

# ECDAR: An Energy-efficient, Channel- and Depth-Aware Adaptive Routing for Underwater Sensor Networks

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## ABSTRACT

With growing demands in marine monitoring, resource exploration, and defense, Underwater Wireless Sensor Networks (UWSNs) have become an increasingly critical technology in aquatic environments. However, the underwater environment is affected by multiple factors, such as high latency, limited bandwidth, and multipath signals, making the design of routing algorithms and models highly complex. This study proposes a solution to enhance the routing process of the RBCDDE protocol by integrating channel positioning, depth, and energy for adaptive transmission in UWSNs, named ECDAR (Energy-efficient, Channel- and Depth-Aware Adaptive Routing). The ECDAR protocol focuses on multi-hop routing and optimizes transmission range based on a node's residual energy, employing four levels: basic, normal, maximum, and emergency. Additionally, the proposed method incorporates a fallback mechanism: if no forwarder node is found within the normal range, the system automatically switches to emergency transmission range and reduces the energy threshold to a minimum (10%), while updating energy consumption after each data transmission/reception. The results of simulation-based evaluation demonstrate that this solution significantly reduces connection loss rates compared to traditional methods, particularly in terms of packet delivery ratio, end-to-end delay, throughput, and energy efficiency. These results highlight ECDAR's effectiveness in addressing the harsh constraints of UWSNs and its potential for real-world deployments in large-scale ocean monitoring and deep-sea sensing applications.

## CCS CONCEPTS

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• **Networks** → **Sensor networks**; Routing protocols; Network performance analysis

## KEYWORDS

underwater sensor network routing, adaptive routing, sink channel, end-to-end delay, energy-efficient, throughput, PDR.

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## 1 INTRODUCTION

Underwater Wireless Sensor Networks (UWSNs) are advanced technological systems designed to operate in aquatic environments, comprising sensor nodes and wireless communication devices. Fixed-depth sensor nodes are tasked with collecting environmental parameters such as temperature, salinity, pressure, pH levels, and other ecological factors. Meanwhile, other sensor nodes, distributed at varying random depths, serve as relay nodes forwarding data packets to surface (Sink nodes) [1]. UWSNs have diverse applications, ranging from marine environmental monitoring, disaster prediction, and oceanic resource exploration to scientific research and defense operations. However, UWSN deployment faces significant challenges, including high communication latency, multipath propagation, substantial energy consumption, and the need for high resilience in harsh environmental conditions.

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The general architecture of UWSN is illustrated in Figure 1. The system typically consists of:

- A Base Station (BS) is stationed onshore, connected to satellites via radio waves.
- Sink nodes are linked to the BS through radio communication.
- Sensor nodes are distributed at varying depths throughout the surveyed area and serve as intermediate forwarders.
- Bottom-placed sensor nodes are organized into clusters, with each cluster electing a Cluster Head (CH).

Other sensor nodes collect and transmit data to their respective CH, which then relays the information to forwarding nodes for eventual transmission to Sink nodes. Subsequently, Sink nodes transmit the data to the BS via radio signals. Finally, the data is sent to a central processing system for analysis and decision-making [2].

In [3], the RBCDDE protocol fails to address routing challenges in sparsely distributed networks, where the algorithm cannot identify the next forwarder node due to the excessive distance between the current node and potential forwarders beyond the permissible transmission range. To resolve this issue, our study introduces a distance-adaptive transmission mechanism, the details of which will be presented in the proposed model section.

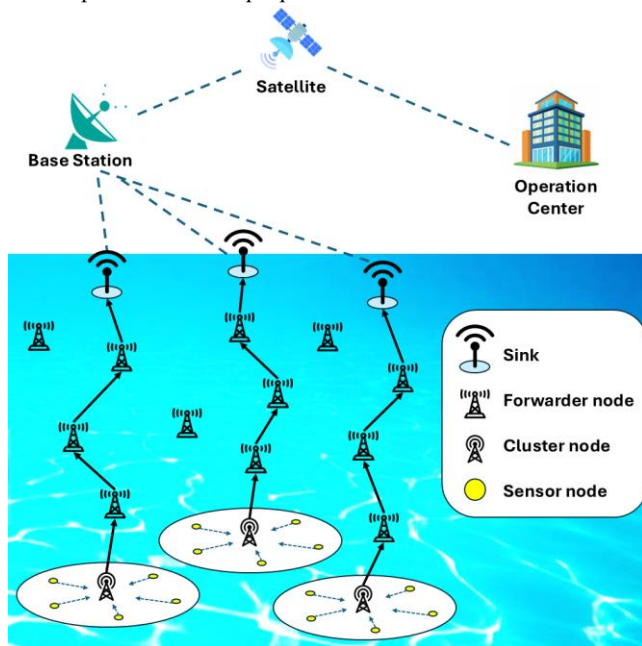


Figure 1: UWSN network architecture

Key Contributions of This Paper:

