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Anchor Nodes Assisted Cluster-Based Routing Protocol for Reliable Data Transfer in Underwater Wireless Sensor Networks

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ABSTRACT Reliable data transfer seems a quite challenging task in Underwater Wireless Sensor Networks (UWSN) in comparison with Terrestrial Wireless Sensor Networks due to the peculiar attributes of UWSN communication. However, the reliable data transmission in UWSN is very limited. Yet, there is a way to achieve reliable data transfer metrics through the design of routing protocols by considering the exceptional features of UWSN communications. With this aim, we propose two schemes with multiple sinks-based network architecture: Anchor Nodes assisted Cluster-based Routing Protocol (ANCRP) to achieve reliable data transfer metrics and Void Handling technique in ANCRP (VH-ANCRP) to cope with the local maximum nodes. For which, the network space is divided into small cubes to form clusters. Then, each cube is assigned with an anchor node as a cluster head (CH). All cluster heads are supposed to be anchored at the centroid of a cube via a string, while source nodes are randomly distributed. In ANCRP, the source nodes are liable to send the sensed data to their designated CH. The CH transmits the sensed data to the next-hop CH and continues this procedure till the successful delivery of the data packets at the surface sinks. In VH-ANCRP, a void handling technique of making the ad-hoc CH is used by the void nodes to reconnect with the network operations. We perform extensive simulations in NS3 to validate our schemes. The simulation outcomes expel that both proposed schemes have improved the network performance when compared with the baseline schemes.

INDEX TERMS Underwater wireless sensor networks, reliable data transfer, routing protocol, anchor nodes, clustering technique, void handling.

I. INTRODUCTION

Currently, Underwater Wireless Sensor Networks (UWSNs) are gaining pivotal considerations in both industrial and academia sector because of their wide and comprehensive implementation areas, such as resource exploration, navigation assisting, military surveillance, calamity preventions, etc. [1]. The underwater WSNs also assist in finding the unexplored underwater resources and aquatic data collection with the help of different computational intelligence approaches [2]. The underwater wireless sensor nodes are supposed to be deployed sparsely from surface-layer to seabed-layer for fetching the data from the underwater harsh environments by using an acoustic modem [3], [4]. Underwater communication through optical signals is not feasible due to absorption loss and rapid attenuation. Thus, underwater communication is carried out in acoustic signals [5]. The underwater wireless sensor node forwards the measured

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data to the known surface sinks by following certain routing techniques while confronting several issues regarding energy as these are furnished with limited power resources in small size batteries [6]. After the deployment arrangements of these sensor nodes, their batteries replacement is a very hard process, because of the challenging underwater harsh environmental conditions [7], [8]. Nevertheless, acoustic communication itself has significant limitations, for example, low bandwidth, high propagation delay, high interference, slow data rates, absorption losses, and multipath fading [9]–[11]. These challenges can therefore motivate the researchers to design reliable, effective, and energy-efficient UWSN routing protocols.

There are numerous routing protocols to be designed for fair use of energy to get a maximum lifetime and reduce the overall propagation delay from source node to surface sinks by using either single-hop or multi-hop communication techniques [12]–[15]. To forward the sensed data towards the destination reliably, a geographic routing is perhaps the easiest way to achieve this task. In geographic routing, the greedy forwarding technique is used in which the shortest path is selected to route the data in the direction of surface sinks [16]. But in the greedy forwarding technique, immutable selection of the forwarder node is unavoidable, which results in exhausting the battery energy of the nodes rapidly and this will create a void hole in the network [17], [18]. To tackle this issue, opportunistic routing (OR) protocols are exploited to select an optimal node in each hop as a forwarding candidate to send the data reliably [19]. In OR protocols, the source node selects the best node from its neighboring set to forward the data. The selection of the best node is carried out by performing different techniques, such as fuzzy-based [20], [21] and weightage calculation [22] on the network metrics, such as depth fitness factor, link quality, hop-count number and so on [16], [20], [23]–[25]. When the best node is selected by the source node in OR, then only the best node can forward the data packets to the next-hop, while other neighbors of the source node will suppress their transmission in the favor of the best node and set a wait time. Once the data has been delivered successfully by the best node then other neighboring nodes will drop the data packet. But in OR, the selection of the best node by the source utilizes more energy to perform the computation as well as to maintain a complex routing table, which increases the communication overhead. Additionally, the OR protocols are suffered from multipath transmission issues as the all members of the relay of set might not be within the transmission range of each other. So, the best node cannot suppress the transmissions of other members [25]. Moreover, underwater sensor nodes are provided with limited battery power and replacement of these batteries is a very tedious job. Thus, various researchers have tried to resolve power issues of the sensor nodes either by suggesting different energy harvesting techniques [26], [27] or by using energy-efficient devices that utilize minimum power cost [28]. In this way, it is not required to replace the batteries of the sensor nodes.

To get rid of high energy consumption, high communication overhead, multipath propagation issues, and relying on a single node, the clustering technique seems a prominent solution. The ultimate goal of the clustering techniques is dividing the network space into small parts [29], [30]. The cluster head (CH) represents the whole cluster, which collects the sensed data from the sensor nodes, and then forwards that data to the surface sinks using other CHs as next-hop. The clustering technique reduces the overall routing distance and communication overhead of the other nodes, as only CH moves the data to the next-hop CH to reach the surface sinks. As there is a very short distance between the neighboring CHs, which reduces the latency and high energy consumption. In addition, by using the clustering technique, possibilities of the redundant packets are also minimized [31]. To enhance the efficiency of the clustering process, an appropriate topology should be chosen for intra- and inter-communication between clusters. The topology has dependency on the size of the cluster and the distance between the CH and the surface sink [32]. The network efficiency of clustering schemes can also be improved by designing a technique that handles the different network attacks, as wireless networks are prone to prey by many malicious attacks [33].

In this paper, two novel schemes: Anchor Nodes assisted Cluster-based Routing Protocol (ANCRP) and Void Handling technique in ANCRP (VH-ANCRP) are proposed to enable the reliable data transfer in UWSN routing protocols. The ANCRP protocol is a cluster-based routing protocol to improve the reliable data transmission in terms of packet arrival rate, network throughput, and network longevity and minimize the packet drop ratio, propagation delay (latency), and energy consumption. While VH-ANCRP scheme is proposed to mitigate the void node issue by integrating a void handling technique and to improve the said network metrics.

We can summarize the paper contribution as follows:

- We divide the network space into a suitable number of 3D cubes. In which each cube represents a cluster. The detailed description of the network division is given in section IV-B.
- The multiple surface sinks are deployed on the sea-surface while the anchor nodes are deployed at the centroid of each cube and perform the job of the cluster head. The source nodes are randomly distributed in the network space as discussed in section IV-C.
- We propose two novel routing schemes named ANCRP and VH-ANCRP to enable the reliable data transfer in UWSN.
- In the ANCRP routing scheme, the process of an efficient route establishment for reliable data transfer metrics at the surface sinks is carried out. In the ANCRP scheme, all the source nodes within the cubes can only route the data packet towards their designated cluster heads. Then all cluster heads send the collected data towards the surface sinks via a hop-by-hop mechanism as discussed in section V.

- VH-ANCRP scheme focuses to integrate a void handling technique for the recovery of void nodes. Once a void node got recovery, it follows the ANCRP scheme to route the data packets in the direction of the cluster heads, which can further be disseminated towards the surface sinks. We discuss the VH-ANCRP protocol in section VI.

The rest sections of the paper are organized as: In section II, a presentation on various existing routing protocols for UWSN is given in terms of different techniques followed by their contribution comparison with our work. In section III, we conceive the problem statement. Section IV discusses the preliminary requirements about this study supported by assumptions, geometry of the network division, deployment architecture, and periodic beaconing procedure. Section V and section VI deliver an in-depth discussion on proposed schemes; ANCRP and VH-ANCRP, respectively. Section VII describes the simulation results in terms of different performance metrics. Section VIII gives the concluding remarks and work for the forthcoming paper.

II. LITERATURE REVIEW

Routing is a technique by which a reliable path is established for sending the data packets towards the destination [34], [35]. A routing protocol provides a set of procedures and rules for creating an appropriate and reliable path between the source node and the destination node by the cooperation of neighboring hops [36]. In the remainder of the section, we provide a brief discussion on existing routing protocols. Although, it is hard to obtain a taxonomic classification. Thus, we categorize the protocols into groups for presentation purposes. In these groups, we present reliable data transfer techniques, network division techniques, clustering techniques, and void handling techniques. In last, we provide a contribution comparison of the proposed study with literature review in underwater wireless sensor networks routing protocols (refer Table. 1).

A. RELIABLE DATA TRANSFER TECHNIQUES

The intention of these types of protocols is on the reliable data transfer. In [37], the authors have presented an Adaptive Energy-Aware Quality of Service (AEA-QoS) scheme to disseminate the data reliably. Their work contributed to the energy and QoS trade-off for achieving high network reliability, quality, and goodput. In addition, an adaptive holding time is used to minimize the latency, and packet collisions and to improve the network lifespan. In [38], authors proposed an Energy-efficient Multipath Grid-based Geographical Routing (EMGGR) approach. In order to curtail the latency, the large packet into small parts. In addition, multiple copies of the same packets are transmitted to improve the network reliability. But their scheme performs complex calculations for establishing a route towards the destination. In [17], authors have presented four schemes to improve data dissemination by incorporating different techniques. The first two schemes: A-DBR and B-DBR are proposed for avoiding the local maximum nodes. The last two schemes: CA-DBR and C-DBR are proposed for avoiding packet collisions during the packet transmissions. Henceforth, all four schemes have collaboratively focused on achieving the reliable data transfer metrics.

In [39], authors have presented an Efficient Data Delivery with Packet Cloning (EDDPC) scheme. The EDDPC scheme utilized the mechanism of packet cloning in order to distinguish the duplicate packets. Also, packets are transmitted on the basis of channel conditions and link quality by which reliability of the network is increased but the energy tax is compromised. In [2], authors have addressed different issues and suggested various techniques for efficient data collection in a harsh underwater WSNs. According to them, computational intelligence technique seems a prominent solution for efficient data collection from underwater environments. In [40], authors have presented a routing scheme named Radius-based Multipath Courier Node (RMCN) to achieve a high packet delivery rate and low latency by compromising the energy consumption and the network lifespan. In RMCN, the multiple sinks-based circular network architecture is divided into multiple arc lengths, in which the static nodes and mobile courier nodes are designated separately. The prime assignment of courier nodes is to collect the data from static nodes and send the couriers to the surface sinks.

