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A Novel Clustering Protocol for Network Lifetime Maximization in Underwater Wireless Sensor Networks

Amitkumar V. Jha, Bhargav Appasani, Mohammad S Khan, and Houbing Herbert Song .

Abstract—Underwater wireless sensor network (UWSN) is a pervasive technology with different characteristics and requirements, where energy conservation is a stringent requirement. Improving the network lifetime can have tremendous practical utility in these networks. The energy of the nodes in the network can be conserved by devising an efficient cluster head selection mechanism. This paper presents a novel energy-efficient clustering protocol (EECP) for the UWSN. The proposed protocol segregates the network based on horizontal clustering. In every iteration, the cluster heads are selected based on the energy level of the nodes. The performance of the proposed protocol is measured in terms of energy efficiency and network lifetime. Moreover, the performance of the EECP is further improved by adding nearest neighbor criteria for selecting the cluster head. This protocol is named as energy-efficient clustering protocol with nearest neighbor (EECP-NN). The efficacy of the proposed protocols is evaluated by comparing their performance with some of the state-of-the-art cluster-based protocols in this study.

Index Terms—Wireless sensor network, Clustering, Routing Protocol, lifetime maximization

I. INTRODUCTION

THE recent advancements in micro-electromechanical sensors and devices have revolutionized the paradigm of short-range wireless communication. The wireless sensor network (WSN) technology uses the ad-hoc network architecture to support short-range wireless communication. However, the WSN and ad-hoc networks are different. They differ in node density, robustness, network topology dynamics, resource, addressing mechanism, communication technology, etc. [1]. The WSN can be used in various applications such as environmental monitoring, traffic monitoring, object tracking, soil monitoring, disaster management, distributed tactical surveillance, mine reconnaissance, etc. [2], [3]. One of the important applications of the WSN is in underwater applications such as oceanographic monitoring, offshore data collection, navigation, disaster management, reconnaissance surveillance, pollution monitoring, and control [4]. The networks where WSN is employed in underwater environments are popularly referred to as underwater WSN (UWSN).

Amitkumar V. Jha and Bhargav Appasani are with the School of Electronics Engineering, Kalinga Institute of Industrial Technology, Bhubaneswar 751024, India email: amit.jhafeet@kiit.ac.in and bhargav.appasanifeet@kiit.ac.in. Mohammad S. Khan is with Department of Computer Information Sciences, East Tennessee State University, Johnson City, USA email: ad-hoc.khan@gmail.com. Houbing H Song is with the Department of Information Systems, University of Maryland, Baltimore County, Baltimore, MD 21250 email: h.song@ieee.org

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The UWSN is a special type of WSN that can be differentiated across several disciplines such as environment, communication medium, node mobility, and energy efficiency from each other as follows [5]. Environment: WSNs are typically deployed in terrestrial environments, such as on land or in the atmosphere. On the other hand, UWSNs are designed for underwater environments, such as oceans, seas, and lakes. They operate in an environment where water is the primary transmission medium. Communication Medium: WSNs use radio frequency (RF) communication for data transmission. Meanwhile, UWSNs use acoustic waves for communication because radio waves are unsuitable for underwater communication due to high attenuation and absorption in water. Node Mobility: Nodes in a WSN are usually stationary or have limited mobility. They are often deployed in fixed locations and do not need to move frequently. However, nodes in UWSNs may need to be mobile to adapt to changing ocean currents or to move to specific areas of interest. Energy Efficiency: Both types of networks face energy challenges, but UWSNs may face more significant challenges due to the energy-intensive nature of acoustic communication and the difficulty of replacing or recharging batteries underwater.

The UWSN consists of many tiny sensors (hereafter referred to as sensor nodes or simply nodes) deployed inside the water spanning particular areas arranged in clusters [6]. The networks are designed to associate each node with a certain cluster. Each node in the UWSN does not transmit the data directly to the sink. Instead, they transmit the data to one of the cluster nodes, designated as the cluster head (CH). The CH then transmits the data from the sensor nodes within a cluster to the base station (BS) or the sink. It may also transmit the data to another CH, which works as a relay in multi-hop communication. The sink communicates the sensor data from the CH to the end user over the Internet infrastructure. Consequently, nodes in a wireless sensor network can be classified into the following main types: source, destination, and coordinator. Source nodes are ordinary nodes with limited capabilities and are responsible for communicating their data to the CH. Destination nodes are the sink nodes, and coordinator nodes are the CH, which serve the purpose of data routing from source to destination.

The UWSN is one of the best-suited technologies for impassable environments to sense the data and communicate the data to remotely located destinations over a wireless link. However, the traditional radio wave is not feasible for establishing a wireless link because it requires very high power

to compensate for the higher attenuation loss in underwater propagation. Moreover, due to high precision in optical communication, which is not feasible in UWSN, even optical communication seems impractical for establishing wireless links in UWSN. Thus, acoustic wireless communication is the only best candidate known for the wireless link in UWSN [7].

The UWSN is still in its nascent stage. It is still plagued with some unique challenges due to its acoustic communication channels, such as [8],

- Higher bit error rate: Underwater acoustic communication is characterized by higher bit error rates, intermittent connectivity, and erratic connectivity. As a result, to get around this crucial limitation, the associated communication protocols should include more sophisticated error detection and correction methods.
- Propagation delay: The propagation delay exceeds that of RF transmission by a wide margin. It is higher specifically by five orders of magnitude. This poses a serious issue for data transmission for real-time applications, such as multimedia communication.
- Bandwidth: In comparison to RF transmission, bandwidth is highly constrained. Furthermore, the distance has a big impact on it. In more detail, it fluctuates between a few KHz at several tens of kilometers and about 100KHz at distances of only a few tens of meters.
- Inability to integrate advanced processing techniques: To overcome the issues and difficulties of underwater acoustic communication channels, advanced signal processing techniques are required. The power consumption and associated energy requirements rise due to these signal-processing processes. This is a crucial issue to consider if we want to extend the network lifetime as much as possible and avoid the unpleasant process of changing or charging batteries in an underwater environment.

In a nutshell, limited bandwidth, random delay, higher bit error rate, limited battery capacity, limited lifetime, limited processing capabilities, etc., are the major constraints in acoustic wireless communication. Apart from these, network security and privacy are the other challenges that hinder the implementation of UWSN for real-time applications.

One of the important problems is the energy constraint of the nodes in the WSN [9]. Since UWSNs are generally deployed in insurmountable environments where electric supply is not feasible, batteries are used as the prime energy source. The limited battery energy restricts the data processing capability of the sensor nodes. The network lifetime is related to the energy consumption of the nodes in the WSN, and the network lifetime can be significantly improved through judicious utilization of the energy of the sensor nodes. Thus, energy conservation and network lifetime maximization are the two vital aspects that must be focused on while designing the UWSN.

It has been shown that the routing protocol plays a significant role in the energy utilization and lifetime maximization of the WSN [10]. Under the delay constraints, the effect of routing protocols on the performance of the WSN is comprehensively discussed in [11], [12]. Nevertheless, significant improvement is observed in the performance of WSNs using

clustered-based routing protocols [13], [14]. The state-of-the-art survey on clustered-based routing protocols is presented in [15]. In a nutshell, an efficient routing protocol is an optimistic approach to realizing UWSN for its ubiquitous applications.

This paper presents novel clustering routing protocols for energy conservation and network lifetime maximization for UWSNs. The significant contributions of this paper are summarized below.

- A novel energy-efficient clustering protocol (EECP) based on a horizontal clustering approach is proposed in this paper.
- The efficacy of EECP is further improved by incorporating the nearest neighboring criteria in CH selection. The improved version of EECP is known as EECP with nearest neighbor (EECP-NN).
- The efficacy of EECP and EECP-NN protocols are evaluated by comparing their performance with some of the well-known state-of-the-art clustered-based routing protocols used in UWSN.

The rest of the paper is organized into the following sections. Section II describes the existing protocols for UWSNs. The constituents of the UWSN and its network model are discussed in the third section. Section IV comprehensively discusses the proposed clustering protocols, followed by the related simulations in Section V. The conclusion is the last section of this work.

II. PROTOCOLS FOR UWSNs

The UWSN is an important network class where energy is one of the major constraints. Researchers have largely focused on the energy constraint as it is a major hindrance to the practical implementation of UWSN. The most comprehensive survey on routing protocols for UWSN is presented by J. Luo et al. in [16] surveyed the UWSN routing protocols under three categories: geographical-based, data-based, and energy-based. Another seminal work is carried out by S. Khisa et al. in [17] in which the most comprehensive survey on routing protocols from an energy efficiency perspective is covered in detail. With the help of these references [16], [17], we reviewed the protocols discussed in this reference and cited references for the comparative analysis of the performance of the proposed protocols. Some of the important protocols relevant to the present work in the domain of UWSN are described in this section.

