



Energy-efficient unequal multi-level clustering for underwater wireless sensor networks

Sathish Kumar^a, Ravikumar Chinthaginjala^{b,*}, Shafiq Ahmad^c, Taehoon Kim^{d,*}

^a Department of ECE, Saveetha School of Engineering, SIMATS Engineering, Chennai 602105, India

^b School of Electronics Engineering, Vellore Institute of Technology, Vellore 632014, India

^c Industrial Engineering Department, College of Engineering, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia

^d School of Information and Electronic Engineering, Zhejiang University of Science and Technology, No. 318, Hangzhou, Zhejiang, China

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ABSTRACT

Underwater Wireless Sensor Networks (UWSNs) have emerged as a critical piece of technology for a wide range of maritime applications, including environmental monitoring, resource exploration, and catastrophe avoidance. An Energy Efficient Unequal Multilevel Clustering (EEUMC) algorithm tailored to UWSNs is proposed in this study. The EEUMC's primary purpose is to enhance the efficiency of data movement inside the network while decreasing the amount of energy lost. The proposed method employs a multilevel clustering framework, which divides the network into hierarchical groups based on node attributes and residual energy content. EEUMC introduces an unequal clustering technique, which differs from traditional clustering approaches. Cluster heads (CHs) are dynamically selected in this technique based on their energy levels as well as their proximity to sink nodes. The EEUMC integrates sophisticated routing protocols and adaptive data aggregation techniques in order to boost the energy economy even further. The routing algorithms route data flows across energy-efficient channels automatically, and adaptive data aggregation reduces redundant transmissions to conserve energy and keep the system functioning smoothly. This particular configuration of unequal clustering, intelligent routing, and adaptive aggregation all work together to improve data-collecting efficiency and network's lifespan. The efficiency of the proposed EEUMC scheme was thoroughly tested through a number of simulations and head-to-head comparisons with alternative clustering approaches. When compared to more traditional approaches, the findings reveal that EEUMC greatly increases network longevity and data transmission rates. Furthermore, the scheme is robust in the sense that it can withstand changing network conditions while still ensuring a balanced consumption of energy across all nodes.

1. Introduction

Underwater Wireless Sensor Networks (UWSNs) have the potential to be extremely useful in a wide range of disciplines, including oceanography, marine biology, environmental monitoring, and offshore resource management [1]. The ability of these networks to collect, transmit, and analyse data in real-time is useful for both underwater

exploration and decision-making. However, due to the harsh and ever-changing nature of the aquatic environment, deploying sensor nodes in the underwater world brings its own unique set of obstacles [2]. Limited energy supplies, acoustic communication restrictions, and unanticipated channel conditions are among the problems.

Because sensor nodes are typically situated in inaccessible locations where it is impractical to repair or replenish batteries, energy efficiency

Abbreviations: UWSNs, Underwater wireless sensor networks; EEUMC, Energy Efficient Unequal Multilevel Clustering; CHs, Cluster heads; WSNs, Wireless sensor networks; EECMR, Energy-Efficient Clustering Multi-Hop Routing; UASN, Underwater Acoustic Sensor Networks; AUVs, Autonomous Unmanned Vehicles; AEC, Assisted Energy-Efficient Clustering; EULC, Energy-Balanced Unequal Layering Clustering; EERBLC, Energy Efficient Routing Protocol based on Layers and Unequal Clusters; DBR, Depth-based routing; EEDBR, Energy efficient depth-based routing; EOCA, Energy Optimization Clustering Algorithm; UWA-CSN, Underwater acoustic cooperative sensor networks; ReE-MEER, residual energy-based Maximum Effective Communication Range; TCEB, Topology Controlling with Energy Balance; MLCEE, Multi-Layer Cluster-based Energy Efficient; SOSNET, Smart Ocean underwater Sensor NETWORK; MFO, Moth Flame Optimizer; CLPSO, Comprehensive Learning Particle Swarm Optimization; ACO, Ant Colony Optimization; GWO, Grey Wolf Optimization.

* Corresponding authors.

E-mail addresses: cvrkvit@gmail.com (R. Chinthaginjala), 323020@zust.edu.cn (T. Kim).

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and robustness is a critical concern in UWSNs. This is one of the reasons why energy efficiency is such a major concern [3,4]. The network's capacity to remain active for as long as possible while still providing reliable data is critical to the success of missions involving underwater surveillance and investigation. Because of the disparity in energy levels and distances to sink nodes, previous efforts at UWSN clustering and routing have focused on evenly distributing roles and responsibilities among nodes. This is due to the fact that the distances between sink nodes can also vary [5–8].

When deployed in an underwater environment, wireless sensor networks (WSNs) face a unique set of challenges. Underwater wireless sensor networks are especially sensitive to these threats due to the harsh and intricate nature of aquatic environments [9]. For UWSNs to be installed and run properly, challenges such as energy efficiency and data transport must be addressed.

1. **Limited Energy Resources:** UWSN sensor nodes are generally situated in deep, inaccessible water, making battery maintenance and recharging problematic. Because of the limitation of available energy sources, power conservation is crucial. To continue collecting data and interacting for extended periods of time, the nodes must closely stick to their energy budgets. Premature node shutdowns caused by poor energy consumption can disrupt network operations and data collection [10].
2. **Variable Channel Conditions:** Acoustic communication is the primary mode of data transmission in UWSNs due to the limitations of radio frequency communications underwater. Acoustic signals' vulnerability to changes in propagation speed, signal attenuation, and multipath fading results in an unpredictable and ever-changing communication environment. As a result of this discrepancy, data transmission quality may decrease, energy may be squandered on unneeded retransmissions, and communication delays may increase.
3. **Data Communication Efficiency:** Timely and reliable data gathering is dependent on the quick transfer of information from spread sensor nodes in the water to a centralized node. However, the communication range of underwater nodes is limited due to the dispersed nature of sensor nodes, necessitating the establishment of multi-hop communication channels. Traditional routing and clustering algorithms may fail to account for changes in energy levels and distances to the sink, resulting in wasteful energy use and data delivery [11].
4. **Unequal Node Characteristics:** Fourth, the quantity of energy available to sensor nodes in UWSNs varies based on factors such as how completely charged their batteries were to begin with and how frequently they utilize power. It's also likely that nodes closest to the sink node have better communication and energy expenditure. If conventional clustering algorithms treated all nodes equally, it is feasible that energy-rich nodes might be assigned energy-intensive jobs while more-suited nodes would lie idle [12–14].
5. **Network longevity and sustainability:** Due to the limited energy resources and demanding communication environment of UWSNs, achieving network longevity and sustainability is a major challenge. The cost-effective deployment and completion of underwater missions are dependent on maximizing the network's operational lifetime while minimizing data gathering and transmission losses [15].

In response to these challenges, EEUMC was established with the purpose of developing a novel and all-encompassing technique to deal with the idiosyncrasies of UWSNs. The goal is to create a clustering and routing strategy for underwater sensor networks that decreases power consumption improves data interchange efficiency, and extends the networks' usable lifetime [16–18]. EEUMC is intended to assist UWSNs in overcoming energy and communication issues so that they can contribute more to the advancement of undersea exploration, research, and monitoring. This is accomplished by multilayer clustering, unequal distribution of cluster head roles, intelligent routing protocols, and

adaptive data aggregation [19].

This work aims to solve the problem of optimizing energy consumption and data transfer efficiency in the context of UWSNs. Due to limited energy resources, fluctuating channel conditions, and unequal node characteristics, UWSNs necessitate a novel clustering and routing strategy to assure network longevity and successful data delivery. The goal is to create a comprehensive scheme that uses multilevel clustering, unequal cluster head selection based on energy and proximity, intelligent routing protocols, and adaptive data aggregation to achieve energy-efficient and balanced data transmission, thereby improving the overall performance and sustainability of UWSNs.

EEUMC is a unique approach described in this article as a solution to the power and connectivity issues associated with UWSNs. The sensor nodes in the EEUMC scheme are grouped into hierarchical clusters utilizing multilevel clustering. These clusters are constructed based on the sensor nodes' energy statuses and their distance from the sink node. In contrast to more traditional clustering methodologies, EEUMC employs an uneven clustering mechanism. This method assigns cluster head positions dynamically to nodes with appropriate energy levels and close geographical proximity to the sink.

The EEUMC's primary goal is to significantly improve the energy efficiency of UWSNs while simultaneously providing stable and secure data transmission. This is accomplished by carefully distributing high-energy jobs around the network. This achievement is made possible by clever routing protocols and adaptive data aggregation algorithms. The goal of EEUMC is to lengthen the amount of time that can pass between maintenance checks on UWSNs and make longer data collection missions possible by automatically selecting energy-efficient pathways for data transfer and eliminating duplicate information sharing.

1.1. Problem formulation

EEUMC problem formulation entails developing a unified framework to handle the energy inefficiency and data communication challenges unique to UWSNs. This includes developing a hierarchical multilevel clustering method that allows for unequal distribution of cluster head positions based on energy levels and distance from the sink node. To optimize data transmission pathways, reduce redundant communication, and increase network's lifetime, the scheme also requires the integration of intelligent routing protocols and adaptive data aggregation algorithms [20]. The goal is to provide a solution that maximizes energy efficiency, balances energy consumption and improves data transfer in UWSNs, therefore contributing to the long-term operation and effectiveness of underwater monitoring and exploration missions.