B. NETWORK DIVISION TECHNIQUES

In [29], authors have developed an Energy-efficient regional based cooperative routing protocol for UWSNs with sink mobility (EERBCR), in which they partitioned the network space into multiple smart portions. They engaged multiple mobile sinks for the data collection from the network partitions. In [41], authors have segmented the network space into 3D small cubes to form clusters. The size of the cube and cluster dimensions are calculated based on the quality-of-service and energy metrics. In addition, a sleep-wake algorithm is designed to augment the network coverage and connectivity, and shorten the energy tax. In [42], authors have presented two schemes, the first scheme named Greedy Geographic Forwarding based on Geospatial Division (GGFGD) and another scheme named Geographic Forwarding based on Geospatial Division (GFGD). In the former scheme, a target cluster is selected but the distance of the target cluster with respect to surface sink should be less than that of the distance from the current cluster. In this way, the overall routing path is reduced. In the latter scheme, a forwarding candidate from the target cluster is selected, but only surface-adjacent target clusters are considered. The GFGD concerns the paths that are shorter than GGFGD to reduce the propagation delay.

C. CLUSTERING TECHNIQUES

Authors in [33] have proposed a novel routing protocol for UWSNs to cope with malicious attacks in order to improve the reliability of the network. They used multi-sink network architecture and clustering techniques in their works. The

TABLE 1. Contribution comparison of proposed study with literature review in UWSN routing protocols.

Contribution	Literature Review																Proposed Study
	[38]	[43]	[37]	[17]	[39]	[44]	[45]	[40]	[3]	[41]	[42]	[46]	[30]	[47]	[48]	[19]	
Reliable data transfer intention	✗	✓	✓	✓	✓	✗	✓	✓	✗	✓	✗	✓	✓	✓	✗	✓	✓
Multiple-sinks	✗	✓	✓	✓	**n/a**	✓	✓	✓	✓	**n/a**	✗	✓	✓	✓	✓	✓	✓
Mobile sinks	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
Layer formation	✓	✓	✗	**n/a**	✗	✓	✗	✗	✓	✓	✗	✓	✗	✓	✗	**n/a**	✗
Network partitioning (cube formation)	✓	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✓	✗	✓
Clustering technique	✗	✓	✗	✓	✗	✗	✗	✓	✓	✓	✗	✗	✓	✓	✗	✗	✓
Void handling technique	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✓	✓
Courier node assisting	✗	✓	✗	✗	✗	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗
Beaconing / hello packet	✗	✓	✗	✗	✗	✓	✗	✓	✓	✗	✗	✗	✗	✓	✗	✓	✓
Packet delivery ratio	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓
Packet drop / loss ratio	✗	✗	✗	✓	✓	✗	✗	✗	✗	✓	✗	✗	✗	✓	✗	✗	✓
Transmission loss	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
Network throughput	✗	✓	✗	✗	✗	✗	✓	✗	✓	✗	✗	✓	✗	✗	✗	✗	✓
Latency / delay	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✓	✓	✓	✓	✗	✗	✓
Energy Consumption / energy tax	✓	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✓	✓	✓	✗	✓	✓
Residual energy	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✗	✗	✗	✗	✗	✗
Network lifetime / operating time	✗	✓	✗	✓	✗	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓
Accumulative propagation distance	✗	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✓	✓	✗	✗	✗	✗
Fractional number of void nodes	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓
Density of alive / operational / working nodes	✗	✗	✗	✓	✗	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗	✓
Density of dead nodes	✗	✗	✗	✗	✗	✗	✓	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗
Routing overhead	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗

cluster heads are being recognized and verified by the gateway to ensure that all nodes within the clusters are valid nodes. Their scheme offered a high data delivery rate and reduced energy tax and latency. Authors in [7], have opted the clustering technique to cope with the high-power utilization and to optimize the network life cycle. They presented a new hybrid clustering scheme, in which they integrate Fuzzy C-Means method along with Moth-Flame Optimization to enhance the performance of the network. Their scheme outperforms the baseline schemes in terms of energy tax and number of operational nodes. The same purpose for optimizing the network lifespan and energy utilization is presented by Weijian Yu *et al.* in [13]. In their scheme, they have clustered the network and used the UAV (Unmanned Aerial Vehicle) to communicate with CHs. They utilized the multi-hop communication technique to perform the routing.

Authors in [12] also presented a clustering technique for balancing the energy consumption. Their scheme unitises the multi-hop technique to perform the routing. In [43], authors have presented the Clustered-Based Energy Efficient Routing (CBE2R) scheme, in which clusters are formed at the seabed layer. The courier nodes are used as CH in the CBE2R routing scheme and collect the data from the anchor nodes via relay nodes. For the enhancement of the network lifetime, the mobility of the courier nodes is controlled via a string. The CBE2R scheme performs better in terms of energy consumption and network lifetime. In [3], authors have introduced Multi-Layer Cluster-based Energy Efficient (MLCEE) scheme for miniaturizing the energy tax and resolving the hotspot issue. The MLCEE scheme is comprised of various stages: 1) layer formation by dividing the network space, 2) clustering the nodes within the layers, and 3) selection of forwarding hop by the cluster head took place. The MLCEE scheme performs better than the baseline schemes in terms of energy tax, network lifetime, and data transmission rate.

D. VOID HANDLING TECHNIQUES

In [46], authors have presented the Weighting Depth and Forwarding Area Division-Depth Based Routing (WDFAD-DBR) scheme to tackle the issue of void nodes. In the WDFAD-DBR scheme, the source node checks the status of the second-hop of the forwarding node, whether it is void or not. In this case, if the second-hop of the forwarding node is void then the source node changes the routing path. Another work for avoiding the void nodes is illustrated in [30]. In which, the authors have presented two schemes titled Adaptive Transmission Range in WDFAD-DBR (ATR-WDFAD-DBR) and Cluster-Based WDFAD-DBR (CB-WDFAD-DBR). In the first scheme, the void hole issue is resolved by the adjustment of transmission range of the void nodes to locate the forwarding node. In the second scheme, the clustering technique is used to curtail energy consumption and latency.

In [47], the authors have presented a scheme that adapts to three different types of networks to cope with the local maximum nodes. Their work offers a high packet transfer rate and low end-to-end delay. In [48], the underwater nodes are geographically distributed in the network space along with cube information. In their scheme, the next-hop candidate is selected on the basis of position information and packet

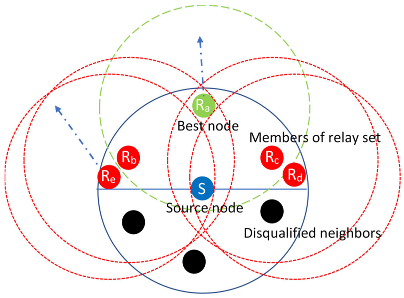

FIGURE 1. Multipath propagation issue.

delivery probability. In addition, the advantage of mobile sinks is taken to capture the data from the void nodes. In [19], the author has proposed three schemes. Out of those three schemes, one scheme named Fallback Approach NADEEM (FA-NADEEM) is given for tackling the issue of void nodes. FA-NADEEM uses the mechanism of adjusting the transmission range of the void nodes dynamically to resume the greedy forwarding technique of transmitting the data packets.

III. PROBLEM STATEMENT

However, both geographic routing and opportunistic routing might be reliable in data transmission. But the biggest flaw of these routing protocols is that they select a single node from the relay set for data transmission in each hop. This means that the whole routing path relies on a single node in each hop. Let us assume that this single node drains its energy completely, then ultimately a void space will be created in the routing path. Although many geographic and OR protocols are available in the UWSN literature to cope with the void issue [16], [19], [23], [24], [46]. Yet the void space remains un-sensed. In addition, the geographic and OR routing protocols are widely suffered from hidden node terminal. Moreover, it seems that the geographic and OR protocols suffered from the multipath problem as all the selected relay nodes are not within the transmission range of each other. So, the packet transmission by the best relay node (Ra) cannot suppress all other unwanted transmissions, for example, relay node (Re) can hear the transmission of the best node hence it may rebroadcast the packet as shown in Fig. 1.

Well, these issues can be resolved by dividing the network space into a suitable number of clusters [3], [41], [43]. The reason behind the cluster formation is to split the whole network space into multiple spaces [7]. Another motive for clustering the network is to optimize the network lifespan [13] and miniaturize the energy tax [29]. Nevertheless, the main issue in the clustering techniques is that the cluster head is selected from the set of ordinary nodes, which means that this set of ordinary nodes perform so many calculations to select a cluster head. After becoming a cluster head, it has to load the data and information of its all members in form of the routing table. This increases the communication overhead and also drains the energy of the cluster head rapidly. To resolve the said issues, we propose two solutions; one is proposed for minimizing the communication overhead and energy consumption by using anchor nodes as cluster heads and the other is proposed for tackling the void nodes issue, named as ANCRP and VH-ANCRP, respectively.

IV. PRELIMINARY REQUIREMENTS

For this work, the preliminary requirements are discussed as under:

A. ASSUMPTIONS

We divide the network virtually in 3D cubes as also suggested in literature [41], [42], [49], [50]. Virtual segmentation provides flexibility and also covers the process of joining to other clusters. The process is not rigid and can be done with less number of communication steps which will not burden the network. We use anchor nodes as cluster heads and control their positions with the help of string (or cable) [41], [43]. Thus, the source nodes can get their 2D location data (x and y *coordinates*) with the aid of received beacon messages sent by the cluster heads on the basis of Time-of-Arrival (ToA) ranging method [51]. The ToA is an energy-efficient technique for finding the location data of the nodes as nodes consume less energy in receiving the messages than in transmitting the messages [52]. Thus, this method reduces extra energy consumption for getting the location data of the nodes. Whereas, nodes can get their depth data ($z - coordinate$) via a depth-pressure sensor [53]. Moreover, the transitions of water waves are mostly observed in horizontal manner, their vertical transitions are very limited and insignificant, so it can be overlooked [51]. For simplicity, we enumerate the above assumptions as follows:

1) The whole network space is divided into small cubes $\mathcal{C}_{\mathcal{K}}$ to form clusters [41], [49].
2) The cluster heads are anchored with the help of string (or cable) [41], [43].
3) The 2D location data (x and y *coordinates*) for all network elements can be obtained through the position algorithm [51].
4) Each node acquires its current level of depth with the help of pressure sensor [51] as in [23], [53].
5) The vertical transitions of the nodes are less significant and can be ignored [51] as in [16], [23].
6) The transmission radius of the source nodes and cluster heads are $T_{rad}^{\mathcal{N}_i} = \frac{\mathcal{CW}}{2}$ and $T_{rad}^{\mathcal{CH}_K} = \mathcal{CW}$, respectively.