As opposed to flat routing, where all nodes perform similar tasks, the hierarchical routing protocols group the nodes into a cluster such that each cluster has a CH, which is responsible for coordinating the other member nodes. It can be inferred from the literature that the hierarchical-based routing protocols are energy-efficient and scalable compared to their counterparts. The low-energy adaptive clustering hierarchy (LEACH) is the first and most popular hierarchical routing protocol proposed in [18] for WSNs. Since its proposal in 2000, the LEACH protocol has been a highly researched protocol from various aspects of the WSN, such as its latency, security, load balancing, scalability, energy efficiency, coverage, connectivity, etc. Even the LEACH protocol is explored across various

application domains, including UWSN. The importance of the LEACH protocol can be understood from an extensive survey presented in [19], which discussed the numerous variants of LEACH. LEACH protocol fails if the distance between CH and sink is more than a certain threshold since the energy dissipation of CH becomes proportional to the fourth power of the distance between CH and sink [20]. Thus, in the case of a large network, the multi-hop LEACH (MH-LEACH) protocol performs better than LEACH [21]. Not only this, but it has also been shown that the MH-LEACH performs better than the hybrid energy-efficient distributed (HEED) protocol [22].

Considering the unique features of the UWSN, SHEENA (sensor hop-based energy efficient networking approach) protocols have been proposed for UWSN by S. Kohli et al. [23]. Furthermore, it has been demonstrated by the authors that SHEENA protocols perform better for UWSN applications than the MH-LEACH protocol. The cluster-based routing protocols for UWSN are proposed by A. Khan et al. in [24] based on the adaptive power control principle, which improves its latency and energy consumption performance. In [25], Ahmed et al. proposed a clustered-based energy efficient routing (CBE2R) protocol in which authors proved that the CBE2R performs better than the reliable and energy efficient protocol (REEP), energy-efficient multipath grid-based geographic routing (EMGGR), and energy-efficient routing protocols (DRP). Another version of cluster-based routing protocols known as anchor node-assisted cluster-based routing protocols (ANCRP) is proposed in [26] by S. Karim et al. The proposed protocol is compared with CBE2R, radius-based multipath courier node (RCMN), and EMGGR clustered-based routing protocols regarding network lifetime, energy consumption, etc. It is observed that the proposed ANCRP outperforms the CBE2R across all performance metrics. Nevertheless, the proposed cluster-based routing protocols outperform the RCMN and EMGGR, which are non-cluster-based. Energy-based clustering routing protocols (EQoS-CRAM) with quality of service (QoS) improvement for UWSN are presented in [27]. In this, it was shown that the proposed protocol performs better than the ANCRP and EMGGR protocols in terms of network lifetime and energy consumption. W. Khan et al. [28] proposed a multi-layer clustered routing-based energy efficient (MLCEE) routing protocol for UWSN. In this, the authors proved that the proposed MLCEE performs better than the depth-based routing (DBR) and Energy-efficient depth-based routing (EEDBR) protocols when compared to network lifetime and energy consumption.

The MH-LEACH works on the principle of unequal clustering, such that the clusters close to the sink have fewer nodes than clusters away from the sink. This approach has been attributed to its significant energy saving compared to the HEED. However, neither HEED nor MH-LEACH has been explored much in the context of UWSN. K. G. Omeke et al. in [29] proposed a distance- and energy-constrained k-means clustering scheme (DEKCS) protocols for the selection of CH in UWSN, where authors have shown that the proposed DEKCS protocols perform better than LEACH by 90% in the context of UWSN. A fuzzy and particle swarm optimization

(PSO) based clustering protocol (FBCPSO) for UWSN was proposed by Krishnaswamy et al. in [30], where it is shown that the proposed protocols perform better than the LEACH and K-means binary PSO (KBPSO) in terms of network lifetime and energy consumption.

In [31], Xiao et al. proposed an energy-efficient clustering routing protocol (EECRP) for UWSN, where it was shown that the EECRP outperforms the fuzzy c means and the moth-flame optimization (FCMMFO), FBCPSO, energy-efficient grid routing based on 3D cubes (EGRC), LEACH based on expected residual energy (LEACH-ERE), and LEACH in terms of both network lifetime and energy consumption. In [32], Nguyen et al. proposed an energy-efficient clustering multi-hop routing protocol (EECMR) for UWSN, where authors have shown that the EECMR outperforms LEACH and DBR in terms of network lifetime and energy consumption. A QoS-aware evolutionary cluster-based routing protocol (QERP) was proposed in [33] by M. Faheem et al., where authors have shown that the proposed protocol performs better than the DBR and vector-based forwarding (VBF) routing protocols across all performance metrics. In [34], a multi-agent reinforcement learning (MLAR) protocol was proposed, based on adaptive reinforcement learning schemes. MLAR uses Q-learning based on a distributed value function to identify relays with an edge regarding energy and location. A depth controlled with an energy-balanced routing protocol (EEP) was proposed in [35] to address energy consumption issues and network lifetime issues. This protocol is based on a genetic algorithm and can swap out lower energy nodes for higher energy nodes as needed to maintain constant energy utilisation. In [36], floating nodes assisted cluster-based routing (FNCBR) is proposed in which clusters are formed by dividing the network space into cuboids. Then, two fixed CHs are suspended at various depth levels, and two floating nodes are assigned to each cuboid. In [37], authors proposed improved metaheuristics-based clustering with multihop routing protocol (IMCMR) and demonstrated that the proposed protocol outperformed the EECRP and the LEACH protocol. The energy efficient layered cluster head rotation (EE-LCHR) routing protocol was proposed in [38], which utilises the multi sink with rotating architecture and creates virtual layers with a variety of sensor nodes so that the number of hops between the sensor nodes in each layer and the surface sink is constant. In [39], the efficient grid-based routing protocol for underwater wireless sensor networks (EEGBRP) protocol was proposed, where authors introduced the TOPSIS technique and 3-dimensional cell division for UWSN. In [40], A cluster-based depth source selection routing (CBDS²R) was proposed for the UWSN to improve its performance from the scalability perspective.

In this paper, we propose an energy-efficient clustering protocol known as EECF for CH selection in UWSN with the objectives of energy conservation and enhancement in network lifetime for 3D UWSNs. The EECF includes three phases: clustering, routing, and data forwarding. The clustering phase involves forming clusters by dividing the whole network into several horizontal clusters. In each horizontal cluster, a CH is primarily selected based on the residual energy in the nodes. The routing phase of the EECF is responsible for selecting the

optimum route for data transmission. Moreover, the routing is of two types: inter-cluster and intra-cluster. The energy constraint of the sink and parent CH are used for multi-hop inter-cluster data transmission. Once the route is established, the transmission can take place based on the TDMA principle. The proposed routing protocol is distinct from the others because of the following features:

- It divides the network into horizontal clusters intending to balance the energy of the CH and load balancing.
- It utilizes the capability of the sink to select the optimum path between the source and the sink for multihop communication.
- Moreover, we present a novel approach to enhance the performance of the EECF further by adding the nearest neighboring criteria in CH selection. The improved version of EECF is known as EECF-NN.
- In EECF-NN, CH is not only selected based on maximum residual energy but also uses the CHs' distance from the receiver for multi-hop routing.
- For the performance analysis, two QoS metrics: energy conservation and network lifetime.
- To comprehensively analyze the efficacy, the performance of the proposed protocols i.e., EECF and EECF-NN are evaluated, and results are comparatively analyzed with some of the popular protocols such as DEKCS, EECRP, DBR, MLCEE, QERP, CBE2R, ANCRP, MLAR, EEP, FNCBR, IMCMR, EE-LCHR, EEGBRP, CBDS²R, LEACH, multi-hop LEACH, and SHEENA to validate the performance of the proposed protocols for UWSN.

III. UWSN SYSTEM MODEL

In this section, the network model for UWSN is described. Nevertheless, the proposed protocol belongs to the network layer. Hence, we make sure that appropriate media access control (MAC) protocol has been implemented at the data link layer to provide channel access to the nodes [41].

