In all three phases of the proposed protocol, PDR increases with the increase in the number of nodes. The key reason behind high PDR is the minimum number of void holes. The minimization is because of two reasons. Firstly, the increase in density of nodes. Secondly, the fastest and energy efficient path selection using Dijkstra's algorithm. The benchmark protocols consider just 2-hop neighbors information for forwarder nodes selection, which is not adequate. However, this idea results in fewer void nodes resulting low PDR. Furthermore, PDR of C-DBR is somewhat higher than WDFAD-DBR (due to cluster formation).

The void holes are minimized by the proposed protocol. In addition, the proposed protocol outperformed in terms of PDR than benchmark protocols. In PA-EPA-Case III, each CH is selected using Dijkstra's algorithm (using residual energy information). Afterward, CH to CH transmission initiates the communication from the source node towards the destined sink. Similarly, in PA-EPA-Case I and PA-EPA-Case II, the PDR is high because of the proactive routing approach (using Dijkstra's algorithm) and vertical layering concept. Therefore, PDR is enhanced in the proposed protocol (in all three phases) than both benchmark protocols.

3) E2E DELAY

The E2E delay of (baseline and existing) protocols is demonstrated in Fig. 14. From the figure, it is observed that the E2E delay of WDFAD-DBR is higher than the other protocols.

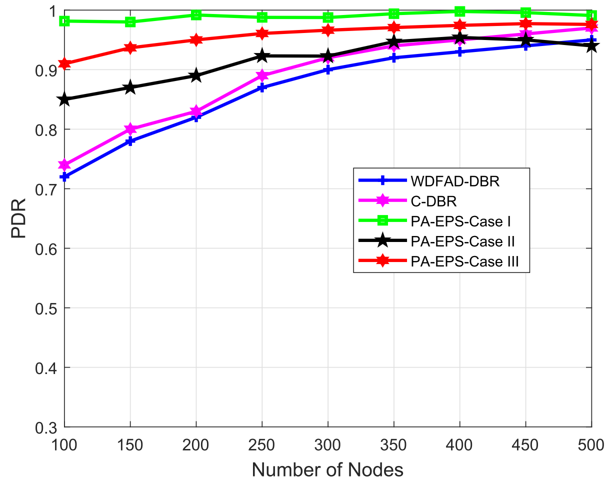

FIGURE 13. PDR.

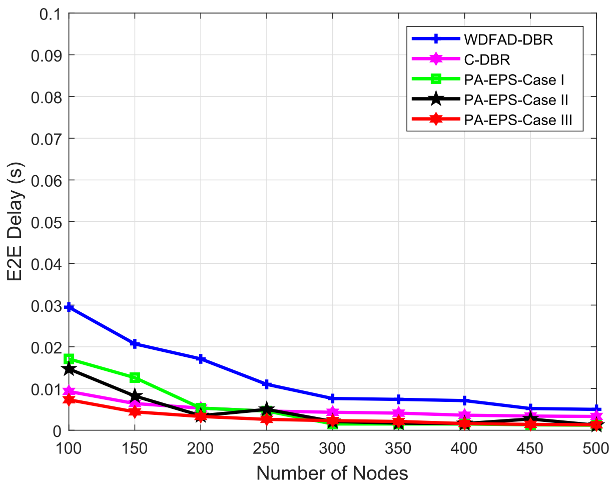

FIGURE 14. E2E delay (s).

This E2E delay is a result of following two reasons: the WDFAD-DBR finds the next forwarder on the base of the nodes depth information. Furthermore, when WDFAD-DBR finds no forwarder node (void node) in its transmission range, it adaptively modifies the node's depth. Therefore, E2E delay is increased due to several depth adjustments and next forwarder node selection (from one hop neighbor nodes). Meanwhile, in C-DBR, the cluster formation helps the routing protocol to collect maximum information from the cluster members.

The proposed protocol overcomes the problem of E2E delay. As, in PA-EPA-Case III, the network forms clusters to minimize the average propagation distance which directly affects E2E delay of the network. The E2E delay of PA-EPA-Case I and PA-EPA-Case II is less than PA-EPA-Case III and both benchmark routing protocols. The reason behind this minimum E2E delay is the hybrid proactive approach. In this approach, the proposed protocol adaptively adjust the communication phase by checking the network congestion, i.e., vertical layering concept implementation for

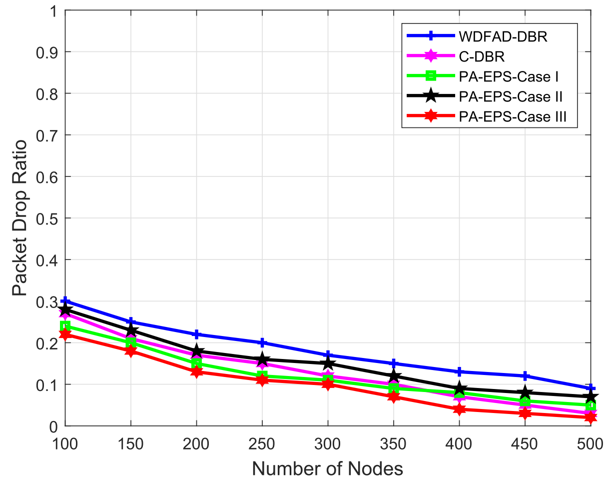

FIGURE 15. Packet drop ratio.

dense and partially dense network and cluster formation for the sparse network. Therefore, it is evident in Fig. 14 that proposed protocol outperformed in terms of low E2E delay than benchmark protocol by paying the cost of EC (on energy efficient and fastest path selection).