1.2. Motivation

EEUMC was created to address the unique challenges given by the underwater environment. The development of the EEUMC was motivated by this necessity. Due to the presence of both energy-rich and energy-poor sensor nodes, as well as limited energy resources and fluctuating channel conditions, traditional clustering and routing algorithms are insufficient for ensuring effective data transfer and an extended network's lifespan. EEUMC's mission is to maximize the potential of multilevel clustering, uneven cluster head assignment, intelligent routing, and adaptive data aggregation in order to reduce energy waste, improve data delivery effectiveness, and extend the time that UWSNs can remain operational. EEUMC expects that by addressing these issues, it will be feasible to promote more effective and sustainable undersea monitoring, exploration, and study. This will allow us to gain a better understanding of marine ecosystems and make crucial applications in oceanography, environmental research, and disaster avoidance easier to apply.

1.3. Contributions

As a solution to these issues, we developed an EEUMC for UWSNs. This research describes a method for constructing an energy-efficient clustering design. The proposed EEUMC offers the following key contributions:

- **Optimized Energy Consumption:** EEUMC dynamically selects cluster heads based on both energy levels and proximity to the sink node, ensuring balanced energy consumption and prolonging network's lifespan.
- **Enhanced Data Communication:** Intelligent routing protocols guide data flows through energy-efficient paths, minimizing retransmissions and improving overall data delivery efficiency.
- **Context-Aware Clustering:** Multilevel clustering assigns cluster head roles based on proximity to the sink, optimizing data aggregation and communication for varying distances.
- **Energy-Balanced Node Roles:** Unequal cluster head assignment leverages nodes with optimal energy levels, reducing energy imbalances and maximizing resource utilization.
- **Adaptive Data Aggregation:** Cluster heads intelligently aggregate data before transmission, reducing redundant information exchange and conserving energy.
- **Extended Network Longevity:** EEUMC's comprehensive approach contributes to longer network operational lifetimes, crucial for sustained underwater missions.

In this brief summary, the remaining sections of the study are summarised as follows: [Section 2](#) presents a review of the relevant literature including its essential ideas, clustering hierarchy, routing tactics, and adaptive data aggregation methods. [Section 3](#) presents the proposed EEUMC UWSN network model, while [Section 4](#) describes the proposed EEUMC UWSN algorithm. In [Section 5](#) simulation environment and results of the experiment are presented. [Section 6](#), provides the conclusion and examines the results.

2. Literature survey

Many studies are examined and evaluated in this area to identify the benefits and drawbacks of UWSN techniques. The key challenges include underwater noise, channel attenuation, bandwidth constraints, acoustic wave speed, and network's lifespan. All of these issues are being investigated from many perspectives, and progress has been made in this section. Node battery capacity is the primary task that reduces UWSN longevity. The area's critical importance attracts the majority of scholarly attention. Because data transmission consumes more energy, UWSN routing algorithms are crucial for managing sensor node energy utilisation.

2.1. Related works

Sathish et.al. [21] Proposed EBREC strategy was designed with the goal of lowering transmission loss, increasing Packet Delivery Ratio (PDR), and ensuring that data packets get at their destination without being destroyed. When EBREC's performance was compared to a number of well-established benchmarks, it was discovered to outperform them. EBREC was able to attain a Residual Energy of 0.615 J, a Consumed Energy of 2.3 mJ, a Throughput of 10 Mbps, a PDR of 97.6 %, a Network Lifetime of 1750 seconds, and 91 Alive Nodes, as indicated by simulation results. The results of this study show that EBREC processes outperform other methods in terms of crucial parameters.

Nhat-Tien Nguyen et.al. [22] Proposed an EECMR protocol in this paper with the purpose of better balancing the energy requirements of individual nodes and enhancing the overall longevity of the network. The network space is divided into layers, each of which corresponds to a different depth of the network. The information is gathered by the nodes

and transferred to the sink via a multi-hop routing method. The cluster leader is chosen after considering the node's depth and the amount of energy it still has. The cluster head is in charge of collecting data packets from each node in the cluster and transmitting them to the upper layer of the sink node. The simulated results demonstrate the efficacy of EECMR in terms of network lifetime and node energy consumption.

Sandeep, D.N et.al. [23] investigated of the performance of Underwater Acoustic Sensor Networks (UASN) was performed in a study, with the primary focus on investigating problems about clustering, coverage, and connection within these networks. The article focused on how atypical communication mechanisms affect the aforementioned properties, notably clustering, coverage, and linkage. Furthermore, the significant challenges that still need to be solved in the field of underwater wireless sensor networks were highlighted. This study is a valuable resource for UWSN researchers, providing insights from the perspective of numerous communication styles. It accomplishes this by providing a complete assessment of existing acoustic communication-based methods for clustering, coverage, and connection.

Khan, M.T.R. et.al. [24] Proposed a solution to the tough job of resource management in an underwater setting with no accessible access for battery recharge or replacement via node clustering. It is well known that picking a cluster head necessitates the exchange of multiple packets, which consumes a significant amount of power. The Wake-up Sleep Cycle for Underwater Nodes Assisted by Autonomous Unmanned Vehicles (AUVs) Assisted Energy-Efficient Clustering (AEC) method is proposed in this study. To relieve the strain on the few accessible underwater sensor nodes, automated underwater vehicles handle functions such as cluster formation, cluster leadership selection, and establishing a wake-up-sleep cycle. The simulation-based validation of this claim shows that the protocol outperforms traditional clustering approaches in terms of efficiency by eliminating the need for additional packet exchange.

Khan, A. et.al. [25] Provided an in-depth examination of routing methods developed for Underwater Wireless Sensor Networks. There are two types of protocols: localization-based protocols and localization-free protocols. These two primary groups are further classified according to the specific routing issues they face or the characteristics they take into account. In contrast to others, this review focuses primarily on the most recent improvements in routing protocols that are currently accessible. Each protocol gives specific information about its routing technique, the specific issue that it addresses and solves, and the benefits that it delivers while also emphasizing the costs associated with utilizing it, and so on. This method provides researchers with a number of distinct advantages, including: improved understanding of each protocol's routing operations; illumination of potential improvements for overcoming drawbacks in future research; laying the groundwork for more intelligent and efficient protocols; assistance in selecting protocols for specific applications based on their merits; and, finally, the presentation of unexplored challenges and future research directions.

Hou, R. et.al. [26] Described the Energy-Balanced Unequal Layering Clustering (EULC) approach, which was created to improve energy efficiency of acoustic sensor networks. The EULC algorithm addresses energy inequities by incorporating unequal layering specified by node depth. This solves the 'hot spot' problem by generating clusters of varying sizes within a single layer. The simulation results show that the method is effective at achieving energy balance among the nodes in the Underwater Acoustic Sensor Network resulting in a longer network's lifespan.

Zhu, F. et.al. [27] Proposed the Energy Efficient Routing Protocol based on Layers and Unequal Clusters (EERBLC) to address the lack of a suitable localization mechanism for UWSNs. The three fundamental phases of operation in the EERBLC protocol are layer and uneven cluster establishment, transmission routing, and cluster maintenance and upgrading. In the first phase, we layer the underwater monitoring region and group nodes in the same layer together. This allows us to solve difficulties related to energy balance and "hotspots," as well as provide a

novel method for calculating cluster sizes and selecting cluster leaders that takes both of these elements into consideration. In the transmission phase of EERBLC, forwarding ratio and residual energy are employed in a novel method to determine the next forwarder. Finally, options for updating information inside and within clusters are described. In the simulation, EERBLC surpasses Depth based routing (DBR) and Energy efficient depth based routing (EEDBR) by establishing a better balance between energy usage and network lifetime and improving data transmission.

Yu, W et.al, [28] offered an enhanced Energy Optimization Clustering Algorithm (EOCA) intended for multi-hop underwater acoustic cooperative sensor networks (UWA-CSN) to address the energy limits of underwater sensor nodes. In the context of multi-hop cooperative communication, the novel EOCA algorithm takes into account a number of important variables, including the number of neighboring nodes, the residual energy of each node, the movement of sensor nodes due to ocean currents, and the distance between the sink node and each underwater sensor node. The approach introduces the concept of residual energy-based Maximum Effective Communication Range (reE-MECR) by dynamically changing the amount of energy utilised for data transmission at each hop based on the residual energy of the nodes involved. EOCA surpasses alternative clustering strategies in terms of extending the lifetime of multi-hop UWA-CSNs and preserving strong communication and networking performance metrics, according to experimental results. Package delivery ratio, energy efficiency, and network coverage are examples of these indicators. By combining the benefits of clustering and cooperative communication, the suggested system efficiently conserves energy in the demanding underwater environment.

Hong, Z. et.al. [29] employed for inter-node information transmission; this requires additional power to ensure network reliability and QoS. Topology Controlling with Energy Balance (TCEB) for UWSNs is a topology management technique meant to reduce network latency, interference, and energy usage. By leveraging a customized underwater network model and energy consumption model, a non-cooperative game-based technique is employed to choose high-performing cluster-head nodes. The next stage is to create an energy-efficient topology by connecting clusters with communication links. This is done in order to reduce total power consumption. In comparison to the three sample algorithms, simulation findings verify TCEB's utility by displaying enhanced energy economy and throughput in complicated underwater scenarios.