A. Network Model

We consider the UWSN, where n number of nodes are deployed randomly over the area of interest. These nodes can be of two types: ordinary nodes and CHs. Ordinary nodes (or simply known as nodes) and CH are represented using N and CH . The ordinary nodes are randomly grouped into a cluster (c) such that each node communicates the data to the sink (S) through the CH. Thus, the nodes in a particular cluster are also known as the member nodes (MN) of that cluster. All nodes belonging to a cluster c can be denoted by the set $N_c = \{N \mid N \in c\}$, and $c = \{1, 2, 3, \dots, C\}$ such that, $C \in \text{Number of clusters}$. For example, if nodes 1, 2, 5, and 10 belong to the cluster-1, then nodes in cluster 1 can be defined by the set $N_1 = \{1, 2, 5, 10\}$. Likewise, a CH in a cluster can be defined by the set $CH_c = \{CH \mid CH \in c\}$, and $c \in \{1, 2, 3, \dots, C\}$. E.g., if nodes 7 and 10 are the CHs in clusters 1 and 2 respectively, then we have, $CH_1 = \{7\}$, and $CH_2 = \{10\}$ respectively.

The network uses hierarchical architecture where clusters are arranged hierarchically. This architecture is necessary

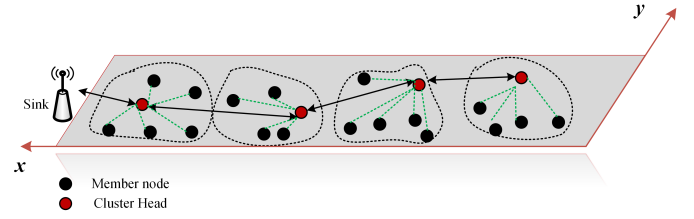


Fig. 1. Normal clustering dominant in UWSN.

for UWSN since nodes are not only deployed in a two-dimensional fashion but also in a three-dimensional fashion i.e., (at different depths). Due to energy constraints, a CH, which cannot directly communicate to the sink, communicates its data to the sink through the nearest CHs, which works as a relay. Thus, the network under consideration captures the features of the large-scale scenario.

One of the novelties of the proposed work is, in fact, the clustering in 3D plane in terms of horizontal clustering. In normal clustering, which is mostly dominant in WSN, the 2D plane is sufficient since nodes, including sinks, are distributed across $x-y$ coordinates. Whereas the nodes, including the sink in UWSN, are distributed not only across $x-y$ coordinates but also z coordinates. With respect to the clustering, the normal clustering is depicted in Fig. 1, and the proposed UWSN model is shown in Fig. 2. The depth needs to be considered in UWSN because data aggregation is performed on the water surface by the sink. The sink has been shown at the highest level of the hierarchy, which is used to route the data from the sensor nodes to the end user through Internet infrastructure. The sink receives data from the CHs, which are distributed over different clusters at different depths. With respect to the proposed horizontal clustering in a 3D plane, different horizontal layers of the nodes are created as per the depth from the sink. For example, as shown in Fig. 2, three levels of horizontal clusters are shown such that the horizontal clusters, namely layer- 1 cluster, layer- 2 cluster, and layer- 3 cluster, are located at depth d_0 , ($d_0 + d_1$), and ($d_0 + d_1 + d_2$) from the sink respectively. In each horizontal layer, different clusters are formed. Depending upon the depth of the CH from the sink, a CH can either communicate the data to the sink or to another CH from another horizontal layer. Nevertheless, communication between two CHs from different clusters within the same horizontal cluster is also possible. For example, two CHs of the layer-3 cluster communicate to each other and to the CHs from the layer-2 cluster, as depicted in Fig. 2.

B. Energy Model of UWSN

This section considers the energy model for UWSNs.

Let $E_t(d)$ be the energy the transmitter requires to transmit a packet of size l bits over the acoustic communication channel with bandwidth $B(d)$. If E_{elec} is the processing energy per bit and E_{amp} is the energy consumed in the amplifier, then the transmitter's energy model, can be given by equation (1) [42].

$$E_t(d) = l(E_{elec} + E_{amp} D^4) + P_t \cdot \frac{l}{hB(d)} \quad (1)$$

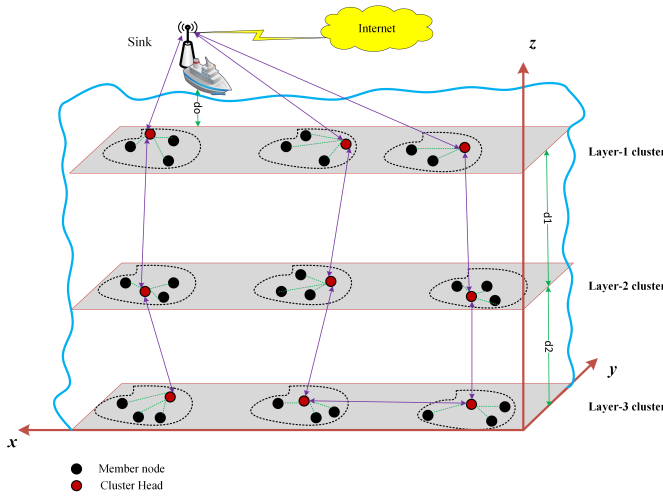


Fig. 2. Proposed network model for UWSN.

where, D is the distance between the transmitting and receiving node, and P_t represents transmitter power. Moreover, h represents the bandwidth efficiency of modulation given in bits/s/ Hz by the following equation.

$$h = \log_2(1 + SNR) \quad (2)$$

Similarly, if E_{DA} represents the data aggregation energy, then the received energy model $E_r(d)$ can be given by the following equation.

$$E_r(d) = l(E_{elec} + E_{DA}) + P_r \cdot \frac{l}{hB(d)} \quad (3)$$

where P_r represents the receiver power.

Hence, the total energy dissipation $E(d)$ of UWSN channel to transmit a packet from one node to another separated by distance d meter can be given by equation (4).

$$E(d) = E_t(d) + E_r(d) \quad (4)$$

Here, the signal-to-noise ratio (SNR) can be represented in the form of source level (SL), noise loss (NL), transmission loss (TL), and directivity index (DI) as shown by equation (5) [43].

$$SNR_{(dB)} = SL - NL - TL + DI \quad (5)$$

We consider hydrophone modems to be omnidirectional; thus, the DI will be equal to 0. Now, the source level depends on the transmission power intensity I_t as given by equation (6).

$$SL = 10 \log \left(\frac{I_t}{0.067 \times 10^{-18}} \right) \quad (6)$$

Knowing the transmitter power, the transmission power intensity at a depth d and 1 m from the source can be obtained using the expression given by equation (7).

$$I_t = \left(\frac{P_t}{k \times 1 \times d} \right) \quad (7)$$

where $k = 2\pi$ and $k = 4\pi$ for shallow and deep water respectively [44].

The noise loss includes the overall ambient noise of the UWSN and is the result of shipping noise, turbulence noise, thermal noise, and wave noise, as expressed below [45].

$$NL = N_s(f) + N_t(f) + N_{th}(f) + N_w(f) \quad (8)$$

Here, $N_s(f)$, $N_t(f)$, $N_{th}(f)$, and $N_w(f)$ can be expressed by the following equations, respectively.

$$10N_s(f) = 40 + 20(s - 0.5) + 26 \log(f) \quad (9)$$

$$10N_t(f) = 17 - 30 \log(f) \quad (10)$$

$$10N_{th}(f) = -15 + 20 \log(f) \quad (11)$$

$$10N_w(f) = 50 + 7.5\sqrt{w} + 20 \log(f) - 40 \log(f + 0.4) \quad (12)$$

where, f is in KHz, w is the wind speed and s is the shipping factor between 0 and 1.

The transmission loss incurred between the transmitter and receiver can be modeled using equation (13) [46].

$$TL = SS + \alpha 10^{-3} \quad (13)$$

where $SS = 20 \log(r)$ which depends on transmission range (r in meters) to represent the spherical spreading factor, and α represents the absorption coefficient in dB.

Knowing the frequency, the absorption coefficient can be obtained using Thorp's equation as given by equation (14) [47].

$$\alpha = \frac{0.1f^2}{1 + f^2} + \frac{40f^2}{4100 + f^2} + 2.75 \times 10^{-4}f^2 + 0.003 \quad (14)$$

C. Distance Estimation

The distance between two nodes can be estimated using Euclidean distance as discussed below.