- Clustering and Cluster Head (CH) Selection: Bottom-positioned nodes are organized into clusters, with CHs elected to act as data aggregation points before transmission to the sink, reducing overall energy consumption.
- Sink-Channel Node Selection: Forwarder nodes within the sink's communication channel are strategically selected to optimize path efficiency.
- Adaptive Forwarder Selection Mechanism: A dynamic forwarder node selection scheme based on adaptive transmission range and residual energy is proposed for diverse scenarios.

- Emergency Transmission Protocol: If no forwarder node is found within the adaptive range, the system switches to emergency transmission mode, ensuring connectivity by temporarily overriding energy constraints.

- Multi-Hop Routing: Data is relayed from CHs to the sink via multi-hop routing, balancing load distribution and minimizing latency.

- Energy-Efficient Transmission Management: Energy consumption is optimized through adaptive transmission range adjustment, extending network lifetime while maintaining reliability.

The general structure of the paper is as follows: In Section 1, we will provide an overview of UWSN. In Section 2, we will review recent studies. In Section 3, we will present the research model proposed in this paper. Section 4 will involve constructing simulation scenarios to compare and evaluate the proposed model. Finally, Section 5 will present the conclusions and future research directions of this study.

## 2 RELATED WORK

According to [4], Maheswari J and colleagues proposed an energy-efficient routing solution named EEMCBR. Specifically, this protocol employs a two-phase process to optimize clustering and routing. In the first phase, the Spotted Hyena Optimization algorithm (SHOA-C) is used to cluster nodes and select Cluster Heads (CH) based on a fitness function related to energy consumption. In the second phase, the Tumbleweed Optimization Algorithm-Based Routing (TWOA-R) is used to determine the most efficient transmission path considering parameters like energy and distance. The EEMCBR-UWSN protocol demonstrates superior performance compared to traditional methods such as LEACH, CUWSN, EOCA, ACOCR, and MCR-UWSN in terms of extending network lifetime, reducing energy consumption, and increasing the number of packets received at the Sink node.

Shyamsundar R et al. [5] proposed a cluster-based routing protocol for UWSNs aimed at maximizing network lifetime using the Gravitational Search Algorithm (GSA). The protocol is executed in four stages: exploration, clustering, routing, and transmission. The proposed results show significant performance improvements compared to other algorithms such as EECMR, EERBLC, and traditional LEACH, with respective improvements of 33.06%, 11.77%, and 57.2%. The effectiveness of the proposed GSA was also benchmarked against established meta-heuristic techniques, including PSO, WOA, and MFO, showing improved results in both load distribution and energy optimization.

To enhance energy efficiency in underwater wireless sensor networks using meta-heuristic algorithms, the authors of [6] proposed a routing algorithm based on the behavior of the Glowworm Swarm, named GSO, for cluster-based packet routing. In GSO, Cluster Heads (CHs) are selected based on factors such as residual energy, total energy consumption, and luciferin value. Simulation experiments showed that the proposed method significantly improved clustering time, total energy consumption, cluster lifetime, and packet delivery ratio compared to other heuristic techniques such as ACO, GWO, MFO, and LEACH.

In [7], Ahmad et al. introduced a routing protocol called CEER (Cooperative Energy-Efficient Routing) designed to enhance energy efficiency in underwater wireless sensor networks (UWSNs). CEER employs a multi-hop cooperative routing mechanism to reduce energy consumption and balance the load among nodes. It combines clustering and path selection based on energy thresholds to extend network lifetime. The algorithm utilizes relay nodes to efficiently transmit data, thereby minimizing signal attenuation. Simulation results show that CEER improves energy efficiency, reduces latency, and increases the packet delivery ratio compared to other protocols such as DBR and EEDBR. Additionally, it achieves better load balancing, helping to prevent early node failures due to energy depletion.