Khan, W et.al. [30] Presented the Multi-Layer Cluster-based Energy Efficient (MLCEE) protocol as a means of resolving difficulties and minimizing energy loss caused by the presence of hotspots in UWSNs. Using MLCEE necessitates a number of steps: first, the network must be stacked, and then the nodes within each layer must be clustered. Cluster heads (CH) decide which CH to send data to base on a number of factors, including the layer number, the size of the Hop id, and the fitness rating of the node. To reduce hotspots, the first layer is left unclustered so that data may be transferred directly to the sink, and CH is chosen using Bayesian probability and residual energy. This is done to reduce the number of problem locations. MLCEE outperforms other currently known techniques in MATLAB simulations of network lifetime, energy utilization, and data transport.

Durrani, M.Y. et.al. [31] Discussed the Adaptive Node Clustering Technique for Smart Ocean Underwater Sensor Network (SOSNET), a new routing protocol developed by us. To identify the ideal number of nodes that should compose a cluster for optimal routing efficiency, SOSNET use the biomimetic Moth Flame Optimizer (MFO). MFO is optimized in the same way as a moth is designed to fly in the direction of light. SOSNET is used to compare and contrast various routing optimization algorithms, such as Comprehensive Learning Particle Swarm Optimization (CLPSO), Ant Colony Optimization (ACO), and Grey Wolf Optimization (GWO). The transmission range, node density, and grid size are all methodically adjusted in the simulations used to determine performance. SOSNET distinguishes itself from the other algorithms

tested because it produces superior results over a broader range of metrics than any of the others.

Table 1 summarizes current research on UWSNs. Sathish. et al. investigate the fundamentals of underwater acoustic communications by examining architectures and cross-layer approaches. Nhat-Tien Nguyen et al. offer the EECMR protocol to achieve energy parity, multi-hop routing, and cluster leader selection. Sandeep, D.N., et al. investigate UASN functionality with an emphasis on clustering, coverage, and connectivity issues. Khan et al. offer an AEC protocol that uses AUVs to better manage resources and reduce energy consumption. Khan, A. et al. examine routing methods, localization-based protocols, and localization-free protocols, as well as their advancements. R. Hou et al. propose the EULC technique for energy-efficient clustering to tackle hotspots and uneven layering. Zhu, F. et al. created the EERBLC protocol, which is an energy-efficient routing strategy that prioritizes transmission innovation and cluster upkeep. Yu, W, et al. propose an EOCA algorithm for multi-hop UWA-CSNs with a focus on residual energy for communication and a longer network lifetime. Hong, Z. et al. offer topology control in TCEB for delay reduction and power savings. Khan, W. et al. propose the MLCEE protocol for resolving hotspots, which uses multi-layer clustering and Bayesian probability. Durrani, M. Y. et al. discuss the SOSNET routing protocol with MFO for adaptive node clustering and optimization. Finally, we present an Energy-Efficient Unequal Multi-level Clustering method that handles scalability and parameter settings issues in large networks while emphasizing the benefits of energy-efficient clustering, multi-level structure, and unequal node distribution.

3. Proposed EEUMC UWSN network model

In this section, we will discuss the network model that would be used by the proposed EEUMC for UWSNs. UWSN node positioning for EEUMC in UWSNs refers to the strategic placement of sensor nodes in an underwater environment with the goal of optimizing energy consumption through the deployment of multilevel clusters of varying sizes and characteristics as shown in Fig. 1. This is done in order to reduce the quantity of energy that is squandered. In order to overcome difficulties that can occur in underwater environments, such as unequal energy consumption and signal attenuation, this technique takes into account variables such as node depth, communication range, and energy limits [32]. These issues may be exacerbated by the environment's proximity to water. The procedure begins with network segmentation based on node depth, then moves on to cluster formation at the cluster level, and finally concludes with the selection of energy-efficient cluster heads [33, 34]. This cutting-edge positioning technique should, in the end, make it possible to provide more continuous and trustworthy service in applications involving underwater sensing and communication because it extends the lifetime of networks, improves the energy economy, and makes communication more effective.

Establishing inter-node links inside the network is critical for EEUMC-UWSNs. By identifying the communication channels that exist between individual sensor nodes in the network, these links create the framework for effective multilevel clustering. The connectedness between nodes is determined by their ideal positioning, which takes a variety of parameters into account, such as node depth, communication range, and energy constraints. By intelligently connecting nodes across several layers and clusters, this technique aims to achieve balanced energy usage, reduce signal attenuation, and improve overall network performance in harsh underwater environments as depicted in the Fig. 2. The design and maintenance of these inter-node links is a critical mechanism for enabling successful communication, resource sharing, and cooperative data transmission, ultimately contributing to the ultimate goal of achieving energy efficiency and network durability in UWSNs. This is due to the fact that inter-node linkages are an important mechanism for promoting efficient communication, resource sharing, and cooperative data transmission.

Table 1
Features of existing UWSNs.

Author [citation]	Methodology	Features	Performance Metrics	Advantages	Disadvantages
Sathish et al. [21]	EBREC	Energy-balanced reliable and effective clustering	Energy consumption, network lifetime	Balanced energy consumption, reliability	Lack of details on scalability or real-world application
Nhat-Tien Nguyen et al. [22]	EECMR protocol	Energy balancing, multi-hop routing, cluster leader selection based on depth and energy	Energy efficiency, network lifetime	Efficient cluster leader selection, extended network lifetime	Potential complexity in multi-hop routing
Sandeep, D.N et al. [23]	Investigation of UASN performance	Addressing clustering, coverage, and connection issues; Insights into communication mechanisms	Coverage, connectivity, energy consumption	Comprehensive investigation of UASN performance	Limited to theoretical analysis, lacks experimental results
Khan, M.T.R. et al. [24]	AEC protocol with AUVs	Resource management, energy-efficient clustering, eliminating packet exchange	Energy efficiency, data transmission reliability	Reduced packet exchange, energy efficiency	Limited to specific scenarios involving AUVs
Khan, A. et al. [25]	Routing methods for UWSNs	Localization-based and localization-free protocols, recent improvements, advantages and challenges	Localization accuracy, energy consumption	Broad overview of routing methods	Does not focus on a single approach, lacks detailed evaluation
Hou, R. et al. [26]	EULC approach for energy-efficient clustering	Unequal layering, cluster balancing, addressing hot spots	Energy consumption, network lifetime	Effective hotspot management, energy efficiency	Potentially complex cluster formation process
Zhu, F. et al. [27]	EERBLC protocol for energy-efficient routing	Layer and cluster establishment, novel transmission routing, cluster maintenance	Energy efficiency, network stability	Stable cluster maintenance, energy-efficient routing	Limited scalability in larger networks
Yu, W et al. [28]	EOCA algorithm for multi-hop UWA-CSNs	Residual energy-based communication range, extended network lifetime, energy efficiency	Network lifetime, energy efficiency	Extended network lifetime, efficient energy use	Sensitive to parameter changes
Hong, Z. et al. [29]	TCEB topology management	Latency reduction, interference reduction, energy efficiency	Latency, energy consumption, interference level	Reduced latency and interference	May not address all UWSN challenges
Khan, W et al. [30]	MLCEE protocol for hotspot resolution	Multi-layer clustering, data transfer optimization, Bayesian probability for CH selection	Hotspot resolution, energy efficiency	Effective hotspot management, energy efficiency	Complexity in cluster head (CH) selection process
Durrani, M.Y. et al. [31]	SOSNET routing protocol using MFO	Adaptive node clustering, Moth Flame Optimizer, comparison with other algorithms	Energy efficiency, network lifetime, stability	Adaptability to different scenarios, efficient routing	Complex optimization process
Our work	Energy-Efficient Unequal Multi-level Clustering	* Energy-efficient clustering, multi-level organization, unequal node distribution * Sensitive to parameter settings, scalability for large networks	Energy efficiency, network scalability	Scalability for large networks, energy efficiency	Sensitive to parameter settings

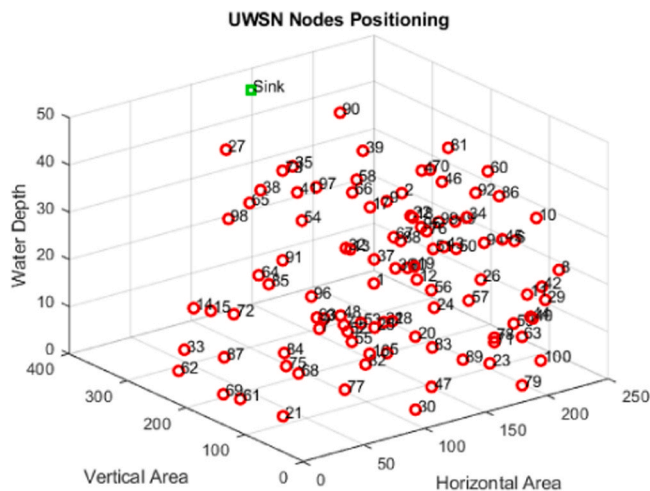


Fig. 1. EEUMC- UWSN Nodes positioning.