1) *2D System*: Let the nodes be arranged in two-dimensional (2D) space, where nodes are located using x and y -coordinates. If the location of nodes n_1 and n_2 are represented using 2D coordinates as (x_1, y_1) , and (x_2, y_2) , respectively, then the Euclidean distance between these nodes can be expressed using equation (15).

$$D_{12} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (15)$$

2) *3D System*: Generally, the nodes in the UWSN are deployed at particular depths, seabed, and on the water surface. Thus, node deployment follows the three-dimensional (3D) system. If the location of nodes n_1 and n_2 in a 3D system is given as (x_1, y_1, z_1) and (x_2, y_2, z_2) , respectively, then the Euclidean distance between these nodes can be given by equation (16).

$$D_{12} = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (16)$$

IV. PROTOCOL DESIGN

In this section, we discuss the important aspects of the proposed protocols. We design EECF and its improved version with the nearest neighboring criteria EECF-NN.

A. Working of the Proposed Protocol

The network is as described in the previous section, where all nodes are grouped into clusters with a CH in each cluster, which acts as a coordinator. The working of the EECF and EECF-NN is similar except for the CH selection criteria and can be summarized as follows:

- First, all nodes are randomly distributed over the area of interest.
- Clusters are created by dividing the area horizontally.
- Pre-determined clusters are assigned to each deployed node.
- A CH is elected in each cluster such that
 - It satisfies the threshold criteria (which will be introduced in a later part).
 - It has maximum energy.
- Every node associates itself with the CH for data transmission.
- CH sends data to the sink based on the distance between CH and the sink.
- If the distance between CH and the sink exceeds the threshold, then CH sends data to neighboring CH, which works as a relay. This process continues until data is sent to the sink. Thus, both EECF and EECF-NN follow multi-hop communication to implement large-scale UWSN.

The EECF and EECF-NN protocols route the data from a node to the sink either using single-hop or multi-hop communication based on the distance between CH and sink. Both the protocols are based on several rounds, each consisting of two phases: setup phase; and steady state phase.

Setup phase: Clustering, CH selection, and channel access strategy are done in the setup phase. The randomly deployed sensor nodes are divided into several clusters by dividing the whole spanning area horizontally.

In each horizontal cluster, a node is chosen as CH. For the first round, each node generates a random probability p_{rand} . This probability is compared with the threshold value $T(n)$ and if $p_{\text{rand}} < T(n)$ then it becomes CH. The threshold value is probabilistic as given by equation (17). Unlike LEACH, it creates horizontal clustering in each round.

$$T(n) = \frac{p}{(1 - p \times (1 \bmod \kappa))} \quad (17)$$

where, $\kappa = \text{round}(1/p)$ such that round gives the nearest integer, and p is the ratio of the number of clusters to the number of nodes.

From the next round onwards, the nodes in each cluster with maximum residual energy which is selected as the CH. Let, the receiver of a member node $j \in N_c$ and CH $k \in CH_c$ is denoted as $\Lambda_j \forall j \in N_c$ and $\Lambda_k \forall k \in CH_c$ respectively. Without loss of generality (W.L.O.G), the receiver for each member node in a cluster will be their corresponding CH,

i.e., $\Lambda_j = CH_c; \forall j \in N_c$. Further, to ensure multi-hop routing, the receiver of CH in one cluster is the CH of the adjacent cluster, and so on, satisfying the condition: $\Lambda_k = CH_{c' \in \{1,2,\dots,C:c \neq c'\}}; \forall k \in CH_{c'}$. Nevertheless, since the last cluster is assumed to be nearest to the sink, thus, receiver for the last CH will be the sink i.e., $\Lambda_m = S; \forall m \in CH_c$. The setup phase of the EECF-NN is similar to the EECF, except it uses additional criteria of distance for CH selection, which will be discussed in detail in Algorithm 2. Once CH is selected in each cluster, CH broadcasts this information to all the nodes using the CSMA-MAC technique. A cluster can either join the CH by replying to this advertisement or choose not to join based on the received signal strength (RSS) in the advertisement message from the CH. Based on this information, a channel access strategy is made using a TDMA frame such that each slot in the TDMA is dedicated to particular member nodes. The dedicated slot ensures collision-free access to the acoustic wireless channel.

Steady state phase: The steady state (SS) phase occurs after the completion of the setup phase. The data transfer from the member nodes can take place in a dedicated time slot only. Since member nodes can go to sleep for a large amount of time (except the dedicated time slot), it minimizes energy consumption by avoiding irrelevant sensing. After receiving data from all the nodes, CH can aggregate the data (also known as data fusion) to generate composite data which can be transmitted to the sink. The SS phase for both EECF and EECF-NN are the same, which is illustrated with different phases as shown in Fig. 3. In this figure, k represents the dedicated time slots for data transmission from k^{th} nodes in a cluster.

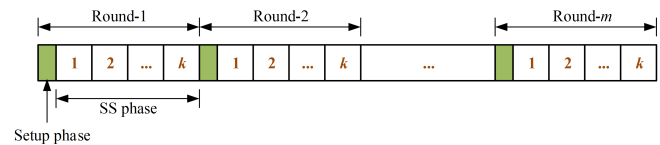


Fig. 3. Illustration of SS phase of EECF and EECF-NN.

B. Flow Chart

The flow chart for both EECF and EECF-NN can be represented together as shown in 4. The first part of the flow chart represents the setup phase where horizontal clustering, CH selection, and advertisement of the broadcast message from the CH is broadcasted. The second part of the flow chart represents the steady state phase where a node joins the CH based on the RSS. Data from member nodes are communicated to the CH through the dedicated slots available in the TDMA frame. A round is said to be completed either a frame is completed or no data is available from the member node to transmit. On completion of a round, all nodes including the CH update their energy and repeat the process, beginning from cluster formation. Using the threshold given by equation (17), each node gets a fair chance to become a CH. Thus, the algorithm does take care of load balancing by a distributed

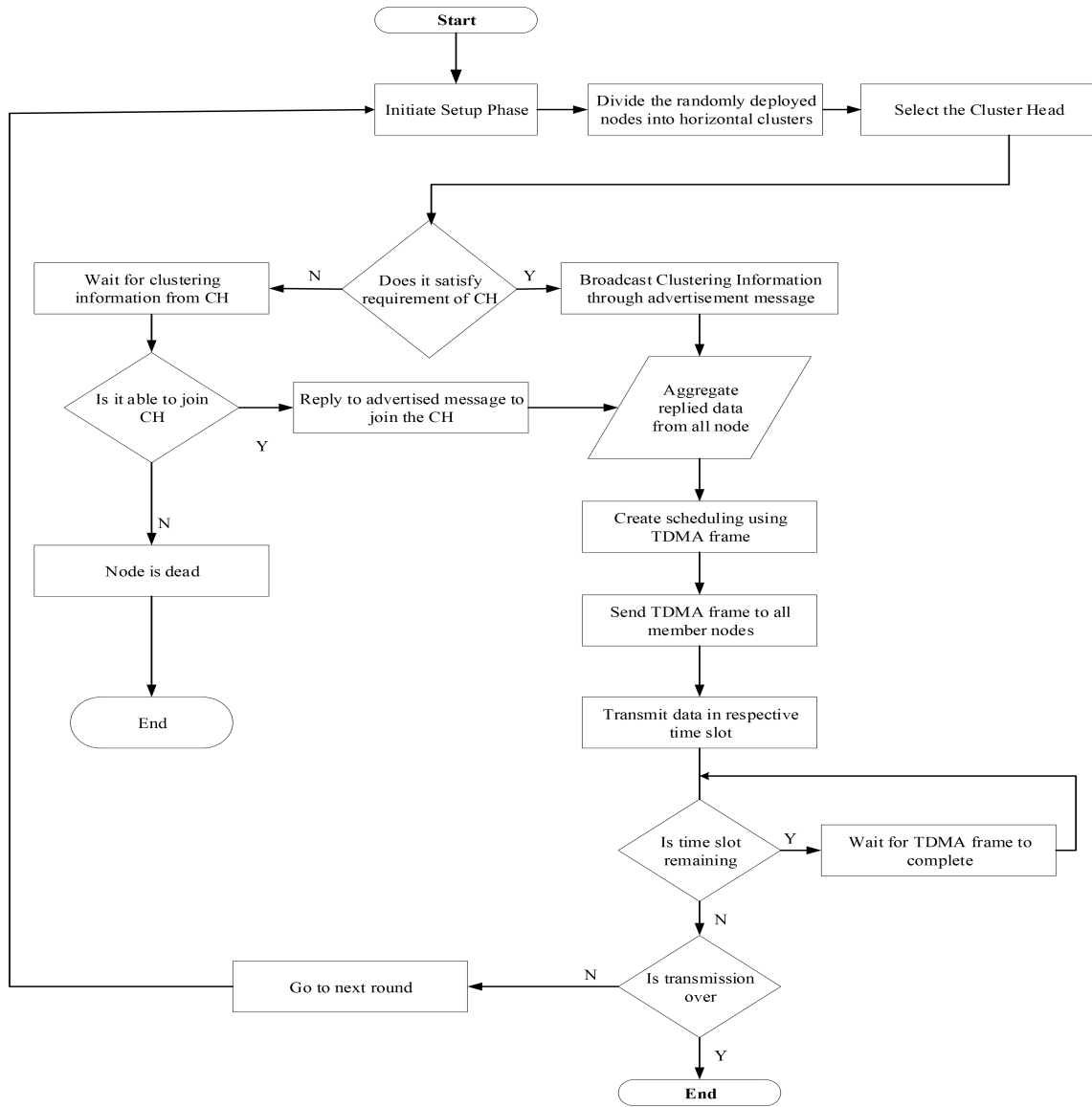


Fig. 4. Flow chart of EECN and EECN-NN.

approach. Thus, the failure of any one node does not disrupt the whole communication system.