B. NETWORK DIVISION FOR CLUSTER FORMATION

The total network space ($\mathcal{NS}$) is given as ($\mathcal{X} \times \mathcal{Y} \times \mathcal{Z}$). Now, we divide the whole network space into non-overlapping small volumes in the form of cubes for making clusters[1].[2] Meanwhile, the volume of a cube ($\mathcal{CS}$) is ($\mathcal{CW} \times \mathcal{CW} \times \mathcal{CW}$) (or $\mathcal{CW}^3$), where $\mathcal{CW}$ denotes the cluster-width (or cubic-width). In the network division, we consider the volume of the network ($\mathcal{X} \times \mathcal{Y} \times \mathcal{Z}$) (3D coordinate system). Where $\mathcal{Z}$-plane represents the depth in underwater. For partitioning

[1] A cube has six sides and eight vertices.
[2] Cube can also be referred to as a cluster and vice versa hereinafter.

TABLE 2. Summary of the network division.

#	Number of clusters	Total network space $(\mathcal{NS} = \mathcal{X} \times \mathcal{Y} \times \mathcal{Z})$ m^3	Single cluster size $(\mathcal{CW} = \mathcal{CW} \times \mathcal{CW} \times \mathcal{CW})$ m^3
1	2^3	$600 \times 600 \times 600$	$300 \times 300 \times 300$
2	2^3	$800 \times 800 \times 800$	$400 \times 400 \times 400$
3	2^3	$1000 \times 1000 \times 1000$	$500 \times 500 \times 500$
7	4^3	$600 \times 600 \times 600$	$150 \times 150 \times 150$
8	4^3	$800 \times 800 \times 800$	$200 \times 200 \times 200$
9	4^3	$1000 \times 1000 \times 1000$	$250 \times 250 \times 250$
7	6^3	$600 \times 600 \times 600$	$100 \times 100 \times 100$
8	6^3	$800 \times 800 \times 800$	$133 \times 133 \times 133$
9	6^3	$1000 \times 1000 \times 1000$	$167 \times 167 \times 164$

the network space into a suitable number of cubes, we have:

$$\mathcal{K} = \frac{(\mathcal{X} \times \mathcal{Y} \times \mathcal{Z})}{(\mathcal{CW} \times \mathcal{CW} \times \mathcal{CW})} \tag{1}$$

or, Equation. 1 can be written as:

$$\mathcal{K} = \frac{(\mathcal{X} \times \mathcal{Y} \times \mathcal{Z})}{(\mathcal{CW}^3)} \tag{2}$$

where $\mathcal{K}$ variable represents the total number of cubes (or clusters). We choose $\mathcal{K}$ as a raised number that is the power of three: $\mathcal{K} = 2^3, 3^3, 4^3, 5^3$ and so on. Because the network space should be divided in equal sizes and the number of partitions should be a perfect cubed as shown in Figure. 3. By rearranging the Equation. 2 and we get:

$$\mathcal{CW} = \sqrt[3]{\frac{(\mathcal{X} \times \mathcal{Y} \times \mathcal{Z})}{\mathcal{K}}} \tag{3}$$

Hence, the width of a single cube can be calculated from the Equation. 3. Now, we can easily divide our network space into more or less number of cubes to get the different number of clusters as per network requirements. The steps of partitioning the network space are described in Algorithm 1. By referring to the Equations. 1, 2 and 3, we have given a summary of different cluster sizes and numbers for different network sizes in Table. 2.

Hence, each cluster $\mathcal{C}_i$ has 3D coordinates $(\bar{x}_i, \bar{y}_i, \bar{z}_i)$, ranges from:

$$\mathcal{C}_i(\bar{x}_i, \bar{y}_i, \bar{z}_i) = \{(\bar{x}_i|_{min}^{max}, \bar{y}_i|_{min}^{max}, \bar{z}_i|_{min}^{max})\} \tag{4}$$

From Equation 4, there will be 8-vertices of a single cube $\mathcal{C}_i$ as shown in Fig. 2.

C. NODES DEPLOYMENT

Henceforth, after the network division into cubes (or clusters), we deploy the network elements as per our network architecture design requirements. We consider a 3D UWSN network architecture as depicted in Fig. 3. The network architecture includes four different network elements, i.e., onshore monitoring center, surface sinks, anchor nodes (or cluster heads), and source nodes. The detailed steps of the network elements' deployment are mentioned in the Algorithm 2. Following different network elements are considered for the network deployment:

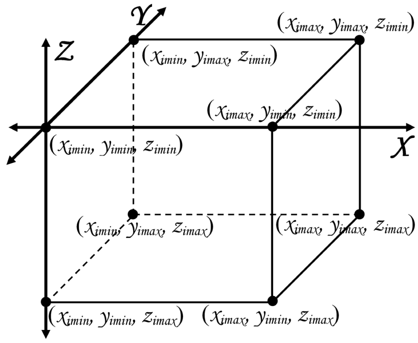

FIGURE 2. 3D coordinates system of a cube.

Algorithm 1 Network Division for Cluster Formation

Input : $\mathcal{NS}$ and $\mathcal{K}$
Output: $\mathcal{CS}$ and $\mathcal{CW}$
Result : Clusters are formed

while *(Clusters are not formed)* **do**
- $\mathcal{NS}$ is $(\mathcal{X} \times \mathcal{Y} \times \mathcal{Z})$
- Divide the $\mathcal{NS}$ into $\mathcal{K}$ cubes
  - ∘ Calculate $\mathcal{CW} = \sqrt[3]{[\frac{(\mathcal{X}\times\mathcal{Y}\times\mathcal{Z})}{\mathcal{K}}]}$
  - ∘ $\mathcal{K}$ is a raised number to the power of three
- Each cube represents the cluster and has space:
  - ∘ $\mathcal{CS} = \mathcal{CW} \times \mathcal{CW} \times \mathcal{CW}$
- The cube $\mathcal{C}_i$ has 3D coordinates:
  - ∘ $\mathcal{C}_i(\bar{x}_i, \bar{y}_i, \bar{z}_i) = \{(\bar{x}_i|_{min}^{max}, \bar{y}_i|_{min}^{max}, \bar{z}_i|_{min}^{max})\}$
  - ∘ $\mathcal{C}_i(\bar{x}_i, \bar{y}_i, \bar{z}_i)$ has 8-vertices

end

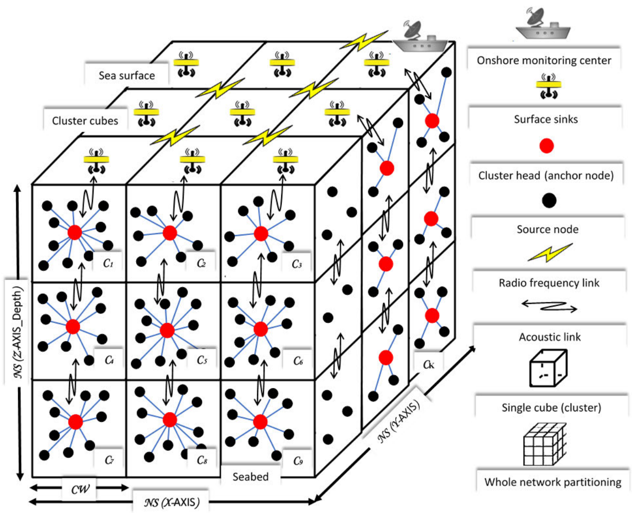

FIGURE 3. 3D UWSN network architecture.

- **Onshore monitoring center** is located at the surface of the water. It uses a radio frequency (RF) link to fetch the collected data from the surface sinks.
- **Surface sinks** have two interfaces of communication; RF link and acoustic link to communicate with monitoring center and underwater nodes, respectively. Surface sinks

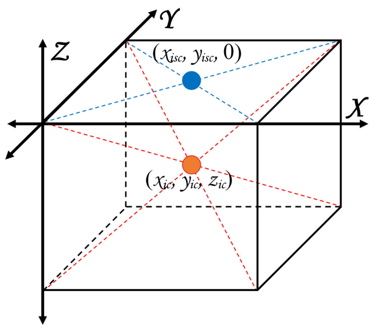

FIGURE 4. Surface-center and centroid of a cube.

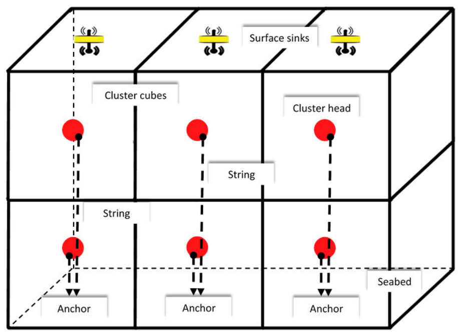

FIGURE 5. Surface-sinks and anchor nodes (cluster heads) placement diagram.

receive the data packets from the cluster heads and then forward the aggregated data to the monitoring center. These are deployed at the center of the surface layer cubes having $\mathcal{Z}-coordinate$ (depth) equals to zero (i.e. $\bar{z}_i = 0$) as shown in Fig. 3. Therefore, if a cube has surface corners $\{(\bar{x}_i, \bar{y}_i, 0)\}_{i=1}^{4}$, then the surface-center $\mathcal{C}_{isc}$ of a cube $\mathcal{C}_i$ can be calculated just by taking the arithmetic mean of the given coordinates by using the Equation. 5:

$$\mathcal{C}_{isc}(\bar{x}_{isc}, \bar{y}_{isc}, 0) = (\frac{\sum_{i=1}^{4}}{4}\bar{x}_i, \frac{\sum_{i=1}^{4}}{4}\bar{y}_i, 0) \quad (5)$$

where $(\bar{x}_{isc}, \bar{y}_{isc}, 0)$ are the surface-center coordinates of cube $\mathcal{C}_i$ as shown in Fig. 4.