4) PACKET DROP RATIO

Fig. 15 illustrates the packet drop ratio of both proposed and benchmark protocols. In the aforementioned existing schemes, C-DBR has lower packet drop ratio as compare to the WDFAD-DBR because WDFAD-DBR looks two-hop neighbors for forwarder nodes selection. However, the chance of void hole occurrence still exists. While the proposed protocol chooses the path that is shortest and fastest from the source node towards the destination sink. The PA-EPA-Case III routing protocol formulates clusters to minimize the collision between the data packets and to make reliable data delivery in the sparse network. If the protocol finds the channel congested until a certain threshold limit, it drops the packet. These parameters help the protocol to make efficient data delivery with minimum packet drop ratio.

While, in PA-EPA-Case I and PA-EPA-Case II, the packet drop ratio is less than all aforementioned protocols. The reason behind this minimum packet drop ratio is the hybrid proactive approach. In this approach, the proposed protocol adaptively adjust the communication phase by checking the network congestion, i.e., dense network, partially dense network and the sparse network. Therefore, in Fig. 15, it is cleared that the proposed protocols outperformed benchmark protocols. They minimize the packet drop ratio by paying the cost of EC (on energy efficient and fastest path selection).

D. PERFORMANCE TRADE OFF

The existing trade off between proposed and existing protocols is discussed below.

In the proposed protocol, three phases for network communication are introduced. In PA-EPA-Case I, fastest and

TABLE 9. Performance trade off of existing and proposed protocols.

Protocols	Features of Protocols	Achievements	Trade offs
WDFAD-DBR [19]	Depth and energy based routing protocol	Improved network lifespan	High E2E delay and minimum EC
C-DBR [8]	Energy based routing along with clustering of nodes	Improved PDR, minimum E2E delay	Increase in EC due to clustering with affordable E2E delay
PA-EPA-Case I	Fastest and shortest path (using proactive routing with three different phases, i.e., dense network, partially dense network and sparse network (using Dijkstra's algorithm with vertical layering approach and cluster formation)	Improved PDR, less packet drop ratio	Increase in EC with minimum delay
PA-EPA-Case II	Fastest and shortest path (using proactive routing with single phase, i.e., partially dense network (using Dijkstra's algorithm with vertical layering approach)	Improved PDR, less packet drop ratio	Increase in EC with minimum delay
PA-EPA-Case III	Fastest and shortest path (using clusters formation)	Improved PDR, less packet drop ratio	Increase in EC with minimum delay

shortest path (using Dijkstra's algorithm with vertical layering approach and cluster formation) is introduced. However, in this case, E2E delay is minimized with high EC. In the same way, PA-EPA-Case II, the same concept is implemented by minimizing the number of vertical layers. However, in this phase, EC is compromised over E2E delay. Whereas, in PA-EPA-Case III, the clustering concept is implemented using Dijkstra's algorithm and in this case, the EC is again compromised over affordable E2E delay. The existing trade offs in both benchmark and proposed protocols are also presented in Table 9.

VII. CONCLUSION AND FUTURE WORK

In current work, an energy efficient proactive routing protocol is proposed. The idea improves the network life expectancy and reduces the void node occurrence by adaptively changing its routing strategy depending on the type of the network, i.e., dense network, partially dense network and the sparse network. This adaptive selection strategy helps the routing protocol to retain its transmission continuous with minimum energy dissipation. The void hole occurrence is minimized using two approaches namely: vertical layering approach for the dense and partially dense network and cluster formation approach for the sparse network. Vertical layering concept (using Dijkstra's algorithm) helps in reliable data delivery for the dense and partially dense regions. Meanwhile, the clustering strategy reduces the average propagation distance of the sensor nodes to make reliable data delivery in the sparse regions. In the end, proposed protocol enhances the PDR with minimum E2E delay and packet drop ratio; however, faces high EC. Simulation results show that the proposed protocol enhances the PDR 14% by minimizing the E2E delay up to 20% and packet drop ratio up to 14.29% than C-DBR. However, EC is increased up to 30% than C-DBR.

In the future, artificial intelligence and data science techniques will be implemented to minimize the EC and E2E delay further. Further, we will explore these techniques using reactive approaches. These techniques will help the UWSN to predict the sudden failures in underwater network environment. Furthermore, optimal throughput and high network lifetime will be our future research directions.

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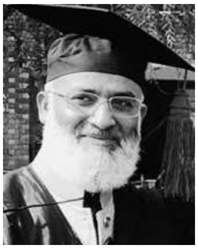

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