C. Pseudo Code

One of the important aspects of energy conservation and network lifetime maximization is the CH selection. The algorithm for CH selection in EECN is as discussed in Algorithm 1.

Algorithm 1 CH Selection in EECN

```

DIVIDE THE NETWORK INTO HORIZONTAL CLUSTERS,
 $c = \{1, 2, 3, C\}$ 
CATEGORIZE ALL NODES BASED ON CLUSTERS,
 $N_c = \{N | N \in c\}$ 
if round = 1 do
    for cluster (c) = 1 : 1 : C do
        for MN = 1 : 1 :  $|N_c|$  do
            EVERY MN GENERATES A RANDOM PROBABILITY,  $p_{rand}$ 
            If  $p_{rand} \leq T(n)$  then
                NODE BECOMES CH
            else SELECT A CH RANDOMLY
            end if
        end for
    end for
else
    for cluster (c) = 1 : 1 : C do
        while  $|N_c| \geq 1$  do
            for member nodes (MN) = 1 : 1 :  $|N_c|$  do
                CH = MN with max E
            end for
        end while
    end for

```

The EECN-NN works in a manner similar to EECN. However, it also uses distance metrics to decide the corresponding CH. In particular, the CH selection in the first round is based on the threshold criteria as given by equation (17). However, the CH selection after 1st round is based on two factors: 1) maximum residual energy in MN, i.e., $\max(E_i^{res}) \forall i \in N_c$. If in any cluster c more than two MNs have the same maximum energy, then we represent such nodes by the set E_c . For example, if nodes 2 and 5 in cluster 1 have the same maximum energy, then they can be collectively represented by the set $E_1 = \{2, 5\}$; and 2) the distance of the nodes with maximum residual energy from the receiver, which is given as $D_{ij} : \{i \in E_c, j = CH_{c' \in \{1, 2, \dots, C: c \neq c'\}}\}$. The nodes with maximum energy as well as minimum distance from the receiver will be selected as the CH. W.L.O.G, the last cluster in the hierarchy is assumed to be nearest to the sink, thus, $D_{ij} = \{D_{ij} : i \in E_c, j = S\}$.

The algorithm for the CH selection in EECN-NN is as discussed in Algorithm 2.

Algorithm 2 CH Selection in EECN-NN

```

DIVIDE THE NETWORK INTO HORIZONTAL CLUSTERS,
 $c = \{1, 2, 3, C\}$ 
CATEGORIZE ALL NODES BASED ON CLUSTERS,
 $N_c = \{N | N \in c\}$ 
  if round = 1 do
    for cluster (c) = 1 : 1 : C do
      for MN = 1 : 1 :  $|N_c|$  do
        EVERY MN GENERATES A RANDOM PROBABILITY,  $p_{rand}$ 
        If  $p_{rand} \leq T(n)$  then
          NODE BECOMES CH
        else SELECT A CH RANDOMLY
        end if
      end for
    end for
  else
    for cluster (c) = 1 : 1 : C do
      while  $|N_c| \geq 1$  do
        for MN = 1 : 1 :  $|N_c|$  do
          FIND MN WITH MAX  $E^{res}$ 
          STORE SUCH NODES IN SET  $E_c$ 
          If  $c = C$  do
            FIND DISTANCE OF NODES IN  $E_c$  FROM ITS RECEIVER
            SUCH THAT  $\{D_{ij} : i \in E_c, j = S\}$ 
            CH = NODES IN SET  $E_c$  WITH MINIMUM  $D_{ij}$ 
          else
            FIND  $\{D_{ij} : i \in E_c, j = CH_{c' \in \{1, 2, \dots, C: c \neq c'\}}\}$ 
            CH = NODES IN SET  $E_c$  WITH MINIMUM  $D_{ij}$ 
          end if
        end for
      end while
    end for
  end if

```

V. SIMULATION RESULTS AND VALIDATION

In this section, the simulation results have been presented under different scenarios. To discuss the efficacy of the pro-

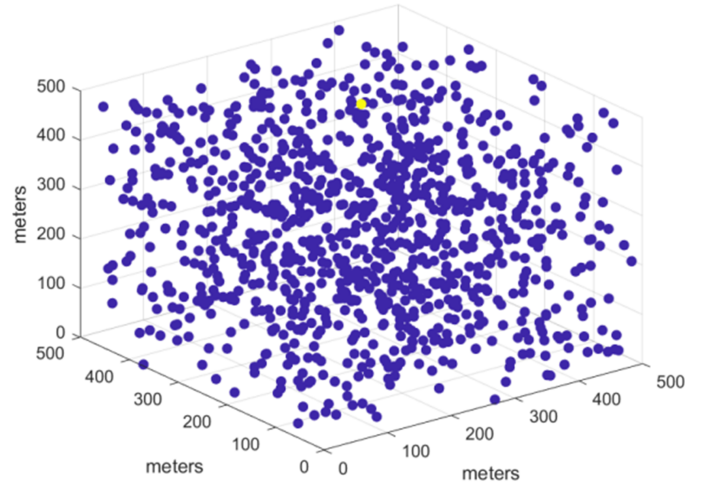


Fig. 5. Node deployment and simulation scenario.

posed protocol, we also compare its performance with some of the highly researched clustering-based routing protocols of UWSNs.

A. Simulation Environment

The network is designed using MATLAB to observe the efficacy of the proposed protocol. We have considered an area of 200 m × 200 m × 200 m in which 1000 nodes are deployed randomly. This is as shown in Fig. 5, where sink and nodes are represented by yellow and blue colors respectively.

Three horizontal clusters are considered to span the whole area in each round of EECN and EECN-NN operation. Some of the vital simulation parameters are shown in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Area	500 m × 500 m × 500 m
Number of nodes	1000
Initial energy of each node	5 J
Packet length	240 Bytes
Energy required for amplifier, E_{amp}	0.0013pJ/bit/m ⁴
Energy required for electronic circuitry, E_{elec}	50 nJ/bit
Energy required for data aggregation	5 nJ/bit
Bandwidth $B(d)$	4KHz
Transmitter power, P_t	70 mW
Receiver power, P_r	16 mW
Distance, d	20 m
Shipping factor, s	0.5
Wind speed, W	6 m/s
range, r	50 m
Frequency, f	10KHz
Number of clusters, C	3

B. Simulation Results and Discussions

The network is designed with the parameters as mentioned in the Table. I. The simulations are performed for 1000 iterations, and the results are plotted. Both the proposed

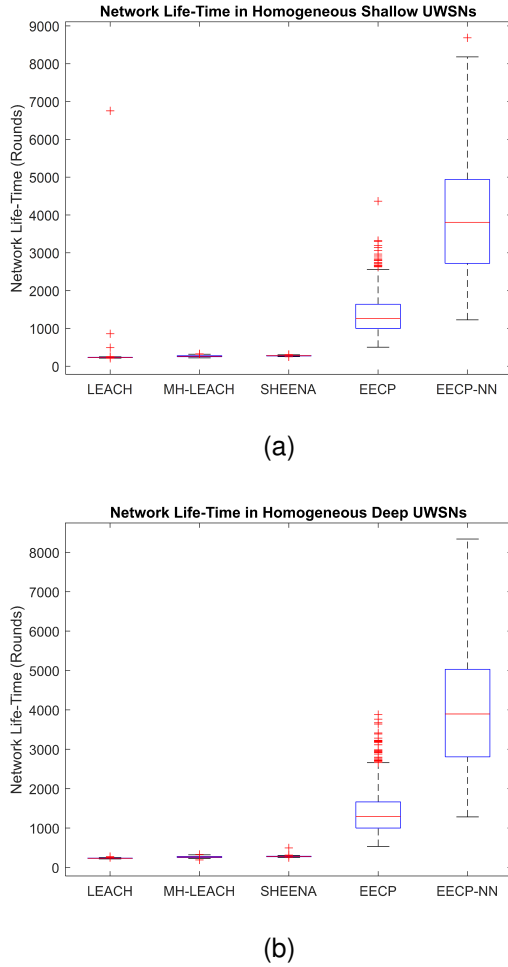


Fig. 6. Network lifetime performance of the proposed protocols in homogeneous (a) Shallow and (b) Deep UWSN.

algorithms have similar time complexity given by $O(nCl)$, where n is the number of nodes, C is the number of clusters, and l is the network lifetime. The performance of the protocols is evaluated for the two classes of the UWSNs: homogeneous UWSN and heterogeneous UWSN.