- **Anchor nodes** collect the data from source (or sensor) nodes and forward it to the next-hop anchor node and continues this procedure till the successful delivery of data packets at the surface sinks. Anchor nodes communicates via an acoustic link with other nodes and surface sinks. These are suspended at discrete depth levels in underwater with the aid of string at the centroid of each cube as a cluster head (see Figure. 5). Therefore, if a cube has corners $\{(\bar{x}_i, \bar{y}_i, \bar{z}_i)\}_{i=1}^{8}$, then the centroid $\mathcal{C}_{ic}$ of a cube $\mathcal{C}_i$ can be calculated from the Equation. 6:

$$\mathcal{C}_{ic}(\bar{x}_{ic}, \bar{y}_{ic}, \bar{z}_{ic}) = (\frac{\sum_{i=1}^{8}}{8}\bar{x}_i, \frac{\sum_{i=1}^{8}}{8}\bar{y}_i, \frac{\sum_{i=1}^{8}}{8}\bar{z}_i) \quad (6)$$

where $(\bar{x}_{ic}, \bar{y}_{ic}, \bar{z}_{ic})$ represents the centroid coordinates of cube $\mathcal{C}_i$ as shown in Fig. 4. We control the mobility of the anchor nodes with the help of a string (or cable) [41], [43] in order to keep them static as shown in Fig. 5.

- **Source nodes** are the ordinary sensor nodes and placed randomly within the network space. The source nodes are employed to collect the aquatic environmental data. These nodes also use the acoustic link for transmitting the data packets to the anchor nodes (or cluster heads). The nodes distribution in each cube can be observed from Fig. 3.

D. PERIODIC BEACONING PROCEDURE

Beacon information enables the network elements for reliable data dissemination from source to destination [49]. Once, we deploy all the network elements in the network space. Initially, all network elements are isolated from each other.

Algorithm 2 Nodes Deployment

Input : $\mathcal{K}$ and $\mathcal{C}_i(\bar{x}_i, \bar{y}_i, \bar{z}_i)$
Output: $\mathcal{C}_{isc}$ and $\mathcal{C}_{ic}$
Result : The network architecture is established
while *(MainCenter, SurfaceSinks, AnchorNodes and Nodes are not set)* **do**
  Deploy the onshore monitoring center at the sea-surface level
  for $i = 1$ *to* $\mathcal{K}$ *with step* $i{+}{+}$ **do**
    The cube $\mathcal{C}_i$ has 3D coordinates:
    ∘ $\mathcal{C}_i(\bar{x}_i, \bar{y}_i, \bar{z}_i) = \{(\bar{x}_i|_{min}^{max}, \bar{y}_i|_{min}^{max}, \bar{z}_i|_{min}^{max})\}$
    if $z = 0$ *(depth = 0)* **then**
      Find the surface-center $\mathcal{C}_{isc}$ of a cube $\mathcal{C}_i$:
      $\mathcal{C}_{isc}(\bar{x}_{isc}, \bar{y}_{isc}, 0) = (\frac{\sum_{i=1}^{4}}{4}\bar{x}_i, \frac{\sum_{i=1}^{4}}{4}\bar{y}_i, 0)$
      Deploy the surface sink $\mathcal{S}_i$
    end
    Find the centroid $\mathcal{C}_{ic}$ of a cube $\mathcal{C}_i$:
    $\mathcal{C}_{ic}(\bar{x}_{ic}, \bar{y}_{ic}, \bar{z}_{ic}) = (\frac{\sum_{i=1}^{8}}{8}\bar{x}_i, \frac{\sum_{i=1}^{8}}{8}\bar{y}_i, \frac{\sum_{i=1}^{8}}{8}\bar{z}_i)$
    Deploy the anchor node as a cluster head ($\mathcal{CH}_i$).
  end
  Deploy the $\mathcal{N}$ nodes randomly in the network ($\mathcal{X} \times \mathcal{Y} \times \mathcal{Z}$).
end

In this context, beacon messages are propagated to cascade all network elements with each other [23]. The beacon message is initiated by the surface sinks for cascading the network. In our work, the beacon message is only broadcasted by the surface sinks and cluster heads. The ordinary source (sensor) nodes are not liable to broadcast the beacon message, which curtails communication overhead and energy utilization. But the source node can receive the beacon message for the estimation of its current cube and designated cluster head to send the data packets. The information in the beacon message is maintained by the all-network elements in the form of a routing table and is updated after the expiry of the beacon interval. Generally, the protocols use random jitters [16], [23], [24] as beacon intervals to avoid packet collisions. Accordingly, we are also using the random jitter for setting the

seq_n (S_i)	ID (S_i)	CubeID (S_i)	coordinates (S_i)

(a) for sink node

seq_n (CH_i)	ID (CH_i)	CubeID (CH_i)	coordinates (CH_i)

(b) for cluster head

FIGURE 6. Beacon packet format.

beacon interval. The beaconing procedure among the network elements is given in Algorithm 3.

The beaconing process consists of a) broadcasting (Algorithm 3: line 1-20) and b) reception of a beacon message (Algorithm 3: line 21-45). The beacon message packet consists seq_n, *unique ID*, *CubeID* and x, y, z *coordinates* information of the surface sinks and the cluster heads (Algorithm 3: line 6-16) as shown in Fig. 6a and Fig. 6b, respectively. Thus, whenever a beacon message is received by the $\mathcal{CH}_i$ from the surface sink(s), the $\mathcal{CH}_i$ update the information in $\mathfrak{B}(\mathcal{CH}_i).Table$ as depicted in Algorithm 3: line 27. Otherwise, the $\mathcal{CH}_i$ updates the neighboring $\mathcal{CH}_n$ information (Algorithm 3: line 29- 30). The $\mathcal{CH}_i$ maintains the information of known surface sink and neighboring CHs in the $\mathfrak{B}(\mathcal{CH}_i).Table$, which comprised of $seq_n(x)$, $ID(x)$, $coordinates(x)$, and $CubeID(x)$ information of the individuals (i.e., surface sink(s) and $\mathcal{CH}_i$). Where x represents the flag. Thus $flag(x)$ changes its status to zero after every successive entry, which indicates that the message has not been spread to its neighbors (Algorithm 3: line 33). A new beacon message will follow Algorithm 3: line 8-14 in each iteration. Similarly, whenever a beacon message is received by the source node $\mathcal{N}_i$ from the $\mathcal{CH}_i$, it also updates the entry in the $\mathfrak{B}(\mathcal{N}_i).Table$. Algorithm 3: line 37-34 demonstrate the beacon messages handling procedure by the source nodes ($\mathcal{N}_i$).

V. ANCRP ROUTING PROTOCOL

In this section, the explanation of the proposed Anchor Nodes assisted Cluster-based Routing Protocol (ANCRP) is given. The ANCRP protocol follows the network architecture as depicted in Fig. 3. In the beginning, all network elements are isolated from each other. They can recognize their visibility through broadcasting a beacon message. The beaconing procedure is used to share the local information of the nodes (surface sinks and cluster heads) with neighboring CHs and ordinary source nodes. By which source nodes can decide a route towards their designated CH, while CH can get the reachability information towards the surface sinks with the help of neighboring CHs. After the establishment of the routing path through a random beaconing procedure, the source node starts sending the sensed data to its respective CH only. By which, average end-to-end delay and energy consumption as reduced. In addition, the network lifetime is increased. Then, all CHs send the collected data to the surface sinks in coordination with other CHs that are nearer to the surface as depicted in Fig. 3. The detailed mechanism for reliable data transfer in ANCRP protocol is explained as follows.

Algorithm 3 Periodic Beaconing Procedure

Input : Random jitter
Output: The network is cascaded
Result : The routing path is established

```
1  procedure BroadcastBeaconMsg(sink, node)
2      𝔅: a modified beacon message with next seq_n
3      if beacon time runs out then
4          𝔅.CubeID ← CubeID(node)
5          𝔅.location ← coordinates(node)
6          if node ∈ CH_n then
7              for x ∈ 𝔅(CH_i).Table do
8                  if flag(x) = 0 then
9                      𝔅.Msg ←add− seq_n(x)
10                     𝔅.Msg ←add− ID(x)
11                     𝔅.Msg ←add− coordinates(x)
12                     𝔅.Msg ←add− CubeID(x)
13                     flag(x) ← 1
14                 end
15             end
16         end
17         Broadcast 𝔅.Msg
18         Set a new time
19     end
20 end
21
22 procedure ReceiveBeaconMsg(𝔅)
23     if 𝔅.Msg is received by S_i then
24         Discard the 𝔅.Msg
25     else if 𝔅.Msg is received by CH_i then
26         if 𝔅.Msg is from sink nodes then
27             update info in (𝔅(CH_i).Table, 𝔅)
28         else
29             modify_neighbor_CH_n
30             (B.seq_n, B.ID, B.coordinates, B.CubeID)
31             for x ∈ B do
32                 if seq_n(x, B) > seq_n(x, 𝔅(CH_i).Table)
                   then
33                     modify info in (𝔅(CH_i).Table, x)
34                 end
35             end
36         end
37     else if 𝔅.Msg is received by N_i then
38         update info in (𝔅(N_i).Table, 𝔅)
39         for x ∈ B do
40             if seq_n(x, B) > seq_n(x, 𝔅(N_i).Table) then
41                 modify info in (𝔅(N_i).Table, x)
42             end
43         end
44     end
45 end
```