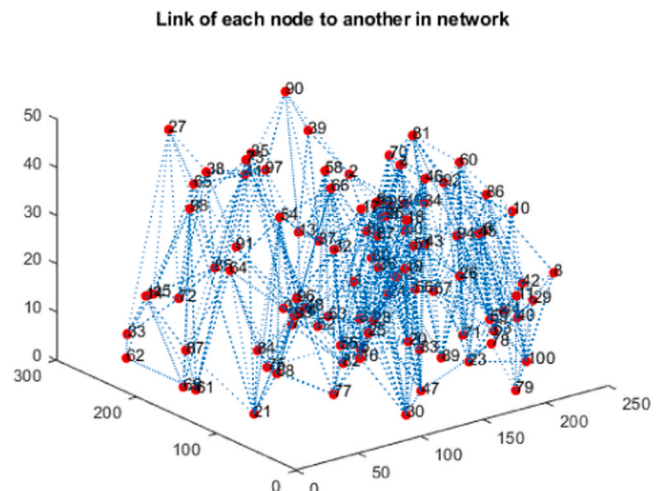


Fig. 2. Inter-node links inside the EEUMC –UWSN network.

In a three-dimensional visualization of the initial Energy Efficient (EE) cluster head selection process of an Unequal Multilevel Clustering scheme tailored for UWSNs, the underwater deployment area is depicted in Fig. 3 as a submerged environment with sensor nodes distributed at varying depths. The visualization depicts the formation of hierarchical clusters, with nodes within each level exhibiting varying energy levels, which are graphically represented by unique colour gradations or sizes. As the algorithm iterates, dynamic visual signals such as pulsing nodes or enhanced illumination are used to show the selection of energy-

conscious nodes as initial cluster heads. The representation of the intricate spatial linkages, energy differentials, and strategic node choices that go into the optimum cluster head selection demonstrates energy efficiency in the context of underwater sensor network management.

The ocean floor is depicted as a flat plane in a two-dimensional visual representation of an Unequal Multilevel Clustering approach for the first-stage EE cluster head selection process in Underwater Wireless Sensor Networks as represented in the Fig. 4. Sensor nodes are

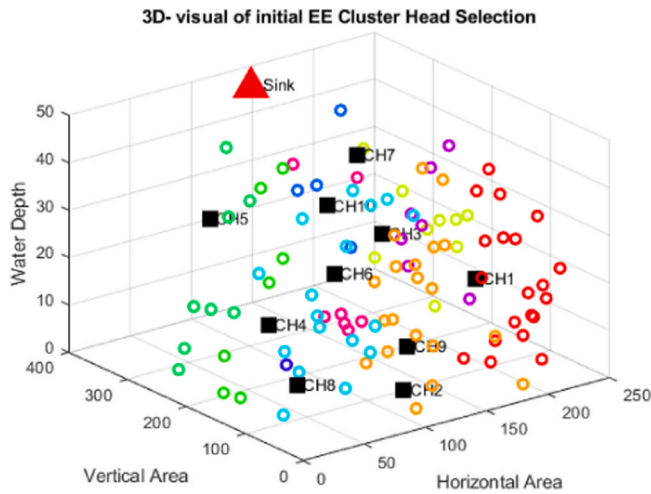


Fig. 3. 3D visual of initial EE cluster head selection.

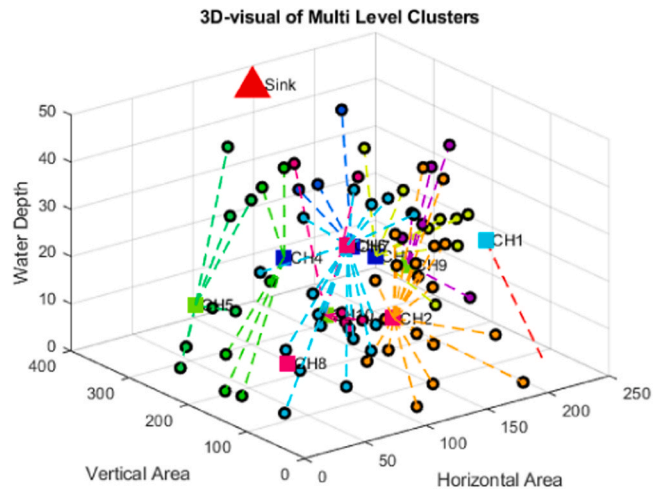


Fig. 5. 3D visual of Multi-level clusters.

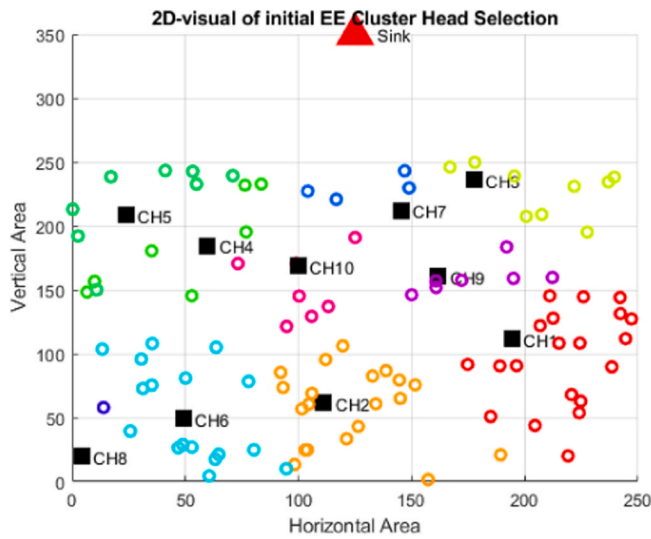


Fig. 4. 2D visual of initial EE cluster head selection.

represented as dots scattered over this plane, with changes in colour or size indicating their energy level. Clustering is graphically depicted by defining groups of nodes with distinct forms or connecting lines. As the process continues, visual signals like as bold outlines or increased colours are employed to highlight the selection of energy-efficient nodes as the original cluster heads. This 2D figure depicts strategic node selection, energy considerations, and cluster design to assist you in achieving the best performance from your underwater sensor network.

A three-dimensional graphic portrayal of the Multi-Level Cluster configuration is used as an example of the third dimension within the scope of EEUMC for UWSNs. The sensor nodes are represented as single dots, each with a distinct colour gradient indicating the quantity of electricity it generates. These nodes are depicted as floating in this watery environment. The Fig. 5 clearly shows how the clusters are structured into layers, with each layer corresponding to the depth of a distinct cluster in turn. These multi-tiered clusters, shown as interconnected spherical or ellipsoidal volumes, comprise nodes with a range of energy reserves. Clusters with a larger perimeter tend to reflect nodes with less energy and are located deeper in the ground, whereas clusters with a greater centralization tend to represent nodes with more energy and are located closer to the earth’s surface. This three-dimensional model of an underwater sensor network’s topology provides a detailed representation of energy-conscious groups, complete with the complex

spatial relationships and hierarchical structure that are hallmarks of the uneven clustering method.

In a two-dimensional visual depiction of the construction of a Multi-Level Cluster within the scope of EEUMC for UWSNs, the underwater domain is portrayed as a flat canvas. The sensor nodes are represented as points scattered throughout the canvas. Each point has been assigned a distinct colour or symbol to represent the energy level for which it is accountable. The visualization depicts a cluster hierarchical structure, demonstrating how nodes with varying degrees of energy can be grouped into large clusters and subordinate clusters. These clusters are divided from one another by concentric circles or layered polygons, demonstrating the multilevel design’s numerous levels. The larger, more central clusters contain nodes with greater energy reserves, whereas the smaller, more peripheral clusters contain nodes with significantly lower energy reserves. This 2D graphic effectively conveys the idea of the uneven clustering process. Fig. 6 depicts the network’s tiered organization and visually illustrates how energy-aware node grouping works in the context of an underwater sensor network.

The approach of collecting energy in the context of EEUMC for UWSNs needs to accumulate the power from all of the nodes that have been carefully clustered together into multi-level clusters. Each cluster’s nodes collaborate to capture ambient energy from submerged sources such as sun radiation, hydrokinetic motion, or thermal differentials.

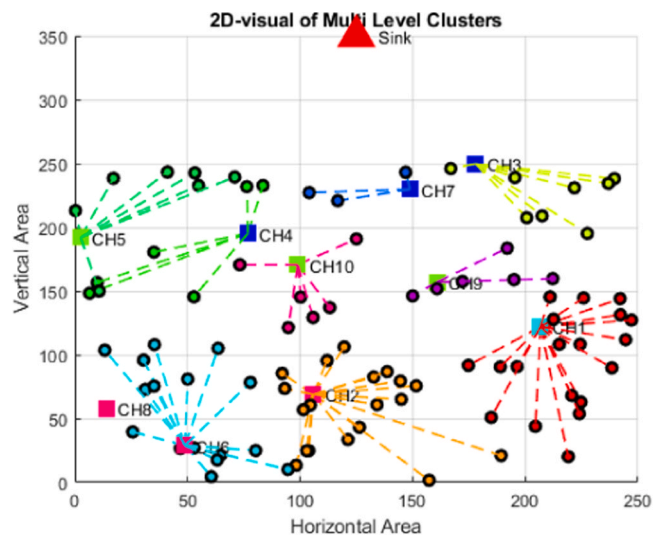


Fig. 6. A 2D visual of Multi-level clusters.