1) *Homogeneous UWSN*: Initially, all nodes of the UWSN are assumed to have 5J of energy. Such a class of network is also known as homogeneous UWSN. Depending upon the depth of the sensor nodes from the water surface, the UWSN can be categorized into two cases: shallow water UWSN, and deep water UWSN. The shallow and deep water homogeneous UWSNs can be designed by putting $k = 2\pi$ and 4π , respectively, in equation (7) without changing the rest of the parameters. The box plots for the network lifetime of the various protocols are shown in Fig. 6.

The results shown in Fig. 6, clearly demonstrate that even the proposed protocols significantly enhance the network-life time. The average, worst, and best times for all the protocols are shown in Table II.

Thus, from Table II, it can be clearly observed that EECP increases the network lifetime by 5.58 times and 5.45 times, compared to LEACH protocol for deep water and shallow water UWSNs, respectively. The EECP-NN, on the other

TABLE II
SIMULATION RESULTS FOR HOMOGENOUS UWSN

Protocol	Deep water			Shallow water		
	Worst	Average	Best	Worst	Average	Best
LEACH	215	232	276	210	232	6754
MH-LEACH	190	329	263	221	263	328
SHEENA	248	278	495	249	278	310
EECP (Proposed)	533	1295	3880	504	1264	4365
EECP-NN (Proposed)	1283	3896	8338	1227	3801	8685

hand, further increases the network lifetime by 16.79 times and 16.38 times, compared to LEACH protocol for deep water and shallow water UWSNs, respectively. For better data visualisation, the average number of alive nodes at every round are plotted in Fig. 7.

From Fig. 7, it can be clearly observed that both the proposed protocols extend the network lifetime significantly. It can also be observed that EECP performs similarly to MH-LEACH in the initial rounds and is outperformed by LEACH and SHEENA, but it significantly reduces the node death rate in the later stages, thereby improving the network lifetime. The improvement in performance of EECP and EECP-NN in the later stages can be explained as follows. In the initial stages, because of the wide horizontal span of each cluster, nodes die quickly, reducing the cluster pan to a smaller area. Once the surviving nodes become concentrated in a smaller area, they survive longer, extending the network lifetime. To corroborate this, the size of each horizontal cluster is limited to 40000 m², and the results are shown in Fig. 8.

Thus, it can be observed for networks spanning a smaller area, the performance of EECP and EECP-NN outperforms other protocols even in the initial rounds. These proposed protocols are more suitable for UWSNs with significant depth and span smaller horizontal areas. They can outperform LEACH and MH-LEACH in extending the network life span even in networks with large horizontal spans but may perform poorly in the initial rounds. To further understand the performance of these protocols, the box plot of the energy remaining in the network after 100 and 250 rounds is shown in Fig. 9 and Fig. 10, respectively.

Thus, it can be observed that in the initial rounds, the energy retained in the network with the proposed protocols is lower than that of the LEACH and MH-LEACH because of the wide horizontal span, but in the subsequent rounds, the proposed protocols conserve more energy than the conventional LEACH and MH-LEACH.

2) *Heterogeneous UWSN*: In practical scenarios, all the nodes in the network cannot have equal energy. In this case, heterogeneous UWSN are considered where the sensor nodes are deployed with different initial energy limited to a maximum of 5J without changing the rest of the parameters. The initial energy associated with every node is randomly distributed between 0J to 5J. The performance of the proposed protocols is summarized in Table III.

Thus, from Table III, EECP increases the network lifetime by 5.6 times and 5.39 times, compared to LEACH protocol for

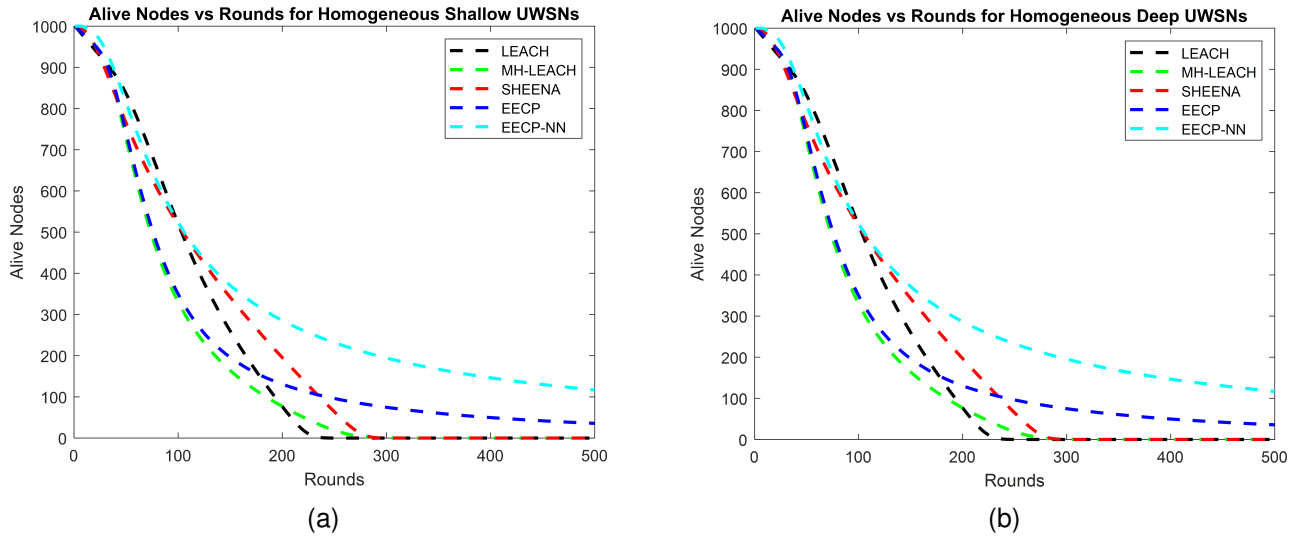


Fig. 7. Alive nodes in every round for homogeneous (a) Shallow and (b) Deep UWSN.

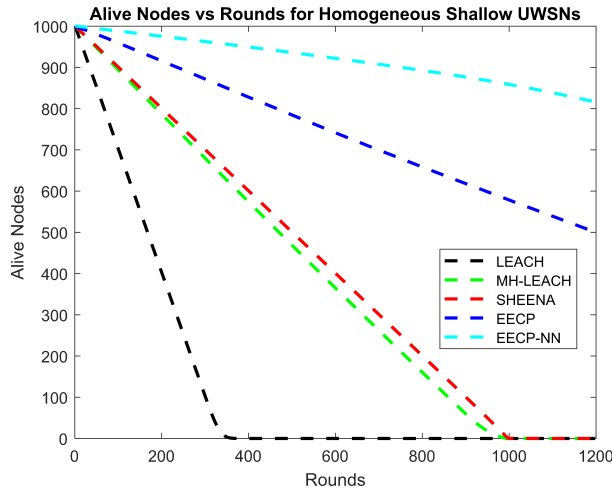


Fig. 8. Alive nodes in every round for homogeneous shallow UWSN with a shorter horizontal span.

TABLE III
SIMULATION RESULTS FOR HETEROGENEOUS UWSN.

Protocol	Deep water			Shallow water		
	Worst	Average	Best	Worst	Average	Best
LEACH	129	145	2270	131	146	461
MH-LEACH	61	159	200	30	159	196
SHEENA	143	166	189	143	167	189
EECP (Proposed)	214	812	2708	252	788	2825
EECP-NN (Proposed)	660	2253	5617	492	2272	5523

deep water and shallow water heterogeneous UWSNs, respectively. The EEC-NN, on the other hand, further increases the network lifetime by 15.54 times and 15.56 times, compared to the LEACH protocol for deep water and shallow water heterogeneous UWSNs, respectively.