Algorithm 4 Reliable Data Transmission in ANCRP

Input : $\mathfrak{B}(\mathcal{N}_i).Table$ and $\mathfrak{B}(\mathcal{CH}_i).Table$
Output: Transmission of data packets
Result : Data packets arrived successfully at destination

procedure *TransmitDataPackets*($\mathcal{N}_i$, *packets*)
  Source node $\mathcal{N}_i$ has its information:
  location: (x_i, y_i, z_i) and cube: $CubeID(\mathcal{N}_i)$
  Fetch data from $\mathfrak{B}(\mathcal{N}_i).Table$
  if $CubeID(\mathcal{N}_i) = CubeID(\mathcal{CH}_i)$ **then**
    Send data packets to CH $(\mathcal{CH}_i)$
  else
    Source node $\mathcal{N}_i$ has set of CHs $(\mathcal{CH}_K)$
    Source node $\mathcal{N}_i$ computes the distance $D_{\mathcal{N}_i}^{\mathcal{CH}_K}$
    Send data packets to the nearest CH $(\mathcal{CH}_j)$
  end
end

procedure *TransmitDataPackets*($\mathcal{CH}_i$, *packets*)
  $\mathcal{CH}_i$ has its information:
  location: $(\bar{x}_i, \bar{y}_i, \bar{z}_i)$ and cube: $CubeID(\mathcal{CH}_i)$
  Fetch data from $\mathfrak{B}(\mathcal{CH}_i).Table$
  if $CubeID(\mathcal{CH}_i) = CubeID(\mathcal{S}_i)$ **then**
    Send data packets to the $\mathcal{S}_i$
  else if $CubeID(\mathcal{CH}_i) \neq CubeID(\mathcal{S}_i)$ **then**
    $\mathcal{CH}_i$ has set of surface-sinks $\mathcal{S}_P$
    $\mathcal{CH}_i$ computes the distance $D_{\mathcal{CH}_i}^{\mathcal{S}_P}$
    Send data packets to the nearest $\mathcal{S}_j$
  else
    $\mathcal{CH}_i$ has set of neighboring $\mathcal{CH}_K$
    $\mathcal{CH}_i$ computes the depths of neighboring $\mathcal{CH}_K$: $d_{\mathcal{CH}_i}^{\mathcal{CH}_K}$
    if $d_{\mathcal{CH}_i} > d_{\mathcal{CH}_K}$ **then**
      Send data packets to the $\mathcal{CH}_j$
    end
  end
end

A. RELIABLE DATA TRANSFER MECHANISM IN ANCRP

The main steps for reliable transmission of data packets in ANCRP protocol are explained in Algorithm 4. There are two parts of Algorithm 4, in the first part, the data transmission mechanism for the source nodes $(\mathcal{N}_i)$ is given, and in the second part, the data transmission mechanism for the CHs $(\mathcal{CH}_i)$ is given.

1) DATA TRANSMISSION MECHANISM FOR SOURCE NODES

The source node $(\mathcal{N}_i)$ measures the information from the aquatic environments. Whenever a source node has data packets to send at the surface sinks $(\mathcal{S}_i)$ then it scans the routing table $\mathfrak{B}(\mathcal{N}_i).Table$ to check its concerned CH $(\mathcal{CH}_i)$, for which the $CubeID(\mathcal{N}_i)$ and $CubeID(\mathcal{CH}_i)$ must be identical. If the *CubeID* matches, then the source node forwards the data packets. In case, the source node didn't find its concerned CH, then it will choose the nearest CH from the routing table. The transmission radius of the source nodes is synchronized with half of the cluster width (i.e., $T_{rad}^{\mathcal{N}_i} = \frac{\mathcal{CW}}{2}$). By which, the source node can reach the CH, even it lies at the border of the cube. In this way, the multipath propagation issue can be avoided. Also, the problem of the hidden node terminal is resolved.

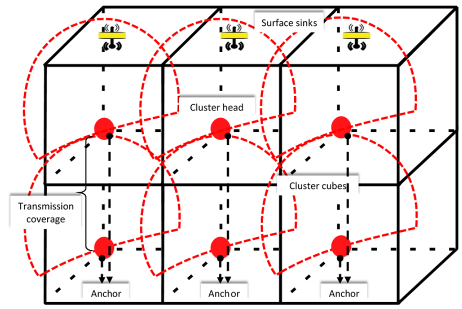

FIGURE 7. Transmission coverage of the cluster heads.

2) DATA TRANSMISSION MECHANISM FOR CLUSTER HEADS

In ANCRP protocol, anchor nodes are used as CHs to collect the sensed data packets from underwater source nodes. Henceforth, CHs have data packets to send at the surface sinks, for which they scan the routing table $\mathfrak{B}(\mathcal{CH}_i).Table$ to find any nearest surface sink $(\mathcal{S}_i)$. The CHs of lower cubes will identify the neighboring CHs as a next-hop that has a lower depth level than themselves. Hence, in this way, the data packets will successfully reach the destination. The transmission radius of the CH is tuned with the cluster width (i.e., $T_{rad}^{\mathcal{CH}_K} = \mathcal{CW}$) to cover the maximum volume of the cluster and can reach the neighboring CH as shown in Fig 7.

B. DATA COLLECTION BY THE SURFACE SINKS

Multiple surface sinks are engaged to collect the information from its trailing clusters only, using an acoustic medium. Which latterly, forwarded to the onshore monitoring center by using RF communication medium.

VI. VH-ANCRP ROUTING PROTOCOL

Here, we discuss the Void Handling technique in ANCRP (VH-ANCRP) in detail. The VH-ANCRP scheme is comprised of two steps: in the first step, a void node detection procedure is given (refer lines: 1 to 17 in the Algorithm 5), and in the second step, a void node recovery procedure is given (refer lines: 19 to 43 in the Algorithm 5).

A. VOID NODE DETECTION

There are so many reasons for occurring a void space, such as the node drains its energy completely [54], it moves away from the network space [50], and the source node does not have any potential neighbor or sinks [49], [55]. Henceforth, due to the dynamic nature of water waves, the nodes are prone to move in a random direction. For nodes mobility,

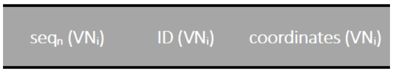

FIGURE 8. Search-neighboring-CH message by the void node.

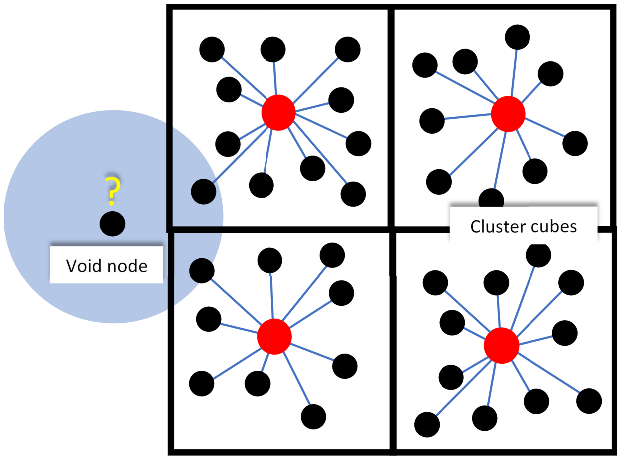

FIGURE 9. Void node detection.

we apply a 2D RandomWalk mobility model with a speed of 1-3 m/s [46], [56]. According to this, nodes can move horizontally in a 2D manner. While vertical movements of the nodes are less significant, so it can be ignored [51]. Now, let us assume that if a node moves with a speed of $\mathcal{V}$ to cover a known distance $\mathcal{D}_{max}$ then we can calculate the time $\mathcal{T}_m$ as [50]:

$$\mathcal{T}_m = \frac{\mathcal{D}_{max}}{\mathcal{V}} \tag{7}$$

Concerning the above context in ANCRP protocol, if a node moves from its current cluster, then there will be two possibilities either this node enters the neighboring cluster or it exists from the network region. The node will check its current position after time $\mathcal{T}_m$. If a node is entering the neighboring cluster then it is still inside the network space and performs its operations. If a node exists from the network region then it becomes a void node ($\mathcal{VN}_i$) as shown in Fig. 9. So, whenever a node does not find its potential CH, it will broadcast a search-neighboring-CH message ($\mathcal{SNCH}_K.Msg$) to all nearby nodes in order to save the data from loss. The void node shares the seq_n, *ID* and *coordinates* information in the $\mathcal{SNCH}_K.Msg$ as shown in Fig. 8.

B. VOID NODE RECOVERY

There are so many methods and techniques are in the literature review of UWSN routing protocols to handle the void hole or recovery of void nodes, for example, topology control via depth adjustment [16], [57], depth variance [54], transmission adjustment [45], mobile sinks [49], bypassing the void space [24], [55], pressure-based [57], [58], power control [55] and cooperation with relay nodes for performing some dedication operation in relaying the data in case of void occurrence [49].

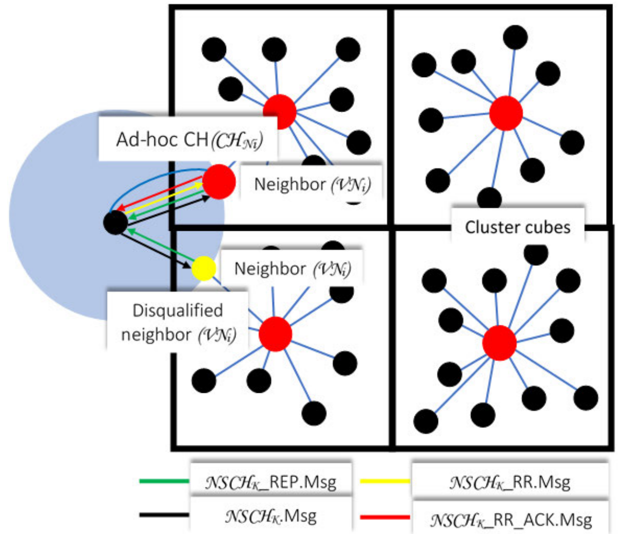

FIGURE 10. Void node recovery.

Thus, our proposed scheme VH-ANCRP deals in the cooperation of neighboring nodes to cope with the void holes. In VH-ANCRP, if a node moves away from the network and does not find any CH in its vicinity, it disseminates a search-neighboring-CH message ($\mathcal{SNCH}_K.Msg$) to inform the neighbors. In the case, this void node does not have any neighbor node or the neighbor node itself is a void node, then the void node discards all the data packets as potential forwarding nodes are not available for collecting the data packets [49]. If the void node has neighbors ($Neighbors(\mathcal{VN}_i)$) that are connected with the cluster, replies a search-neighboring-CH-reply message ($\mathcal{SNCH}_K\_REP.Msg$) along with its reachability information and designated CH. If the void node receives multiple replies from the neighbor nodes, then it computes the depth-differences of the neighboring nodes. The void node selects the neighboring node having the lowest depth and close proximity to the surface sinks and send a route-request message ($\mathcal{SNCH}_K\_RR.Msg$) for becoming an ad-hoc CH. If the neighboring accepts the request, and further replies with an acknowledgment message ($\mathcal{SNCH}_K\_RR\_ACK.Msg$). Hence, the routing path for a void node is established. Once the void node finds the suitable routing path, it follows the ANCRP protocol to broadcast the data packets to the ad-hoc CH for the concerned CH.