In the context of UWSNs facing challenges such as high energy consumption, large transmission latency, and high packet loss rate, Jiasen Zhang et al. in [8] proposed a novel solution called the Hierarchical Transmission Framework. This solution consists of three components: first, dividing the network into clusters to reduce transmission distance and save energy; second, selecting Cluster Heads (CHs) based on residual energy, location, and channel quality, while using an optimization algorithm to balance the load among nodes; and third, employing multi-hop transmission to reduce latency.

In [9], C. Wang et al. proposed an Opportunistic Routing protocol based on Reinforcement Learning (RL), integrating depth information to optimize network performance. The RL algorithm uses Q-Learning with two enhancements: first, a reward function that incorporates depth, residual energy of nodes, and channel quality; second, a forwarder node selection mechanism that prioritizes nodes closer to the Sink and with higher energy. Additionally, the routing process automatically adjusts the routing policy based on Q-values. Simulation results show a 25 - 35% reduction in energy consumption, a 20% decrease in average latency, and a 15 - 20% increase in packet delivery ratio (PDR) compared to DBR and EEDBR.

In [10], Chandra Sukanya Nandyala et al. introduced a new Q-learning-based routing protocol for UWSNs named QTAR. This protocol focuses on energy saving and lifetime improvement by combining topology-aware information with reinforcement learning. QTAR stands out with three key features: first, it identifies Next-Forwarders (NFs) based on network topology and then uses Q-learning to select the optimal NF from the candidates, while also recognizing "cut-vertex" (CV) nodes to prevent network fragmentation. Second, QTAR designs a reward function based on three factors: fixed cost, residual energy, and latency to guide packets toward the Sink node. Third, when network fragmentation is detected due to CV disconnection, QTAR puts nodes in the fragmented part into sleep mode to save energy. QTAR is compared with existing protocols such as QELAR, EEDBR, QDAR, and RLOR, and results show QTAR outperforms them in terms of lower energy consumption, reduced latency, and longer network lifetime.

Xue et al. [11] proposed MEMAC, an adaptive clustering approach designed to enhance the performance of UWSNs in marine environmental monitoring applications. The main goal is to

optimize energy consumption and extend network lifetime, as underwater sensor nodes typically use limited and hard-to-replace battery power. To achieve this, the authors proposed two solutions: first, placing power supply systems on floating platforms to continuously provide energy to central underwater nodes, enabling more efficient data collection; second, using an adaptive clustering algorithm that includes a non-cooperative game model to select CHs based on multipath channel information and traffic weight; balancing energy using a utility function that incorporates residual energy; and a CH rotation mechanism to ensure network stability. Experimental results show that MEMAC outperforms algorithms like LEACH, CCCS, and GTC, extending network lifetime by 58.9% and 19.17% compared to GTC and CCCS, respectively, while also improving data transmission efficiency.

Shi Y. et al. [12] developed HECRA (High-Efficiency Clustering Routing Algorithm), a protocol designed for underwater sensor networks with AUV support, comprising four operational phases to improve communication efficiency. As an enhancement to the LEACH protocol, the first phase incorporates residual energy and node degree into the CH selection threshold to ensure more balanced cluster formation. The second phase forms clusters based on CH residual energy (prioritizing CHs with the highest energy). The third phase uses multi-hop transmission based on depth and residual energy of other CHs. Simulation results show that HECRA outperforms LEACH, EERBLC, and EECMR in terms of network lifetime, residual energy, and packet delivery success rate.

Sun, L. et al. in [13] introduced a new routing protocol named FLRAF (Fuzzy Logic Reasoning Adaptive Forwarding) for underwater acoustic sensor networks (UASNs). This protocol defines a cone-shaped forwarding zone to prioritize nodes with greater advancement distance (AD), reducing path deviation and the number of hops. It then uses a nested fuzzy reasoning system to evaluate Link Quality Index (LQI) based on signal-to-noise ratio (SNR). According to simulation results, FLRAF delivers higher packet delivery rates, longer network lifetime, and lower energy usage than traditional routing schemes including VBF, HH-VBF, ALRP, and GTRP.

In summary, although existing approaches improve energy efficiency and routing reliability, they often lack dynamic adaptability under sparse and high-latency conditions. ECDAR aims to address this by integrating adaptive range selection and emergency fallback mechanisms.