TABLE IV
PERCENTAGE IMPROVEMENT IN COMPARISON TO LEACH

Protocols	Modeling type	Network lifetime improvement compared to LEACH (%)
MH-LEACH [21]	2D	170.967
SHEENA [23]	3D	161.290
DEKCS [29]	2D	937.5
EECRP [31]	3D	47.69
DBR [32]	2D	108.511
MLCEE [28]	2D	179.939
QERP [33]	2D	125.178
CBE2R [25]	2D	188.889
EECP (Proposed)	3D	460% (HetDeUWSN) 439% (HetShUWSN) 458% (HoDeUWSN) 445% (HetShUWSN)
EECP-NN (Proposed)	3D	1454% (HetDeUWSN) 1456% (HetShUWSN) 1579% (HoDeUWSN) 1538% (HetShUWSN)

C. Comparative Analysis

In this section, the comparative analysis of the proposed protocols is presented with some of the state-of-the-art cluster-based routing protocols such as DEKCS, EECRP, DBR, MLCEE, QERP, and CBE2R, in addition to the LEACH, MH-LEACH, and SHEENA protocols to validate the efficacy of the proposed protocols for UWSN. The comparative results are summarized in Table IV.

The comparative results are comprehensively summarized in Table IV, in which the percentage improvement in the network lifetime is analyzed. In the table, HetDeUWSN, HetShUWSN, and HoDeUWSN represent heterogeneous deep UWSN, heterogeneous shallow UWSN, and homogeneous deep UWSN respectively. The LEACH protocol is considered a reference protocol for the comparative analysis. The percentage improvement is seen to be the highest for the proposed protocol compared with some state-of-the-art protocols such as DEKCS, EECRP, DBR, MLCEE, QERP, and CBE2R.

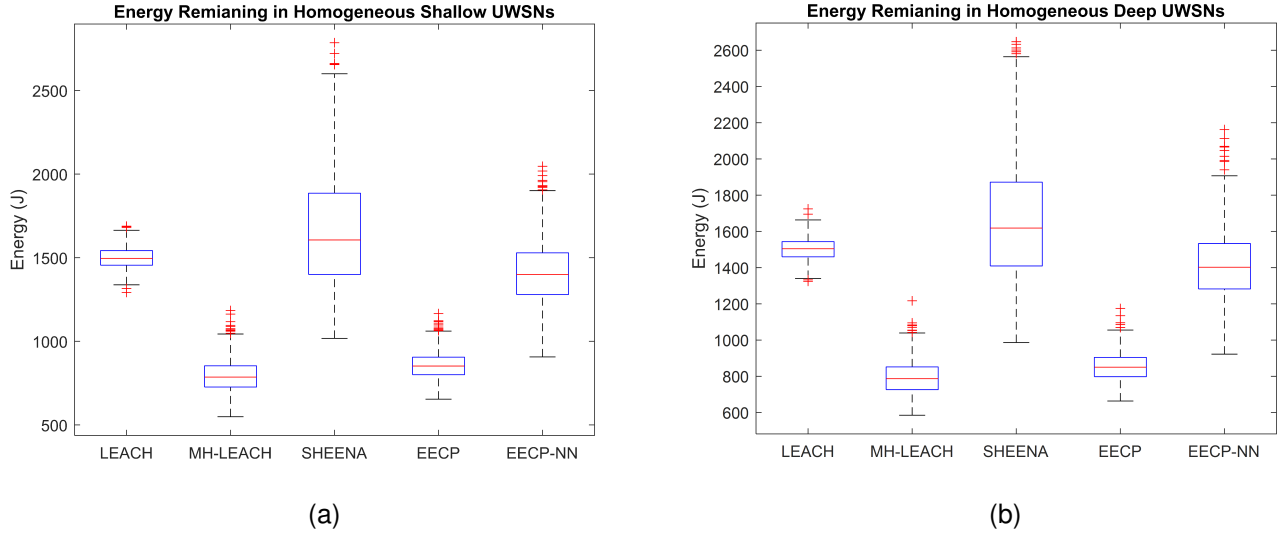


Fig. 9. Energy remaining after 100 rounds in homogeneous (a) Shallow and (b) Deep UWSNs.

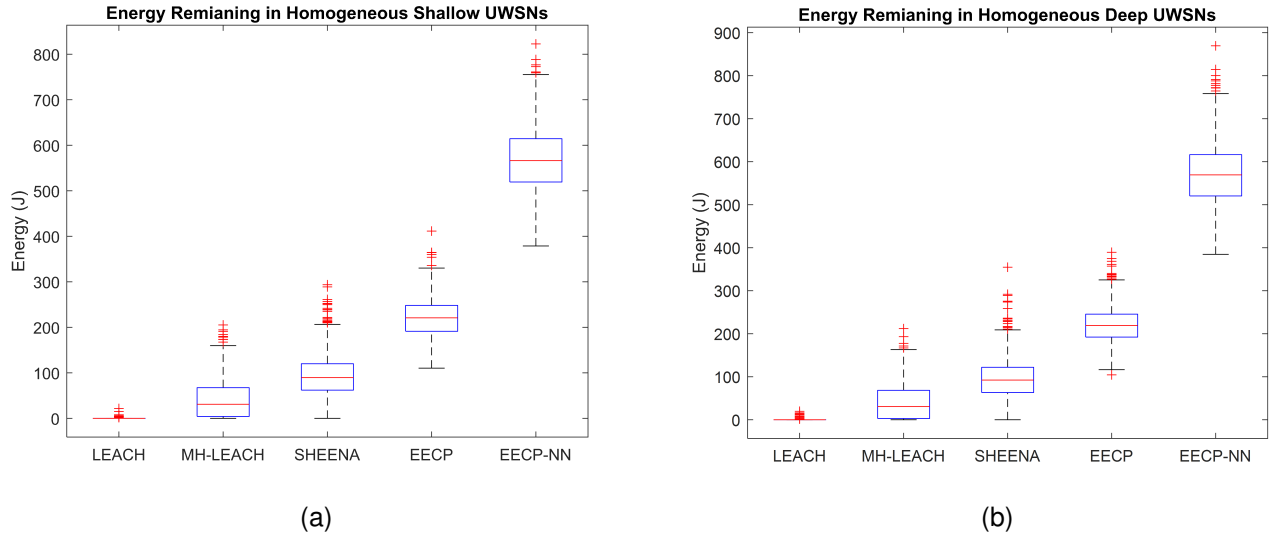


Fig. 10. Energy remaining after 250 rounds in homogeneous (a) Shallow and (b) Deep UWSNs.

Further, some of the recent cluster-based routing protocols that show the relevancy of the proposed work in the domain of UWSN are ANCRP, MLAR, EEP, FNCBR, IMCMR, EELCHR, EEGBRP, and CBDS²R. A comparative analysis of the proposed protocols with these recent protocols is briefly summarized as follows.

- In [26], authors demonstrated that the ANCRP is superior to benchmark protocols such as RMCN, CBE2R, EMGGR, and VH-ANCRP. Specifically, it was shown that for 400 simulation rounds, more than 250 nodes survived in ANCRP, whereas in the case of EMGGR, only 150 nodes can survive.
- In [34], the performance of the MLAR protocol is compared which on analysis reveals that the MLAR performs better than the MLCEE.
- In [35], authors demonstrated that EEP performs better

than the LEACH, DBR, and EEDBR. As for round 80, the proposed EEP model shows 20% energy consumption which is better than existing DBR and EEDBR methods. Further, it has been shown that the number of alive nodes in EEP becomes about 50 for 1000 rounds, which is more than the DBR and EEDBR.

- In [36], the comparative analysis is performed for the FNCBR protocol and the results demonstrate its superiority when compared to the ANCRP. Specifically, the number of alive nodes in the proposed FNCBR protocol are observed to be about 80 when 600 simulation rounds.
- In [37], authors demonstrated that the IMCMR protocol outperforms the EECRP and, obviously, the LEACH protocol. Specifically, the authors demonstrated that at least one alive node is observed in IMCMR for 1000 rounds, whereas it is observed only for 900 rounds in

EECRP and 650 rounds in LEACH.