Because of the network's hierarchical structure, energy-rich nodes, which are frequently found in primary clusters closer to the water's surface, contribute more significantly to the energy pool. These nodes are in charge of collecting and efficiently transferring energy to cluster heads, who are subsequently in charge of managing energy distribution within their particular clusters as shown in Fig. 7. This dynamic energy-gathering technique optimizes resource consumption, extending the network's operating lifetime. This is achieved by taking advantage of energy gradients and successfully balancing energy distribution among nodes at various levels of the clustering hierarchy.

The final clustering output of EEUMC for UWSNs is shown in three dimensions, with depth, representing the undersea domain. The visualization displays a highly tiered cluster design, with sensor nodes classified as primary, secondary, or even higher tiers based on their energy levels and geographical proximity to one another. The nodes within each cluster are colour-coded or scaled differently based on the number of energy reserves they possess to illustrate the varied functions they perform. The center clusters are larger and brighter, whereas the outside clusters are smaller, contain lower-energy nodes, and are located deeper in the structure. The highest-energy nodes are located towards the surface of the water, with the largest clusters in the core. Connecting lines or other dynamic visual signals focuses attention on inter-cluster communication, emphasizing data flow between nodes and cluster heads. This detailed 3D graphic highlights the essence of the energy-efficient uneven multilevel clustering strategy and provides an intuitive representation of the network's enhanced organization, energy dynamics, and increased communication patterns inside an underwater sensor network environment as depicted in the Fig. 8.

4. Proposed EEUMC – UWSN algorithm

In order to optimize energy consumption and data transfer efficiency, the pseudo-code technique for EEUMC in UWSNs goes through a series of steps. It starts by computing normalized energy and distance measurements for each sensor node and then combining them to identify probable cluster heads at various levels. Based on their proximity, the nodes are subsequently sorted into clusters around these selected heads. Intelligent routing is established to locate ideal data transmission paths by taking into account energy levels, network quality, and distance. To reduce redundancy, data aggregation is done within clusters. Data is transferred from non-cluster head nodes to their respective cluster heads, and finally to the sink node via the defined routing channels. The system continuously analyses node energy levels and, if necessary, reassigns cluster head jobs to maximize energy efficiency. EEUMC effectively balances energy usage, improves data delivery, and extends

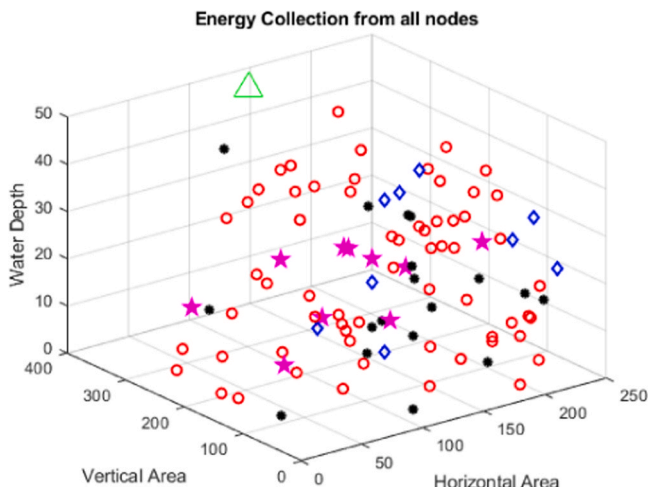


Fig. 7. Energy collection from all nodes.

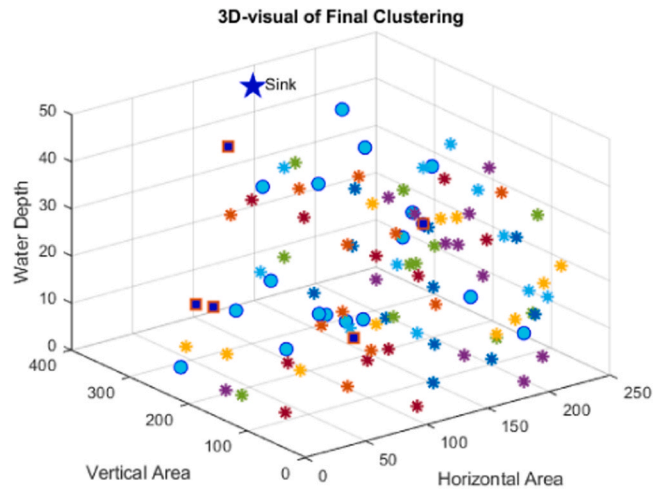


Fig. 8. Energy collection from all nodes.

network lifetime in underwater wireless sensor networks by following these procedures followed by the mathematical equations [35–37].

1. Determine the number of levels (L) for multilevel clustering based on node-sink distances.
Set initial energy thresholds for each level $E_{\text{threshold}}$.
2. **Node Classification and Cluster Head Selection:**
 - For each level i ($i = 1$ to L):
 - Calculate normalized energy $E_{\text{normalized}}$ for each node as in Eq. (1):

$$E_{\text{normalized}} = \frac{E_{\text{node}} - E_{\text{min}}}{E_{\text{max}} - E_{\text{min}}} \quad (1)$$
 - Calculate the normalized distance $D_{\text{normalized}}$ of each node from the sink as in Eq. (2):

$$D_{\text{normalized}} = \frac{D_{\text{sink}} - D_{\text{min}}}{D_{\text{max}} - D_{\text{min}}} \quad (2)$$
 - Calculate the combined metric M_{combined} for each node as in Eq. (3):

$$M_{\text{combined}} = \alpha * E_{\text{normalized}} + (1 - \alpha) * D_{\text{normalized}} \quad (3)$$

Where $0 \leq \alpha \leq 1$ is a weighting factor.
 - Select cluster head(s) based on the highest M_{combined} within a level.
3. **Cluster Formation:**
 - Assign non-cluster head nodes to the nearest cluster head based on Euclidean distance [38].
4. **Intelligent Routing:**
 - For each cluster head:
 - Calculate the routing metric (R_{metric}) for each neighbour node as in Eq. (4):

$$R_{\text{metric}} = \beta * E_{\text{normalized}} + \gamma * LQ_{\text{normalized}} + \delta * D_{\text{normalized}} \quad (4)$$

Where β , γ , and δ are weights, and $LQ_{\text{normalized}}$ is the normalized link quality.
 - Select the next hop based on the lowest R_{metric}
5. **Data Aggregation:**
 - For each cluster head:
 - Aggregate data from member nodes.
 - Apply data aggregation function to reduce redundant data [39].

6. Data Transmission:

- Non-cluster head nodes transmit aggregated data to their respective cluster heads.
- Cluster heads transmit aggregated data to the sink node along the established routing paths [40–42].

7. Energy Monitoring and Update:

- Periodically monitor node energy levels.
- If E_{node} falls below a threshold, reassign the cluster head role to a neighbouring node with higher energy.

8. Performance Evaluation:

- Simulate the network and evaluate metrics such as energy consumption, residual energy, and number of dead nodes and received packets.
- Compare EEUMC's performance with other clustering and routing methods.

The EEUMC-UWSN algorithm takes into account data on the energy and position of an underwater sensor network, as well as the position and communication range of the sink node. The ultimate goal is to create a clustered network topology with predefined cluster heads and transmission channels. The algorithm is composed of the following stages: analyzing link quality, computing routing metrics based on link quality, selecting cluster heads for different levels, forming clusters around cluster heads, determining the next hop for data transmission, and so on. When a node's power falls below a certain threshold, the system begins monitoring and adjusting the node's energy consumption in order to reach the best level of efficiency feasible. The algorithm will keep looking for the optimum way until it finds one, and it will prioritize the possibilities that consume the least amount of energy.

5. Simulation results and discussions

The simulation results will be evaluated in MATLAB and compared to state-of-the-art approaches in this section. This will be done so that the method can be used to extend the life of UWSN.

Algorithm 1. : EEUMC-UWSN algorithm

Input:

- Set of underwater sensor nodes with energy levels and geographic coordinates.
- Sink node's geographic coordinates.
- Communication range of nodes.

Output:

- Clustered network topology with designated cluster heads.
- Routing paths for data transmission.

1. Create the network
2. Calculate Normalized Energy (node) using Equation 1
3. Return $E_{\text{normalized}}$
4. Calculate Normalized Distance (node) using Equation 2
5. Return $D_{\text{normalized}}$
6. Calculate the Combined Metric (node) using Equation 3
7. Return M_{combined}
8. Calculate the Routing Metric (node, neighbour, link quality) using Equation 4
9. Return R_{metric}
10. Select Cluster Heads for each level i ($i = 1$ to L)
11. Node. $M_{\text{combined}} =$ Calculate Combined Metric (node)
12. Select the node with the highest M_{combined} as cluster head for level i
13. Cluster Formation for each neighbour node
14. Link Quality = Calculate Link Quality (cluster head, neighbour)
15. Neighbour. $R_{\text{metric}} =$ Calculate Routing Metric the (cluster head, neighbour, link Quality)
16. Select the next hop based on lowest R_{metric}
17. Energy Monitoring and Update, if node. Energy < Energy Threshold
18. Find neighbouring node with highest energy
19. Best path is found
20. End

Table 2
Simulation parameters and its values.

Simulation Parameters	Values
Nodes	100
Rounds	2000
Packet size	6400 bits
Initial Energy	5 J
Energy Threshold	0.5 J
Transmission Range	100 m
Transmission Energy	50 nJ/bit/m ²
Reception Energy	50 nJ/bit/m ²

Table 4
Residual energy (J) for 150 m.