## 3 RESEARCH MODEL

### 3.1 System model

Following the approach outlined in [14], [15], we consider the deployment of an underwater wireless sensor network (UWSN) comprising  $N$  sensor nodes randomly distributed within a three-dimensional monitoring region defined by dimensions  $L \times W \times D$ , representing the length, width, and depth of the target area. Each underwater sensor node is equipped with an acoustic modem, allowing communication with neighboring nodes within its transmission range. The Sink nodes are deployed on the water surface and are equipped with both radio frequency (RF) modems

and acoustic modems. The acoustic modem facilitates data exchange with underwater sensor nodes acting as relay (forwarder) nodes, while the RF modem is responsible for transmitting the collected data to a centralized Base Station (BS) located onshore or on a surface platform.

Due to the dynamic nature of the underwater environment, sensor nodes are subject to random mobility influenced by water currents, typically moving at velocities ranging from 1 to 3 meters per second. This mobility results in a continuously evolving network topology, which poses significant challenges for reliable data transmission and network maintenance. The network scenario can be illustrated as shown in Figure 2. The network model is constructed based on the following assumptions:

- Initially, all nodes are aware of their respective positions and depths.
- Sink nodes are deployed at fixed coordinates on the water surface.
- Nodes located on the seabed may become Cluster Heads (CHs) or Cluster Members after the clustering process is completed.
- Cluster Heads may be replaced when their residual energy below a predefined threshold.

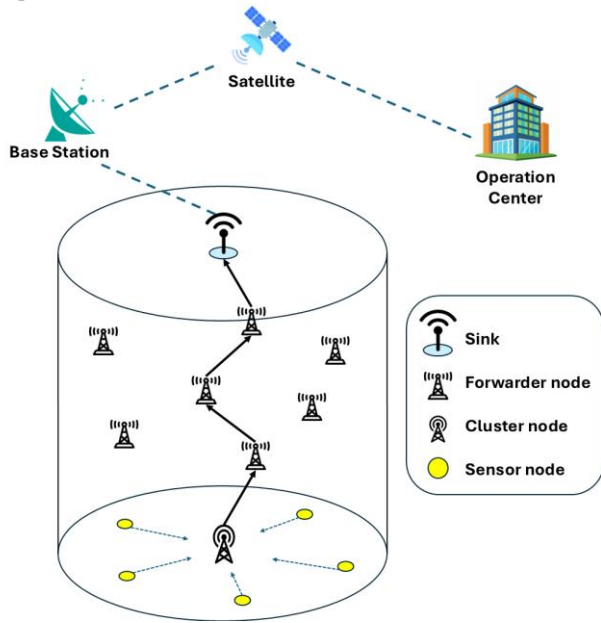


Figure 2: System model

### 3.2 Acoustic wave propagation

In Underwater Wireless Sensor Networks (UWSNs), acoustic waves are chosen as the primary communication medium due to the severe limitations of electromagnetic and optical waves in aquatic environments, including high energy attenuation and strong scattering effects [15]. Energy efficiency in UWSNs is influenced by several factors, including the distance between sensor nodes, the frequency of the acoustic waves used, the data transmission rate, and the energy consumption during signal transmission and reception.

According to [16], the authors adopted the Thorp model to characterize acoustic signal attenuation and estimate sensor energy consumption in underwater environments. This model offers a quantitative approach to evaluating the degradation of acoustic waves during underwater propagation. The corresponding transmission loss is computed using Equation (1).

$$A(d, f) = d^k \alpha(f)^d \quad (1)$$

Where  $f$  denotes the frequency of the acoustic signal,  $d$  is the propagation distance,  $k$  is the spreading factor (empirically set to 1.5), and  $\alpha(f)$  represents the acoustic absorption coefficient, which is further defined in Equation (2).

$$10 \log \alpha(f) = 0.11 \frac{f^2}{1 + f^2} + 44 \frac{f^2}{4100 + f^2} + 2.75 \times 10^{-4} f^2 + 0.003 \quad (2)$$

To transmit  $l$ -bit of data from a sending node to a receiving node separated by a distance  $d$  ( $d < d_{max}$ ), the energy consumption ( $E_{Tx}$ ) of the sensor node is calculated using Equation (3).

$$E_{Tx}(l, d) = l P_0 A(d, f) = l P_0 d^k \alpha(f)^d (E_{Tx} < E_{remain}) \quad (3)$$

where  $P_0$  denotes the minimum power required for a node to transmit data,  $d_{max}$  is the maximum transmission range, and  $E_{remain}$  represents the node's residual energy. Notably,  $E_{remain}$  also serves as the upper bound for  $E_{Tx}$  (transmission energy).