VII. SIMULATION WORK

In this section, we have described the detailed description of simulation work for the evaluation of the proposed protocols.

A. SIMULATION SETTING

We used a discrete event type network simulator (NS3) [59] to carry out the extensive simulations to check the performance of ANCRP and VH-ANCRP routing protocols. In simulation setting, we assumed a 3D network space $\mathcal{NS}$ of dimensions 600m × 600m × 600m and divide the $\mathcal{NS}$ in clusters ($\mathcal{K} = 3^3$). We used 9 surface sinks, 27 anchor nodes based

Algorithm 5 Void Handling Mechanism

Input : $\mathcal{D}_{max}$, $\mathcal{V}$, $\mathcal{T}_{sim}$ and $\mathcal{NS}$
Output: Void node detection and recovery
Result : Void node issue resolved

procedure *VoidNodeDetection*($\mathcal{VN}_i$)
  if *Node* $\mathcal{N}_i$ *moves with speed of* $\mathcal{V}$ **then**
    Compute $\mathcal{T}_m = \frac{\mathcal{D}_{max}}{\mathcal{V}}$
    for $j = 0$ *to* $\mathcal{T}_{sim}$ *with respect to* $\mathcal{T}_m$ **do**
      Node $\mathcal{N}_i$ has coordinates (x_i, y_i, z_i)
      Network $\mathcal{NS}$ has coordinates $(\mathcal{X}, \mathcal{Y}, \mathcal{Z})$
      if $(\mathcal{X}, \mathcal{Y}, \mathcal{Z})_{min} \leq (x_i, y_i, z_i) \leq (\mathcal{X}, \mathcal{Y}, \mathcal{Z})_{max}$
      then
        $\mathcal{N}_i \in \mathcal{NS}$
      else
        $\mathcal{N}_i \notin \mathcal{NS}$
        The node $\mathcal{N}_i$ becomes void node $\mathcal{VN}_i$
      end
    end
  end
  The void node $\mathcal{VN}_i$ broadcasts: $\mathcal{SNCH}_K.Msg$
end

procedure *VoidNodeRecovery*($\mathcal{VN}_i$)
  The *Neighbors*($\mathcal{VN}_i$) will receive $\mathcal{SNCH}_K.Msg$
  if *Neighbors*($\mathcal{VN}_i$) $= \varnothing$ **then**
    Drop the data packets
  else if *Neighbors*($\mathcal{VN}_i$) $=$ *VoidNode* **then**
    Drop the data packets
  else
    The *Neighbors*($\mathcal{VN}_i$) broadcast:
    $\mathcal{SNCH}_K\_REP.Msg$
    if *The void node* $\mathcal{VN}_i$ *receives multiple replies:*
    $\mathcal{SNCH}_K\_REP.Msg$ **then**
      The void node $\mathcal{VN}_i$ computes the depth-differences of *Neighbors*($\mathcal{VN}_i$)
      if $d_{\mathcal{N}_i} < d_{\mathcal{N}_j}$ **then**
        The node $\mathcal{VN}_i$ will broadcast:
        $\mathcal{SNCH}_K\_RR.Msg$ for $\mathcal{N}_i$ to become Ad-hoc CH ($\mathcal{CH}_{\mathcal{N}_i}$)
      else
        The node $\mathcal{VN}_i$ broadcasts:
        $\mathcal{SNCH}_K\_RR.Msg$ for $\mathcal{N}_j$ to become Ad-hoc CH ($\mathcal{CH}_{\mathcal{N}_j}$)
      end
    end
    The Ad-hoc CH ($\mathcal{CH}_{\mathcal{N}_i}$) broadcasts:
    $\mathcal{SNCH}_K\_RR\_ACK.Msg$ for $\mathcal{VN}_i$
    The node $\mathcal{VN}_i$ sends data packets to Ad-hoc CH ($\mathcal{CH}_{\mathcal{N}_i}$)
  end
end

CHs, and distribute the source nodes ranging from 50 to 350 randomly in the $\mathcal{NS}$. The behavior of network elements is supposed to be hybrid in terms of mobility (i.e., surface sinks and CHs are kept fix at their positions, while source nodes can move in 2D fashion with a speed of 1-3m/s.). For the mobility of the nodes, we used RandomWalk 2D mobility model as used in [46], [56].

We set various other simulation parameters as defaults according to LinkQuest UWM1000 (an underwater acoustic modem) [60]. The transmission radius of CHs and source nodes was set as $\mathcal{CW}$ m and $\frac{\mathcal{CW}}{2}$ m, respectively. The sound wave speed is 1500 m/sec. The channel bit rate and bandwidth were set as 10 kbps, 4 Khz, respectively. We fixed 1200 sec for one simulation round, and the results obtained from the simulations are averaged from a total of 400 rounds. The values for various simulation parameters are tabulated in Table. 3.

TABLE 3. Simulation setup.

Sr #	Parameter	Value
1	3D Network size	600m x 600m x 600m
2	Cluster $\mathcal{CW}$	200m x 200m x 200m
3	Number of clusters $\mathcal{K}$	3^3
4	Number of surface sinks	9
5	Number of anchored CHs	27
6	Number of nodes	50 to 350
7	Compared algorithms	CBE2R, RMCN, EMGGR
8	Physical modem	LinkQuest UWM1000 [60]
9	Modulation type	BPSK
10	Mobility model	2D random walk
11	Transmission radius of CH	$\mathcal{CW}$ m
12	Transmission radius of source node	$\frac{\mathcal{CW}}{2}$ m
13	Acoustic Propagation speed	1500 m/s
14	Data packet size	50 bytes
15	Channel bit rate	10 kbps
16	Bandwidth	4 Khz
17	Transmission Power	90dB re μ Pa
18	Power tax to transmit packet	2 units
29	Power tax to receive packet	0.75 W
20	Power tax to overhear packet	8 mW
21	Simulation time	1200 sec
22	Total simulation rounds	400
23	Simulating software	NS3 [59]

B. PERFORMANCE METRICS

We assess the performance of proposed schemes; ANCRP and VH-ANCRP with baseline solutions (CBE2R [43], RMCN [40] and EMGGR [38]) in terms of following performance metrics:

1) *Average Packet Delivery Ratio (PDR):* It can be defined as the sum of number of received packets successfully ($PKTs_{rx}$) at the surface sinks to the sum of number of transmitted packets ($PKTs_{tx}$) by the source node. Avg. PDR in terms of ratio (%) can be calculated as [38]:

$$Avg.PDR = \frac{\sum PKTs_{rx}}{\sum PKTs_{tx}} \times 100 \quad (8)$$

2) *Average Packet Drop Ratio (PDrR):* It can be defined as the ratio of total sum of dropped packets ($Total\ PKTs_{gen}$) at the surface sinks during the data transmission versus the total sum of generated packets

($Total\ PKTs_{gen}$) by the source node. We can calculate it in terms of ratio (%) as follow [46]:

$$Avg.PDrR = \frac{\sum Total\ PKTs_{dropped}}{\sum Total\ PKTs_{gen}} \times 100 \quad (9)$$

3) *Average Network Throughput (NT):* It can be defined as the sum of total number of packets received ($PKTs_{rx}$) successfully at the surface sinks with respect to total time (*Time*) for entire network. It is usually measured in Kbps. It can be calculated as [43], [46]:

$$Avg.NT = \frac{\sum PKTs_{rx}}{Time} \quad (10)$$

4) *Average End-to-End Delay (E2E delay):* It can be defined as the average time is required by a data packet to reach at the surface sinks. The Avg. E2E delay is the total time being taken by a data packet from generation to the successfully delivery at the destination. We have considered only those packets that were successfully arrived (D_{rx}) at the destination. It can be calculated as [38]:

$$Avg.E2E = \frac{\sum_{n=1}^{D_{rx}} (Arrival\ Time_n - Send\ Time_n)}{D_{rx}} \quad (11)$$

5) *Average Energy Consumption (EC):* It can be defined as the total amount of energy utilized by all network nodes throughout the network operation during the simulation. It is set of transmitting power ($Tx\ Pow_n$), receiving power ($Rx\ Pow_n$) and idling power ($Idle\ Pow_n$) utilized by all nodes ($\mathcal{N}$). Mathematically it can be calculated as [38]:

$$Avg.EC = \sum_{n=1}^{\mathcal{N}} Tx\ Pow_n + Rx\ Pow_n + Idle\ Pow_n \quad (12)$$

6) *Average Network Lifetime (NLT):* It can be defined as the total time span during which the network operations are remained fully functional. NLT is computed in seconds. Hence, network lifetime in unit time ($NLT(t)$) can be calculated as [17]:

$$Avg.NLT = \sum_{t=1}^{t_{max}} NLT(t) \quad (13)$$

7) *Fractional Number of Void Nodes:* It can be defined as the number of nodes that are outside from the cluster region and unable to find any CH for forwarding the data packets. In can simply be defined as the number of nodes that are unable to find any forwarding node in the neighboring set to route the data packets in the direction of surface sinks. It can be calculated as [49]:

$$Frac.No.Void.Nodes = \frac{Frac: \#\ of\ void\ nodes}{Total\ \#\ of\ nodes} \quad (14)$$

8) *Number of Operational Nodes (ON):* It can be defined as the total number of nodes that are still alive or fully operational even after the suspension of the network operations (or simulation). Mathematically, we can calculate the ON by subtracting the dead nodes ($\mathcal{DN}$) from total number of nodes ($\mathcal{N}$) as follows [17]:

$$ON = \mathcal{N} - \mathcal{DN} \quad (15)$$

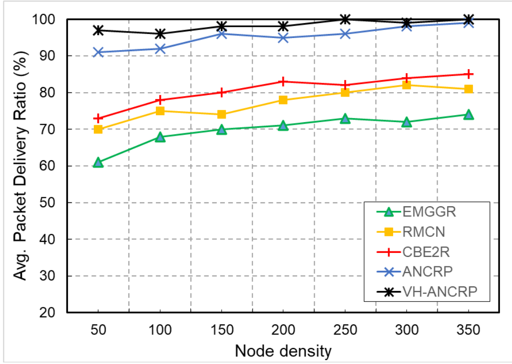

FIGURE 11. Avg. packet delivery ratio versus node density.