No. of Rounds	Proposed EEUMC	EBREC	EECMR	DBR
200	4.01	2.7	2.1	1.5
400	3.03	1.7	0.8	0.4
600	2.06	1.2	0.4	0.1
800	1.2	1.06	0.003	0.01
1000	1	0.8	0.2	0.001

The efficiency of EEUMC is compared to that of EBREC, EECMR, and DBR in this study. A large number of simulations are run using the MATLAB software. To compare the proposed EEUMC to current protocols such as EBREC [21], EECMR [22], and DBR [23], metrics such as residual energy, number of dead nodes, and received packets are used. To evaluate and establish the overall quality of the findings, the EBREC, EECMR, DBR algorithms are utilised as benchmarks. The simulation parameters and its values is tabulated in Table 2.

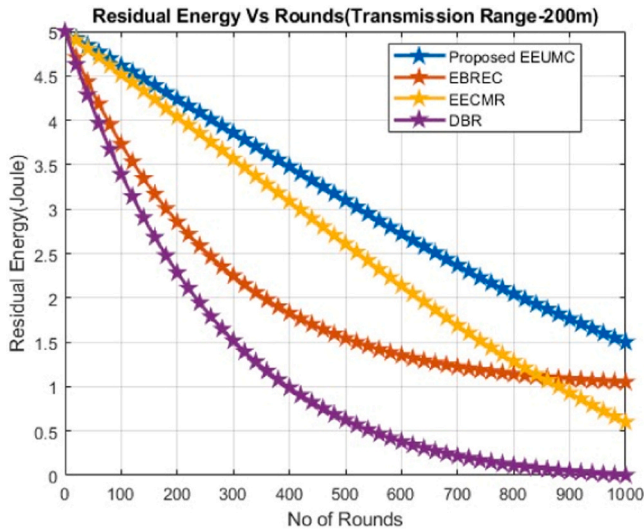


Fig. 9. Residual energy versus Rounds for 200 m transmission range.

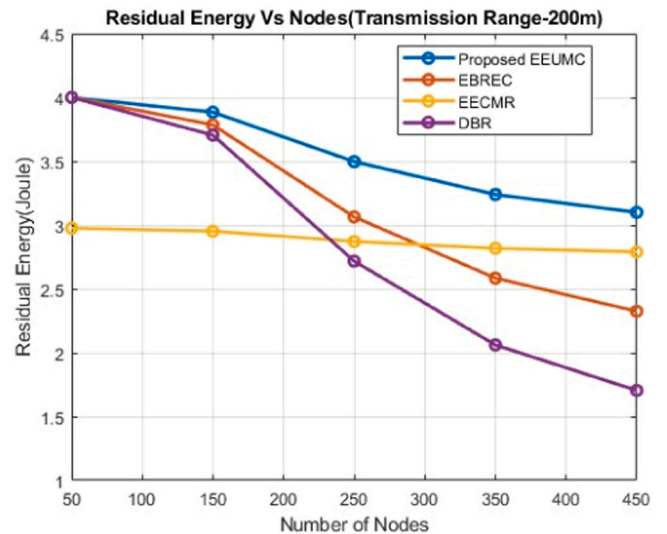


Fig. 11. Residual energy versus Nodes for 200 m transmission range.

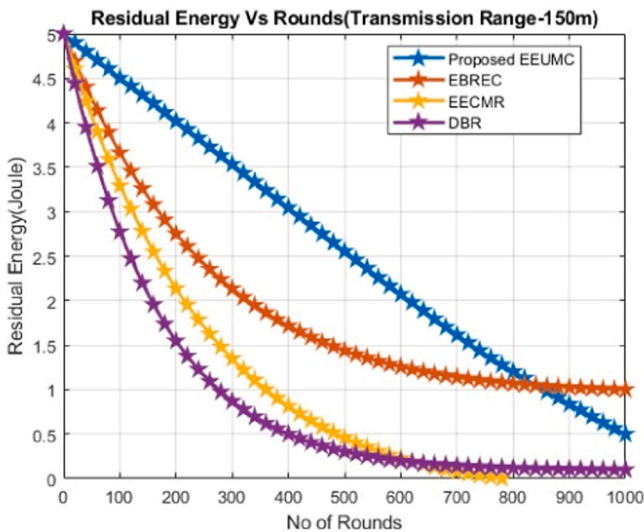


Fig. 10. Residual energy versus Rounds for 150 m transmission range.

Table 3
Residual energy (J) for 200 m.

No. of Rounds	Proposed EEUMC	EBREC	EECMR	DBR
200	4.2	4.0	2.8	2.2
400	3.9	3.1	1.8	0.9
600	2.7	2.1	1.3	0.3
800	2.2	1.3	1.1	0.1
1000	1.5	1.05	0.6	0.01

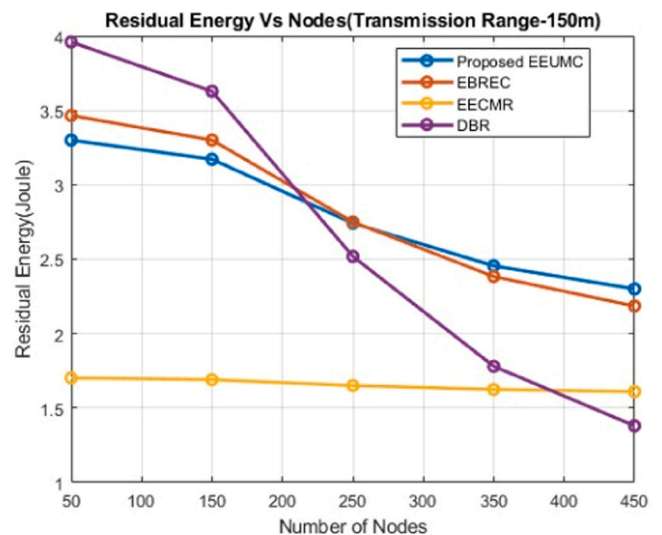


Fig. 12. Residual energy versus Nodes for 150 m transmission range.

Table 5
Residual energy (J) for 200 m.

No. of nodes	Proposed EEUMC	EBREC	EECMR	DBR
150	3.3	2.8	2.7	2.3
250	3.1	2.7	2.3	1.7
350	3.1	2.4	2.3	1.7
450	3.1	2.7	2.3	1.7

5.1. Residual energy (J)

5.1.1. Residual energy versus rounds

The residual energy versus rounds analysis within a transmission range of 200 meters and 150 m as depicted in Fig. 9 and Fig. 10 respectively as part of EEUMC developed for UWSNs, depicts the dynamic evolution of energy levels across rounds of network operation. The goal of this study was to calculate the amount of energy wasted by the network during each cycle. The graph depicts how the algorithm iterates across rounds and modifies the residual energy of the sensor nodes as a result. Because of their diverse duties and ways of communication, the nodes that comprise distinct multilevel clusters consume energy at varying rates. The scatter plot illustrates energy consumption patterns and highlights potential discrepancies in energy consumption rates between primary and secondary classifications. The graphic properly depicts the algorithm’s efficiency in optimising energy distribution and routing tactics in order to extend the network lifetime and the statistical values represented in Table 3 and Table 4 respectively. This sheds insight into the practicality EEUMC in the demanding environment of an underwater wireless sensor network, where dependable communication and smooth operation are critical.

5.1.2. Residual energy versus nodes

An analysis of residual energy versus nodes at a transmission range of 200 meters and 150 m as depicted in Fig. 11 and Fig. 12 respectively demonstrates how the network’s sensor nodes are dispersed in terms of their remaining energy. The graph displays the change in residual

Table 6
Residual energy (J) for 150 m.

No. of nodes	Proposed EEUMC	EBREC	EECMR	DBR
150	2.5	2.3	2.1	1.6
250	2.3	2.2	1.6	1.4
350	2.3	2.1	1.6	1.3
450	2.3	2.1	1.6	1.3

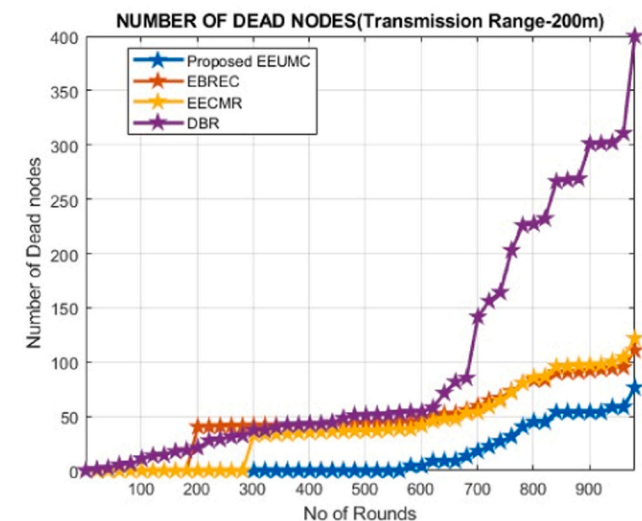


Fig. 13. Number of dead nodes versus rounds for 200 m transmission range.