Similarly, the energy consumption of a node to receive  $l$ -bit data is calculated using Equation (4).

$$E_{Rx}(l) = l P_r \quad (4)$$

Where  $P_r$  denotes the receiving power, which varies depending on the specific characteristics of the device employed.

The relationship between the transmission distance  $d$  and average Signal-to-Noise Ratio (SNR) is formulated in Equation (5).

$$SNR(d) = \frac{E_b / A(d, f)}{N_0} = \frac{E_b}{N_0 d^k \alpha(f)^d} \quad (5)$$

Where  $E_b$  denotes the average energy required to transmit a single bit, and  $N_0$  is the noise power spectral density in an Additive White Gaussian Noise (AWGN) channel.

According to [17], Binary Phase Shift Keying (BPSK) is a widely adopted modulation scheme for acoustic signal transmission. Based on this scheme, the probability of successfully transmitting an  $l$ -bit data packet over a distance  $d$  is expressed in Equation (6).

$$p(d, l) = \{1 - p_e(d)\}^l \quad (6)$$

In this context,  $p_e(d)$  refers to the bit error rate associated with transmitting data over a distance  $d$ , and it is determined according to Equation (7).

$$p_e(d) = \frac{1}{2} \left( 1 - \sqrt{\frac{SNR(d)}{1 + SNR(d)}} \right) \quad (7)$$

### 3.3 Proposed model

In this section, we present the detailed improved routing model for our proposed approach. The network is deployed in a 3D underwater environment, as illustrated in Figure 2, and consists of three types of nodes:

- Sink Node: Positioned on the water surface, it connects to a radio base station via radio waves and communicates with underwater forwarder nodes using acoustic signals.
- Forwarder Node: Randomly distributed at varying depths (from the seabed to the surface), responsible for relaying data back to the sink node.
- Sensor Node: Deployed on the ocean floor, tasked with data sensing and anchored in place. These nodes communicate via acoustic signals.

According to [3] and [15], the system operates under the assumption that all sensor nodes are time-synchronized, ensuring coordinated communication across the network. Each node periodically exchanges beacon packets with its neighboring nodes to maintain updated information about local topology. These beacon messages include the sender's current energy level and spatial coordinates (depth and horizontal position), allowing each node to construct and maintain a local neighbor table.

In terms of communication modeling, the transmission channel between sensor nodes and the Sink is conceptualized as a vertical cylinder whose radius is equal to the baseline acoustic transmission range of the Sink node. This cylinder extends from the water surface to the seabed, and its height corresponds to the depth of the surveyed area. Only the nodes within this cylindrical channel are considered eligible for forwarding during the routing process.

To formalize the proposed routing mechanism, the complete algorithm is presented in Pseudocode of ECDAR, which outlines the main steps for forwarder node selection, adaptive transmission range adjustment, and energy threshold management under both normal and emergency routing conditions.

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#### Algorithm 1 ECDAR Routing

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**Require:**  $N, M, \text{MinEnergyThreshold}, \text{txEnergy}, \text{rxEnergy}$