- In [38], authors demonstrated that EE-LCHR performs better than the DBR and EE-DBR.
- In [39], the EEGBRP protocol was proposed, and it was demonstrated to outperform the EMGGR by about 9% in network lifetime expectancy.
- In [40], authors proposed CBDS²R, in which authors demonstrated that the CBDS²R performs better in network lifetime expectancy by 58.88% compared to the latest cluster-based routing protocols.

The comprehensive analysis of these protocols reveals that the maximum lifetime of the UWSN is about 1000 simulation rounds under the best possible circumstances. The proposed EECF and EECF-NN protocols have significantly improved the network lifetime compared to the existing protocols. Moreover, it can be observed that most of the state-of-the-art protocols are on 2D UWSNs. Thus, the proposed protocols are superior to the other cluster-based routing protocols in energy conservation and network lifetime maximization.

D. Challenges

The current work proposes the EECF and EECF-NN clustered-based routing protocols. The proposed protocols have been evaluated and compared with some other standard protocols, and it was observed that the proposed protocols outperform these protocols in terms of both the parameters, i.e., network lifetime maximization and energy conservation. The proposed protocols consider a wide range of scenario-specific parameters for analysis of UWSN in addition to the homogeneous and heterogeneous UWSN such as shallow water homogeneous UWSN, deep water homogenous UWSN, shallow water heterogeneous UWSN, and deep water heterogeneous UWSN.

Despite the proposed protocols fulfilling the main objective of the UWSN in terms of network lifetime maximization and energy conservation, there are some specific challenges that can be considered for further exploration of UWSN in this direction. It has been observed that the proposed protocols tend to lose energy quickly in networks spanning a large horizontal area. Usually, the 3D UWSNs focus on depth-related applications; however, having a wide horizontal coverage can be of enormous advantage. This limitation can be overcome by using more sinks on the water surface. The proposed study does not consider the reliability aspects of the networks in UWSN. For example, only one sink in the network may lead to a single-point failure issue. The challenge of single-point failure can be addressed by using component redundancy at the sink. The sink is accessible as it is usually present on the water surface and so redundancy becomes practically feasible. The unstable wavy surface and depth-temperature-dependent characteristics significantly complicate providing reliable communication links for UWSN. Additionally, the misalignment brought on by the communication channel's dynamics seriously impairs performance and restricts their useful uses. Further, the work can be extended to improve the security mechanism in UWSN. Another important challenge is that synchronizing each node's clock needs additional control

packets, reducing the effective payload delivered. Designing asynchronous protocols for this environment can be considered a future challenge.

The cross-layer architecture is very successful in WSN. Thus, the developed cluster-based routing protocols can also be analyzed from the cross-layer perspective such that the physical layer constraints, MAC layer challenges, and routing protocols are coordinated. Another vital challenge is to develop clustering algorithms that prioritize QoS parameters, such as latency, reliability, and data rate, in addition to the network lifetime maximization and energy conservation, to meet the requirements of specific underwater applications like oceanographic monitoring, underwater surveillance, or environmental sensing. Likewise, mobility-aware clustering is another research direction that can be explored in which node mobility is considered in clustering schemes while designing clustering algorithms that adapt to the movement of sensor nodes, ensuring efficient communication while maintaining cluster integrity. Moreover, some machine learning techniques can be applied in selecting horizontal clusters, CHs, and optimum routes for better response. One of the major constraints is the deployment of the routing protocols in practical scenarios. Extreme environmental conditions such as ocean current, signal instability, signal interference, and lack of expertise to handle the devices in the marine environment are some hindrances that restrict the practical deployment of UWSN. Signal instability can be addressed by using additional transmitters and receivers. Another, alternative solution is to develop effective re-transmission mechanisms in the communication protocol. However, these solutions can lead to increased energy consumption. Modeling nodes with multiple transmitters and receivers for their energy consumption, can be an interesting extension of the proposed research.

VI. CONCLUSION

The clustering technique, an essential part of the routing protocol, has a significant impact on the QoS (energy conservation and network lifetime maximization) of the UWSN. It has been shown that the proposed protocols, i.e., EECF and EECF-NN, perform better in energy conservation and network lifetime maximization than the existing protocols, such as LEACH, MH-LEACH, and SHEENA. Further, the proposed protocols are comparatively analyzed with some of the recent cluster-based routing protocols, including ANCRP, MLAR, EEP, FNCBR, IMCMR, EE-LCHR, EEGBRP, and CBDS²R. Moreover, it has been shown that the nearest neighbor criteria and the maximum residual energy improve the QoS of the UWSN significantly as seen in EECF-NN. Even in heterogeneous UWSN with different initial constraints, the EECF-NN has shown exemplary results for both QoS metrics. Nevertheless, a drastic enhancement in the network lifetime is observed with the proposed protocols compared to some of the state-of-the-art cluster-based routing protocols such as DEKCS, EECRP, DBR, MLCEE, QERP, and CBE2R. EECF-NN performs best compared to the reference protocols, including the proposed EECF. The proposed protocols also outperform the existing state-of-the-art cluster-based routing

protocols such as ANCRP, MLAR, EEP, FNCBR IMCMR, EE-LCHR, EEGBRP, and CBDS²R.

However, the proposed work assumes the link between sink and CH is reliable and secure, which is not obvious in all practical cases. Thus, the proposed protocols can be further improved from a reliability and security perspective. Nevertheless, the other aspects, such as cross-layer optimization (in which physical layer constraints, MAC protocols, and routing algorithms are considered in a coordinated manner), QoS aware clustering (algorithms that prioritize QoS parameters to meet the requirements of specific underwater applications like oceanographic monitoring, underwater surveillance, or environmental sensing), mobility aware clustering (which considers node mobility in clustering schemes while design clustering algorithms that adapt to the movement of sensor nodes, ensuring efficient communication while maintaining cluster integrity) can be seen as few of the immediate future research directions. The authors will consider improving the performance of the proposed protocols in the initial phases of network deployment, which has a large geographical span in their future work.

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Houbing Song (Fellow, IEEE) received the M.S. degree in civil engineering from The University of Texas at El Paso, El Paso, TX, USA, in December 2006, and the Ph.D. degree in electrical engineering from the University of Virginia, Charlottesville, VA, USA, in August 2012. He has been serving as an Associate Technical Editor for IEEE Communications Magazine since 2017, an Associate Editor for IEEE Internet of Things Journal since 2020, IEEE Transactions on Intelligent Transportation Systems since 2021, and IEEE Journal on Miniaturization for Air and Space Systems since 2020, and the Guest Editor for IEEE Journal on Selected Areas in Communications. He is an ACM Distinguished Member and an ACM Distinguished Speaker. He is a Highly Cited Researcher identified by Clarivate™ (2021, 2022) and a Top 1000 Computer Scientist identified by Research.com. He received the Research.com Rising Star of Science Award in 2022 (World Ranking: 82; USA Ranking: 16). He was a recipient of more than best paper awards from major international conferences, including the IEEE CPSCoM-2019, the IEEE ICII 2019, the IEEE/AIAA ICNS 2019, the IEEE CBDCoM 2020, the WASA 2020, the AIAA/IEEE DASC 2021, the IEEE GLOBECOM 2021, and the IEEE INFOCOM 2022.



Amitkumar V. Jha received an M.Tech degree from IIT Guwahati, India, and a Ph.D. from KIIT University, India. He has been working as an assistant professor at KIIT since 2015. He has authored over 40 articles in international journals and conference proceedings. His research interests include wireless sensor networks, communication technology, computational techniques, etc.



Bhargav Appasani has completed his Ph.D. from Birla Institute of Technology in 2018. He is currently working as an Assistant Professor in the School of Electronics Engineering, Kalinga Institute of Industrial Technology, India. He has published over 135 articles in reputed international journals and conferences. He has five patents filed to his credit and has published a book with Springer. He is the academic editor of the Journal of Electrical and Computer Engineering (Hindawi). His research interests include Terahertz Sensing, Smart Grid, 5G,

Wireless Sensor Networks, etc.



Mohammad S. Khan (Senior Member, IEEE) received the M.Sc. and Ph.D. degrees in computer science and computer engineering from the University of Louisville, KY, USA, in 2011 and 2013, respectively. He is currently an Associate Professor of Computing at East Tennessee State University and the Director of the Network Science and Analysis Lab (NSAL). His primary research areas include ad-hoc networks, network tomography, connected vehicles, and vehicular social networks. He has been on technical program committees of various

international conferences and a technical reviewer of various international journals in his field. He serves as an Associate Editor for IEEE Access, IET ITS, IET WSS, and Telecommunication Systems (Springer).