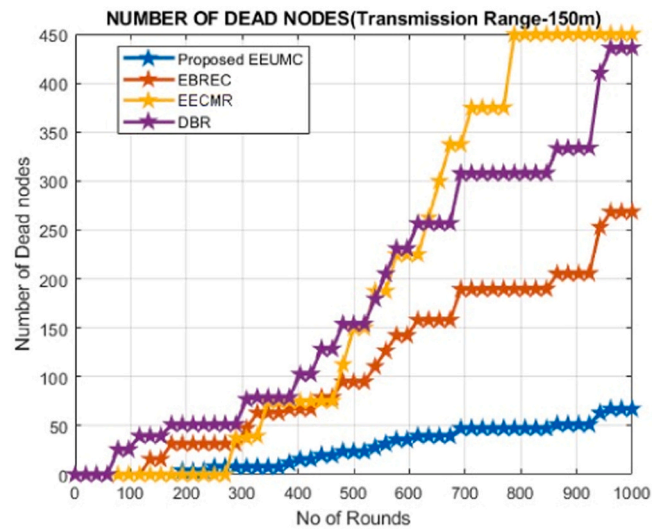


Fig. 14. Number of dead nodes versus rounds for 150 m transmission range.

Table 7
No. of dead nodes for 200 m.

No. of Rounds	Proposed EEUMC	EBREC	EECMR	DBR
200	1	4	8	7
400	2	8	9	6
600	6	10	24	28
800	9	23	41	53
1000	12	18	52	68

Table 8
No. of dead nodes for 150 m.

No. of Rounds	Proposed EEUMC	EBREC	EECMR	DBR
200	2	10	14	18
400	4	16	58	64
600	7	100	120	178
800	20	150	340	321
1000	60	420	441	408

energy per node as a function of the total number of operational nodes. Lower energy depletion rates may be observed for nodes located in secondary clusters or further away from the sink than for nodes

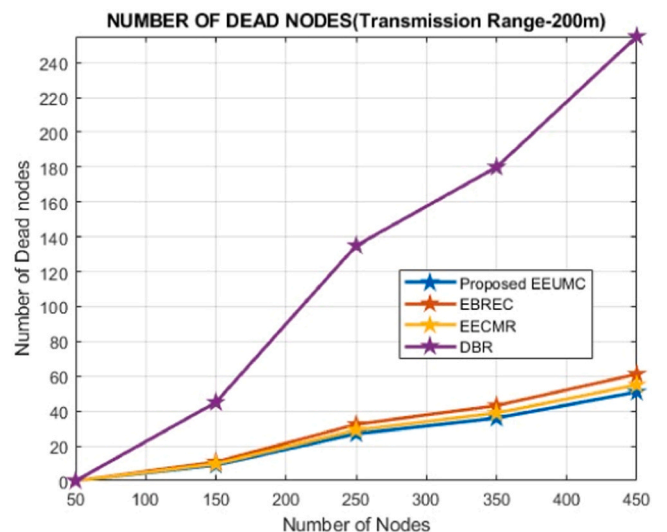


Fig. 15. Number of dead nodes versus nodes for 200 m transmission range.

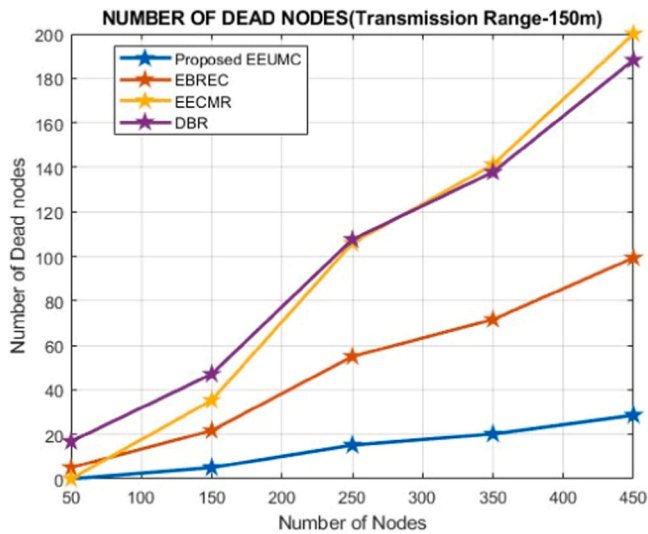


Fig. 16. Number of dead nodes versus nodes for 150 m transmission range.

Table 9
Number of dead nodes for 200 m.

No.of nodes	Proposed EEUMC	EBREC	EECMR	DBR
150	12	14	18	20
250	21	24	26	36
350	25	29	33	42
450	29	40	58	124

Table 10
Number of dead nodes for 150 m.

No.of nodes	Proposed EEUMC	EBREC	EECMR	DBR
150	11	46	83	95
250	16	62	116	123
350	19	70	133	138
450	28	101	195	200

positioned closer to the sink or within primary clusters with higher energy levels. This diagram demonstrates the algorithm’s ability to maximize energy efficiency by balancing energy use among nodes and clusters and accounting for the influence of distance on communication

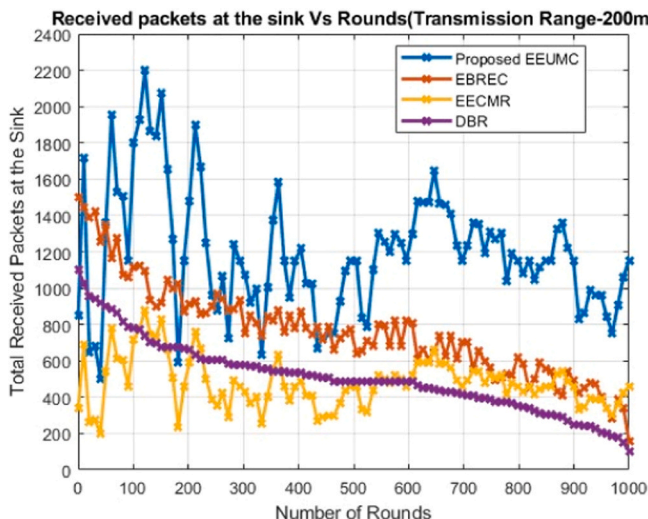


Fig. 17. Received packets versus rounds for 200 m transmission range.

efficacy and the statistical values represented in Table 5 and Table 6 respectively. This research shows that EEUMC is a viable alternative for underwater wireless sensor networks because of its capacity to conserve energy, extend network life, and ensure reliable communication.

5.2. Number of dead nodes

5.2.1. Number of dead nodes versus rounds

The number of cluster heads can be used to evaluate the performance of different clustering. The number of dead nodes in EEUMC for UWSNs signifies the number of sensor nodes that have run out of energy and are thus unable to participate in network operations within a transmission range of 200 meters and 150 m as depicted in Fig. 13 and Fig. 14 respectively. Because of the restrictions and limited energy supply of the undersea environment, nodes placed outside this transmission range may experience increased energy consumption for communication. This could result in early energy depletion and the node’s probable collapse. The accurate number of dead nodes at a transmission range of 200 meters and 150 metres reflects the network’s energy efficiency and resilience, demonstrating the algorithm’s ability to optimize node placement, communication strategies, and energy management to lessen the impact of dead nodes and sustain network longevity and the statistical values represented in Table 7 and Table 8 respectively.

5.2.2. Number of dead nodes versus nodes

The dynamic progression of node failures over the course of consecutive rounds of network operation in the field of EEUMC for UWSNs is depicted by the depiction of dead nodes versus rounds at a transmission range of 200 meters and 150 m as depicted in Fig. 15 and Fig. 16 respectively. This is accomplished by illustrating how the number of dead nodes decreases as the transmission range rises. As the number of rounds increases, so does the percentage of sensor nodes that have run out of power and stopped operating. The analysis emphasizes the algorithm’s utility in decreasing node mortality and prolonging network longevity by orchestrating energy-aware approaches. Optimal communication channels and uneven multilevel grouping are two of these strategies. The graph illustrates how network architecture and routing decisions affect node lifespan. It also demonstrates the EEUMCs ability to maintain network performance while negotiating the hurdles of energy scarcity and communication range inside the complex environment of an underwater wireless sensor network and the statistical values represented in Table 9 and Table 10 respectively.

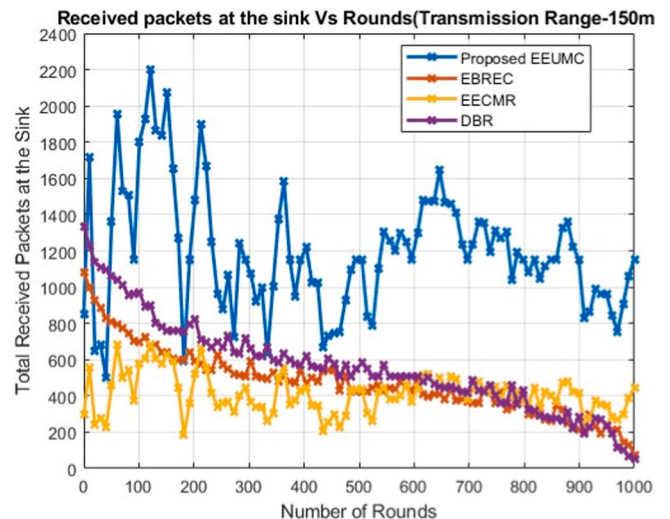


Fig. 18. Received packets versus rounds for 150 m transmission range.

Table 11
Received packets for 200 m.