C. PERFORMANCE EVALUATION

Here, we discuss the simulation results with respect to the performance metrics (discussed in section VII-B) in detail.

1) AVERAGE PACKET DELIVERY RATIO

In Fig. 11, the average PDR versus node densities for the proposed schemes (ANCRP and VH-ANCRP) and the baseline schemes (EMGGR, RMCN, and CBE2R) is plotted. It is obvious that the PDR can be increased by increasing the node densities in all schemes. This is because a greater number of nodes are engaged to cover the maximum volume of the network and void spaces are also occupied by increasing the node density. The Fig. 11, reflects that the proposed schemes have given a high value for the PDR than the benchmark schemes. The key reason behind the good PDR rate is that the transmission range for source nodes is tuned with the cluster width to reach the CH. On the contrary, in CBE2R, some nodes are unable to reach the CH. Thus, offered a lower PDR rate than the proposed schemes. Another motivation for getting a high PDR rate in the proposed is that of using anchor nodes as cluster heads. While other schemes, such as RMCN and EMGGR have not considered the clustering technique in their work. Therefore, suffered from packet redundancy issues.

Furthermore, the VH-ANCRP scheme achieves better PDR results than the ANCRP scheme, because the VH-ANCRP scheme uses a void handling technique to rescue the void nodes. The rescue mission of finding the void nodes is carried out by making ad-hoc CHs. Which plays the role of a bridge between the void nodes and anchored CH. Hence, the PDR rate is slightly more in VH-ANCRP than in ANCRP protocol. While in benchmark schemes, the CBE2R achieves high PDR than other benchmarks schemes, such as RMCN and EMGGR, because the CBE2R has used the fixed courier nodes as a CH, which collects the data from seabed nodes in

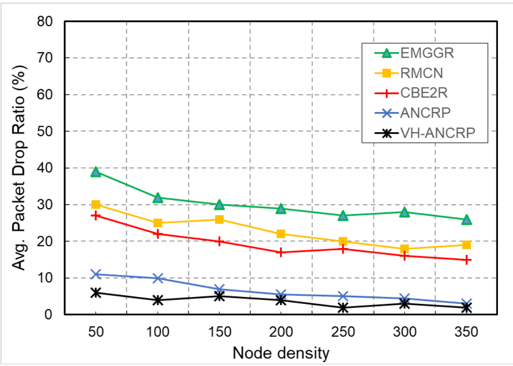

FIGURE 12. Avg. packet drop ratio versus node density.

coordination with relay nodes. Whereas PDR in the RMCN scheme is more than the EMGGR scheme. Because the RMCN scheme has used mobile courier nodes to augment the PDR, while EMGGR used a grid-by-grid mechanism to relay the data packets. In the grid-by-grid routing technique, the routing-path is changed dynamically and resulted in a low PDR rate. Therefore, it can be concluded that the reliable data transmission motive in the proposed schemes has been achieved successfully.

2) AVERAGE PACKET DROP RATIO

The average packet drop ratio for the proposed schemes and baseline solutions is depicted in Fig. 12. We can observe that the baseline solutions gave poor results for dropped packets as compare to ANCRP and VH-ANCRP protocols. As stated in the above PDR results, the ANCRP and VH-ANCRP offer good PDR than the existing protocols, that's why the packet drop ratio is minimum in the proposed schemes and vice versa for the aforementioned existing protocols. Similarly, the packet drop ratio is minimum in CBE2R protocol than the RMCN and EMGGR protocols. Because CBE2R protocol has used the clustering technique. While EMGGR and RMCN did not use the clustering technique in their schemes. Another reason for the high packet drop ratio in EMGGR is that the usage of gateways for collecting the data packets from source nodes, and the mobility of the gateways is uncontrollable. But all rest of the schemes have used the special nodes to collect the data packets from the source nodes and their mobility is also controllable. VH-ANCRP has the least contribution in the packet drop ratio than all other schemes because it tackles the void node issues. By which void nodes can also contribute to the PDR, resulting in a low packet drop ratio. Therefore, it is concluded that the packet drop ratio is significantly less in the proposed schemes than the baseline schemes.

3) AVERAGE NETWORK THROUGHPUT

Fig. 13 portrays the graph for the average network throughput versus different node densities for the proposed protocols and the benchmarks protocols. It can be observed that the VH-ANCRP and ANCRP protocols achieve better average

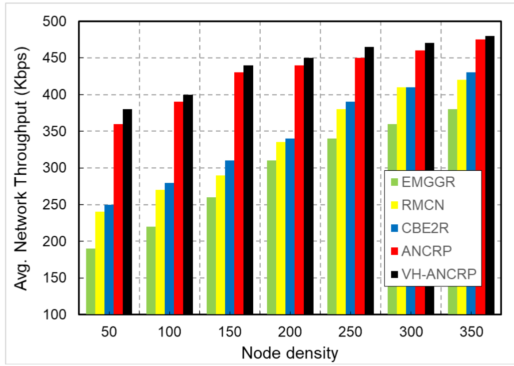

FIGURE 13. Avg. network throughput versus node density.

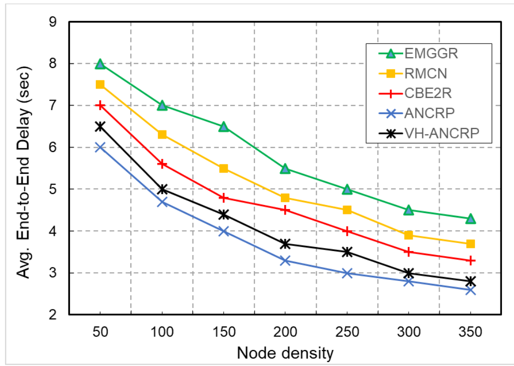

FIGURE 14. Avg. end-to-end delay versus node density.

network throughput than CBE2R, RMCN, and EMGGR protocols. The proposed protocols get a high data rate at the surface sinks because the transmission range for source nodes are adjusted as per cluster width by which nodes can easily send the data packets at their respective CHs. In addition, the proposed schemes also avoid the hidden terminal issue, packet redundancy, and retransmissions. The network throughput of CBE2R and RMCN are moderate for both sparse and dense networks because these protocols have not focused to resolve the hidden terminal issue and the void space issue, which curtails the network throughput.

On the other hand, the ANCRP protocol avoids the hidden terminal problem, and the VH-ANCRP protocol tackles all three issues as stated earlier. The EMGGR protocol has the lowest contribution to the average network throughput than the rest of the compared protocols. Because the EMGGR protocol performs very complex mathematics, which ultimately brings a reduction in the network throughput. EMGGR protocol has given no solution regarding the hidden terminal and void space. Hence, it can be concluded that the proposed schemes have achieved better results for the average network throughput than existing schemes as the number of redundant packets are reduced due to transmission range adjustment of source node and CHs as per $\mathcal{CW}$.

4) AVERAGE END-TO-END DELAY

Fig. 14 demonstrates the average end-to-end delay comparison between the proposed protocols (ANCRP and VH-ANCRP) and the existing protocols (CBE2R, RMCN, and EMGGR). The results are plotted for the average E2E

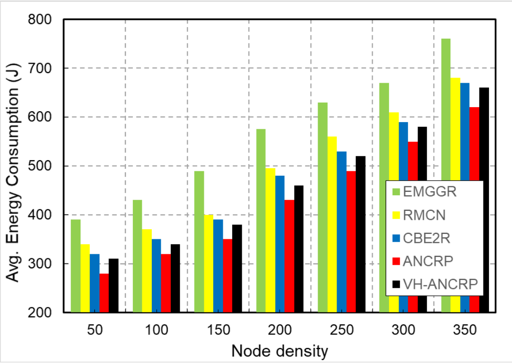

FIGURE 15. Avg. energy consumption versus node density.

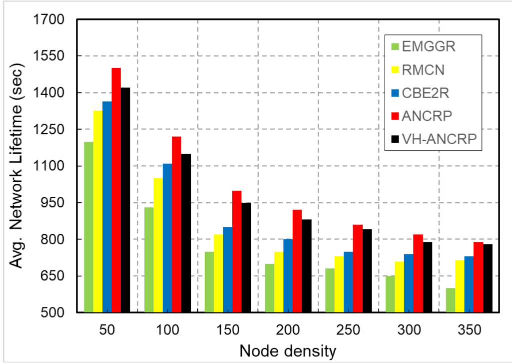

FIGURE 16. Avg. network lifetime versus node density.

delay with respect to different node densities. It can be observed that ANCRP has the lowest E2E delay and EMGGR has the highest E2E delay in both sparse and dense networks. The average E2E delay of ANCRP and VH-ANCRP is lower than other protocols because these protocols have used anchored CHs, which reduce the E2E delay. Meanwhile, the clustering technique also reduces the overall propagation distance of the routing in ANCRP and VH-ANCRP, resulting in a low E2E delay. Also, the effective route selection in ANCRP and VH-ANCRP for reliable data transmission is opted, which ultimately reduces the E2E delay.

The average E2E delay for CBE2R and RMCN is higher than the ANCRP and VH-ANCRP routing protocols, although both existing protocols have used powerful courier nodes to fetch the data packets from the source nodes. The main reason behind this is that the transmission range for the source nodes in ANCRP and VH-ANCRP protocols is tuned as per cluster width by which nodes can easily and shortly reach the CH. While other schemes have overlooked to incorporate a technique for reaching the destination in a short period. The average E2E delay for EMGGR is maximum than the rest of the protocols because it uses a complex technique for the route selection, such as grid-by-grid, which consumes a lot of time to establish a routing path. Besides this, EMGGR has not used the clustering technique and the node mobility is also not defined in EMGGR, due to which the data packets are required more time to reach the destination.

5) AVERAGE ENERGY CONSUMPTION

Fig. 15 depicts the average energy consumption comparison between the proposed protocols and the existing protocols with respect to multiple node densities. It can be observed that the ANCRP and VH-ANCRP protocol consume less energy in the packet sensing, processing, and transmitting than CBE2R, RMCN, and EMGGR protocols. Because ANCRP and VH-ANCRP have used anchored CHs and set the transmission range of the source nodes according to the length of the clusters, which helps to cope with multipath propagation issues. On the other hand, all benchmark schemes have not integrated any technique to suppress the multipath transmissions. Henceforth, the same packet is transmitted by the multiple relay nodes and have to pay a high energy tax accordingly.