No.of Rounds	Proposed EEUMC	EBREC	EECMR	DBR
200	1600	740	607	503
400	965	646	403	336
600	922	524	405	324
800	901	644	378	285
1000	922	369	222	100

Table 12
Received packets for 150 m.

No.of Rounds	Proposed EEUMC	EBREC	EECMR	DBR
200	1519	641	497	422
400	920	101	541	392
600	1014	621	384	301
800	1022	628	341	224
1000	904	284	205	98

Table 13
Received packets for 200 m.

No.of nodes	Proposed EEUMC	EBREC	EECMR	DBR
150	253	126	80	75
250	411	205	140	123
350	567	283	208	170
450	707	353	268	212

Table 14
Received packets for 150 m.

No.of nodes	Proposed EEUMC	EBREC	EECMR	DBR
150	200	90	82	64
250	339	152	136	121
350	480	216	192	178
450	626	281	251	237

5.3. Received packets

5.3.1. Received packets versus rounds

In EEUMC for UWSNs, the number of packets received at the sink is plotted against the number of rounds within a transmission range of 200 meters and 150 m as depicted in Fig. 17 and Fig. 18 respectively to visualize data aggregation and transmission efficiency over multiple rounds of network operation. The number of transmission rounds is displayed in relation to the number of packets received. This graph depicts how the number of packets successfully received at the sink fluctuates throughout the course of the algorithm’s many iterations. The graph provides insights into the algorithm’s ability to optimize data routing, energy-efficient communication, and cluster coordination as sensor nodes collect data and transmit it to cluster heads, and ultimately to the sink. This visualization depicts the effectiveness of EEUMC in ensuring data transmission, reducing packet loss, and enhancing overall network performance and lifetime in an underwater wireless sensor network. To accomplish this, we examine how frequently packets are received in the network in relation to the number of rounds and the statistical values represented in Table 11 and Table 12 respectively.

5.3.2. Received packets versus Nodes

Fig. 19 and Fig. 20 shows the number of packets received at the sink plotted against the number of nodes within a 200 meters and 150 m transmission range respectively in the context of EEUMC for UWSNs provide insight into the efficiency of data collection and transmission as network size changes. This graph depicts the efficiency of data collecting and transmission as network size changes. When the total number of nodes in the network is varied, this graph demonstrates how the total number of nodes in the network has an effect on the number of packets that are successfully received at the sink. The graphs depict how the algorithm’s energy-conscious clustering, routing, and communication strategies influence the consistent delivery of data to the sink as the network’s node count grows. One method for quantifying the efficacy of EEUMC in optimizing data aggregation, network efficiency, and communication reliability while addressing the challenges of limited energy resources and transmission range in an underwater wireless sensor network environment is to examine the correlation between received packets and the number of nodes and the statistical values represented in Table 13 and Table 14 respectively.

5.4. Comparative analysis

The research that have been presented centers on conducting a comparative comparison of the efficiency with which EEUMC operates within the framework of UWSNs. In the study, the dynamic evolution of energy levels over the many rounds of network operation is analyzed from the perspective of residual energy versus rounds. The iteration of

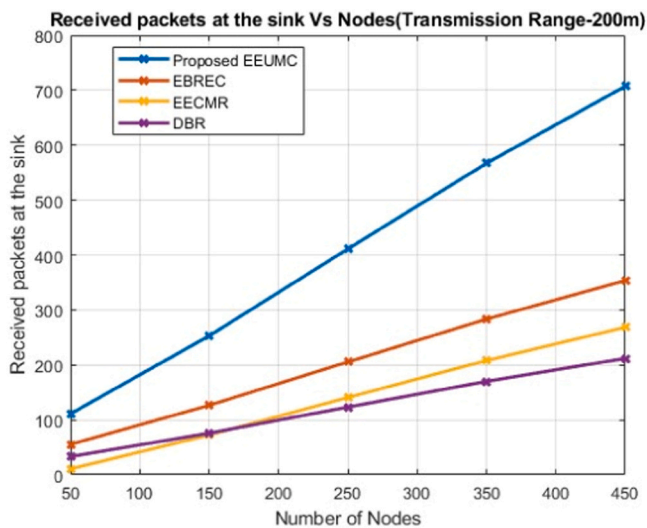


Fig. 19. Received packets versus nodes for 200 m transmission range.

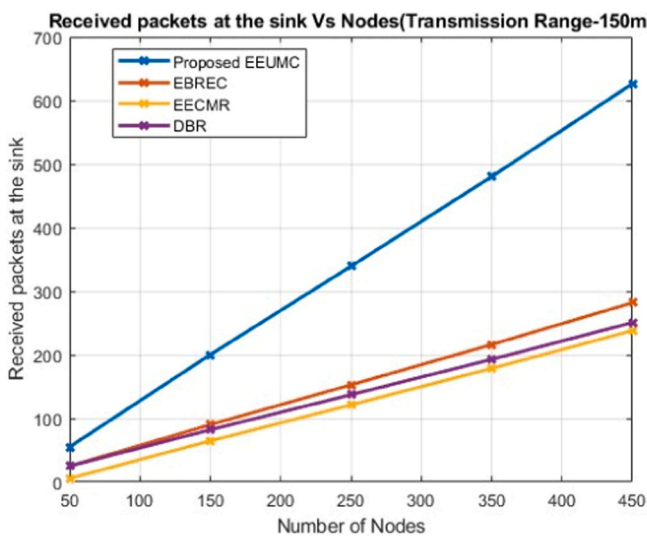


Fig. 20. Received packets versus nodes for 150 m transmission range.

the algorithm over rounds alters the remaining energy of the sensor nodes, with energy consumption rates differing between separate multilevel clusters due to the diversity of the responsibilities and communication mechanisms involved. The scatter plots illustrate potential disparities in energy consumption rates, highlighting the algorithm's efficiency in optimizing energy distribution and routing strategies. This is emphasized by the fact that the algorithm is highlighted. In addition, the statistical results that are supplied in Table 3 and Table 4 demonstrate how successful the algorithm is in extending the lifetime of the network.

When analyzing residual energy versus nodes, the research demonstrates how the remaining energy of sensor nodes is distributed throughout the network. Nodes that are located in secondary clusters or that are further away from the sink have a rate of energy depletion that is lower than that of nodes that are located in primary clusters. This exemplifies the algorithm's capacity to maintain a consistent level of energy consumption across all nodes and clusters. The algorithm's effectiveness is further demonstrated by the statistical figures presented in Tables 5 and 6.

The inquiry into the number of dead nodes looks at nodes that have lost all of their power, which has a negative impact on the operations of the network. The algorithm's energy efficiency and robustness can be inferred from how accurately it counts the number of dead nodes at varying transmission ranges. The ability of the algorithm to optimize node location, communication techniques, and energy management is made clear by the analysis of dead nodes in comparison to rounds and nodes, which is depicted in Fig. 13 through Fig. 16, along with the tables that correspond to those figures. In its final step, the research investigates the packets that were successfully received, which reveals data aggregation as well as transmission efficiency across rounds and network sizes. Through the examination of received packets in comparison to rounds and nodes, as well as the statistical values that are shown in Table 11 through Table 14, the algorithm's optimization of data routing, communication that is efficient with energy, and cluster coordination is made abundantly clear.

Overall, the study highlights EEUMC as a feasible solution for the issues of underwater wireless sensor networks. More specifically, it highlights the method's capacity to save energy, extend the life of the network, assure effective connection, and optimize data transmission.

6. Conclusion

Finally, the EEUMC approach provides a big step towards resolving the tough difficulties that plague UWSNs. The EEUMC approach is well-suited for situations characterized by restricted availability of energy sources, inconsistencies in communication ranges, and varied node capabilities. The data presented demonstrates the algorithm's extraordinary performance in extending network lifetime, reducing energy waste, and increasing data transmission efficiency. The EEUMC strategy has the potential to fundamentally revamp UWSNs by using multilevel organization and energy-conscious techniques. Long-term, dependable communication and data collecting in aquatic environments will be possible as a result. The EEUMC approach clearly shines like a beacon, poised to herald in a new era of efficiency, resilience, and innovation in underwater wireless sensor network applications. Despite its overall increased performance in terms of residual energy, network lifetime, and received packets, this discovery shows a potential shortcoming of the proposed EEUMC. Because of the significant energy consumption at the cluster relay points across different depth levels, issues such as re-clustering or repeated re-clustering may arise. These occurrences could be caused by the increased energy expenditure necessary for transmitting data across nodes located at different depths.

In future, this work extended by investigating adaptive algorithms that dynamically adjust clustering parameters based on real-time conditions, investigating novel energy harvesting techniques to improve node autonomy, integrating machine learning to predict network

behaviour and optimise energy usage, ensuring robust security mechanisms, and conducting extensive field trials to validate performance in real underwater scenarios are all part of this effort.

Author contributions

All authors contributed equally to the conceptualization, formal analysis, investigation, methodology, and writing and editing of the original draft. All authors have read and agreed to the published version of the manuscript.

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CRediT authorship contribution statement

Ravikumar chinthaginjala: Writing – review & editing, Investigation, Data curation. **Satish Kumar:** Conceptualization. **Shafiq Ahmad:** Supervision, Investigation. **TaeHoon Kim:** Visualization, Supervision, Funding acquisition, Formal analysis.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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