In addition, the ANCRP and VH-ANCRP protocol have engaged anchored CHs for collecting the packets from ordinary source nodes. The average energy consumption of the VH-ANCRP protocol is higher than the ANCRP protocol but less than CBE2R, RMCN, and EMGGR protocols because it consumes more energy in the finding of void nodes. The void node broadcasts certain messages to the neighbors for requesting to become an ad-hoc CH. The ad-hoc CH helps the void nodes to establish a routing path towards the designated CH. The energy consumption of the VH-ANCRP protocol is slightly less than CBE2R and RMCN in sparse and dense networks. But the difference margin is higher when compared with EMGGR protocol because EMGGR performs complex calculations to establish the routing paths. Hence, we can conclude that the average energy consumption of proposed protocols is less than the benchmark protocols.

6) AVERAGE NETWORK LIFETIME

The average network lifetime is referred to as a time until the network operation is fully functional, and all elements of the network are operational and alive. Fig. 16 determines a quantitative comparison of proposed protocols with existing protocols in terms of average network lifetime against different node densities. The average network lifetime of ANCRP and VH-ANCRP is higher than other protocols. Because these protocols have used the simple technique of cluster formation and assign anchor nodes as predetermined CHs. The nodes that lie within the cluster can easily reach the CH. Hence source nodes cannot send multiple copies of the data packets, which increases the lifespan of the nodes. Meanwhile, the network lifetime of ANCRP is higher than VH-ANCRP because the VH-ANCRP protocol requires extra energy for the determination and recovery of void nodes. Therefore, the network lifetime of VH-ANCRP is shorter than ANCRP but greater than CBE2R, RMCN, and EMGGR, respectively.

The CBE2R and RMCN have offered less network lifetime than ANCRP and VH-ANCRP protocols. Because in CBE2R protocol, the data packets are routed towards the CHs via relay nodes, and these relay nodes are prone to change their

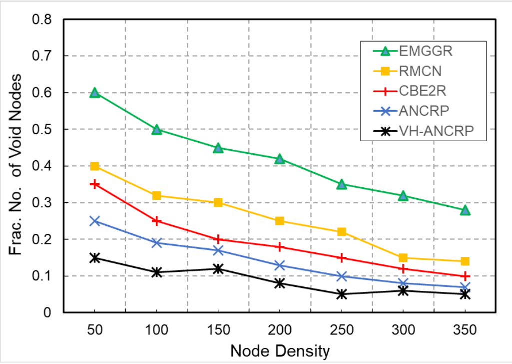

FIGURE 17. Fractional number of void nodes versus node density.

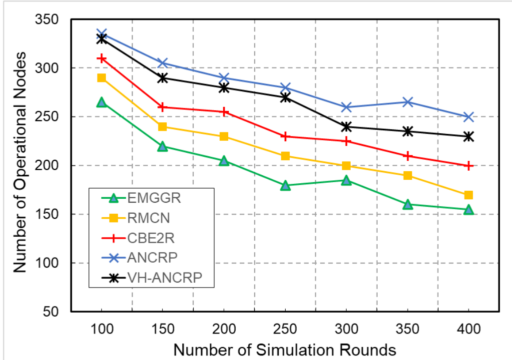

FIGURE 18. No. of operational nodes.

positions by water waves, which disturbs the network topology. Hence, nodes require extra energy to send the packets multiple times. While in RMCN protocol, a lot of energy is wasted in controlling the mobility of the courier nodes, which ultimately reduces the network lifetime. The average network lifetime of EMGGR is the lowest than all other protocols. As in EMGGR protocol, the virtual cell formation through the 3D grid mechanism is highly complex and dynamic. The position of the virtual cell is also quite away from the destination. Hence, the nodes of the virtual cell are suffered from multipath propagation issues and resulting in a low network lifetime.

7) FRACTIONAL NUMBER OF VOID NODES

Fig. 17, we perform a comparison on the fractional number of void nodes versus varying node densities for the proposed schemes and the benchmark schemes. It can be observed that the graph of VH-ANCRP and ANCRP protocols for the fractional number of void nodes is declining gradually by increasing the node densities. The fractional number of void nodes for the VH-ANCRP and ANCRP is quite less than other baseline schemes. This happens because the VH-ANCRP and ANCRP are dealing with anchored CHs and synchronized transmission range of the source nodes with respect to the cluster dimensions.

These features help the VH-ANCRP and ANCRP schemes in reducing the fractional number of void nodes. VH-ANCRP protocol has a less fractional number of void nodes than ANCRP protocol because it takes advantage of the void handling mechanism. After the proposed protocols, CBE2R and RMCN have a less fractional number of void nodes than EMGGR protocol because of opting the controlled mobility technique for the courier nodes. This controlled mobility of the nodes reduces the occurrence of void nodes than the uncontrolled mobility of the nodes as in EMGGR protocol. Moreover, in EMGGR protocol, the possibility of the void nodes occurrence is high because it is difficult and complex to find the next-hop candidate node for routing the data packets in the direction of the surface sinks in the grid-by-grid routing mechanism. This issue can be minimized by integrating a clustering technique in the routing protocols as in VH-ANCRP, ANCRP, and CBE2R protocols. The key difference between VH-ANCRP and other schemes is that of using a void handling technique. Henceforth, the VH-ANCRP protocol shows better performance in this metric than the rest of the schemes.

8) NUMBER OF OPERATIONAL NODES

The number of operational nodes versus simulation rounds for different routing protocols can be observed in Fig. 18. Fig. 18 shows that the proposed schemes (ANCRP and VH-ANCRP) offer more reliability and stability in terms of operational nodes than other existing works (CBE2R, RMCN, and EMGGR). The operation of the nodes depends on the network longevity [61]. Thus, the number of operational nodes can be improved by avoiding unnecessary transmissions and re-transmissions to minimize the surplus energy consumption. The proposed schemes improve the reliability and achieve better results for this metrics because of integrating the anchor nodes as CHs and tune the transmission range of the nodes according to the cluster size. Thus, all the nodes within the cluster region can easily approach the corresponding CH and send the data packets easily. Hence, the probability of the redundant packets is significantly reduced and the packet re-transmissions can also be avoided.

On the other hand, the existing protocols did not incorporate any mechanism to either control or avoid the redundant packets and packet re-transmissions, resulting in high energy consumption and the number of working nodes are reduced. Although, the CBE2R protocol used the clustering technique but did not consider any strategy regarding energy consumption and network lifetime so that nodes can remain operational for a long period. After the CBE2R scheme, the RMCN protocol achieved better results in terms of the number of operational nodes against simulation rounds than the EMGGR protocol. The EMGGR protocol has the lowest figure in terms of operational nodes because it failed to control the unnecessary packet transmissions by which network longevity is suffered and nodes cannot remain operational for a long period.

9) SUMMARY OF THE SIMULATION RESULTS

Here in this section, we provide a summary and concluding remarks on VH-ANCRP, ANCRP, EBE2R, RMCN, and

TABLE 4. Summary of the simulation results.

Protocol	Reference	Features	Concluding remarks
EMGGR	[38]	Grid-by-grid routing is performed in coordination with gateways to route the data packets via disjoint paths.	Low performance in terms of all network metrics.
RMCN	[40]	Triangular-based network segmentation is performed and mobile courier nodes are used to collect the data from static nodes.	Fair performance and void hole issue exists.
CBE2R	[43]	Clustering technique and controlled courier nodes are used to collect the data from anchor nodes. The CBE2R scheme is suitable for deepwater applications and harsh environmental conditions.	Improved network network lifetime, low energy consumption, and multipath transmission issue exists.
ANCRP	This works	Network division, clustering technique, and anchor nodes as cluster heads are used to achieve the reliable data transfer metrics. The ANCRP scheme also mitigates the multipath transmission problems	The reliable data transfer metrics have been achieved successfully in terms of all performance metrics.
VH-ANCRP	This works	This is an extended version of the ANCRP scheme that exploits a void handling technique to cope with the void nodes.	Void node issue has been resolved at the cost of energy consumption and network lifetime.

EMGGR protocols on basis of simulation results in terms of all performance metrics as given in Table 4. The simulation results revealed that the EMGGR protocol has shown low performance with respect to the aforementioned performance metrics. The RMCN protocol has used mobile courier nodes to achieve a high PDR rate and minimize the latency. But the RMCN protocol has shown fair performance when compared with other protocols. The CBE2R protocol is found suitable for deepwater and harsh environmental conditions. The performance of the CBE2R protocol is better than RMCN and EMGGR protocols but less than VH-ANCRP and ANCRP protocols. The ANCRP protocol has utilized the clustering technique by dividing the network region into equalized cubes and used the anchor nodes as CH. The simulation results declare that the ANCRP protocol performs very well in all performance metrics and provide a technique for reliable data dissemination. It has been concluded from the simulation results that the VH-ANCRP protocol provides a solution for the recovery of void nodes. On the contrary, all other protocols did not consider the issue of void nodes in their works.

VIII. CONCLUSION

In this paper, we have proposed two novel routing protocols to achieve reliable data transmission metrics along with optimum energy consumption and enhanced network lifetime to make the protocols more reliable and efficient. The first scheme ANCRP is proposed to augment the performance metrics of the network. While the second scheme VH-ANCRP is proposed to cope with the void nodes. The 3D network division into small equalized cubes has been carried out to form the clusters. Then each cluster is assigned with an anchor node as a cluster head to collect the data packets from randomly distributed source (sensor) nodes. The multiple surface sinks are used to collect the data packet from CHs. We perform a quantitative comparison of proposed schemes with existing schemes (CBE2R, RMCN, and EMGGR) in terms of average PDR, average packet drop ratio, average network throughput, average end-to-end delay, average energy consumption, average network lifetime, fractional number of void nodes and number of operational nodes. The ANCRP scheme showed better effectiveness in end-to-end delay, network lifetime, and energy consumption than the VH-ANCRP scheme. Whereas, the VH-ANCRP scheme gave better results for average PDR, average packet drop ratio, and network throughput at the cost of high energy consumption and low network lifetime than the ANCRP scheme. It has been revealed in the simulation results that both proposed schemes outperform the existing approaches in all said performance metrics. For future work, we intend to design a secure and encrypted data aggregation techniques for clustered architecture to improve the network reliability and authenticity.

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