**Ensure:**  $\text{path}$

```

1: Step 1. Initialization
2:   Randomly generate  $N$  sensor nodes in 3D space
3:   Generate  $M$  seabed nodes at a fixed depth
4:   Place the  $\text{sinkNode}$  at the surface
5: Step 2. Cluster Head Selection
6:    $\text{CH} \leftarrow \text{KMeans}(\text{seabedNodes})$ 
7: Step 3. Find the Path to the Sink
8:    $\text{path} \leftarrow []$ 
9:    $\text{currentNode} \leftarrow \text{ChooseStartNode}(\text{CH})$ 
10:  while  $\text{currentNode} \neq \text{sinkNode}$  do
11:     $\text{nextNode} \leftarrow \text{FindNextHop}(\text{currentNode}, \text{sinkNode}, \text{allNodes}, \text{MinEnergyThreshold})$ 
12:    ADD Node TO  $\text{path}$ ;  $\text{Append}(\text{path}, \text{nextNode})$ 
13:     $\text{currentNode} \leftarrow \text{nextNode}$ 
14:  end while
15: Step 4. Update Energy
16:  for  $i \leftarrow 0$  to  $\text{length}(\text{path}) - 2$  do
17:     $\text{path}[i].\text{energy} \leftarrow \text{path}[i].\text{energy} - \text{txEnergy}$ 
18:     $\text{path}[i + 1].\text{energy} \leftarrow \text{path}[i + 1].\text{energy} - \text{rxEnergy}$ 
19:  end for
20: return  $\text{path}$ 

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### 3.4 Adaptive transmission model

Adaptive communication is a transmission technique in wireless networks, particularly in underwater wireless sensor networks (UWSNs), which adjusts communication parameters (such as transmission power, data rate, and transmission range) based on environmental conditions and system states (energy, noise, distance) [19]. The objective is to optimize network performance, conserve energy, and enhance reliability. The model is implemented using Equation (8).

$$\text{transR} = \text{minTr} + (\text{maxTr} - \text{minTr}) * \left( \frac{\text{cur\_energy}}{\text{initialEnergy}} \right) \quad (8)$$

Where:

$\text{transR}$ : Transmission range of the node.

$\text{minTr}$ : Minimum transmission range of the node.

$\text{maxTr}$ : Maximum transmission range of the node.

$\text{cur\_energy}$ : Current energy level of the node.

$\text{initialEnergy}$ : Initial energy of the node.

This technique dynamically adjusts the transmission range based on the node's available energy. Specifically, the node adapts its transmission power to reduce energy consumption when the distance is short or increases power when the distance exceeds the default transmission range. In exceptional cases, the node transmits at maximum power to ensure packet delivery, despite the energy trade-off.

### 3.5 Clustering model

According to [20], the K-means algorithm performs unsupervised clustering by partitioning data into  $K$  distinct clusters, typically based on minimizing the Euclidean distance between points and their respective centroids. The objective is to optimize intra-cluster cohesion (minimizing distances between points within the same cluster) while maximizing inter-cluster separation. The algorithm iteratively executes two steps until convergence:

**Assignment step:** Each node is assigned to the nearest cluster centroid based on Euclidean distance.

**Centroid Update step:** The centroid's position is recalculated as the arithmetic mean of all nodes within the cluster.

The proposed model implements K-means as follows:

**Step 1:** Initialization

- Randomly select  $K$  initial centroids.

**Step 2:** Iteration

- Compute the Euclidean distance between each seabed node and every centroid, then assign the node to the closest cluster.
- Update centroids by averaging the positions of all nodes within each cluster.

**Step 3:** Termination

- Halt when centroids stabilize (no further changes) or the maximum iteration count is reached.

## 4 SIMULATION AND ANALYSIS

### 4.1 Simulation scenario

In this section, we conduct simulations based on the parameters specified in [3] to evaluate the performance of the proposed

protocol. The simulations are implemented using the MATLAB platform. The investigated area measures 1000x1000x500 meters, corresponding to length, width, and depth. The number of sensor nodes varies between 200 and 600, randomly distributed throughout the environment.

The seabed nodes are randomly deployed at a depth of 500 meters and are responsible for data collection. The sink node is positioned on the water surface at the center of the surveyed area. Table 1 summarizes the detailed parameter values used in the simulations, as adopted from [3]. To assess the effectiveness of the proposed protocol, QoS metrics including energy consumption ( $E_{consum}$ ), packet delivery ratio (PDR), end-to-end delay (E2ED), and network throughput are analyzed with respect to varying numbers of sensor nodes.

**Table 1: Simulation parameters**

Parameters	Value
Network region (m)	1000*1000*500
Number of seabed nodes	200
Number of forwarder nodes	200 - 600
Cluster Head seabed nodes	1
Number of Sink node	1
TransRange sink node (m)	200
TransRange forwarder node (m)	200
Carrier frequency (KHz)	100
Acoustic propagation speed (m/s)	1500
Speed of the ocean current (m/s)	4.5
Transmitting power (W)	2
Receiving power (W)	0.1
Data rate (kbps)	10
Data packet size (bit)	128
Back-off time (s)	1

## 4.2 Energy

Due to the inherent energy constraints and the infeasibility of battery replacement in underwater environments, evaluating energy consumption plays a vital role in the design and operation of UWSNs. Unlike terrestrial networks, the aquatic environment causes significant signal attenuation due to absorption and scattering phenomena, necessitating higher transmission power. According to [3], we apply Equations (9) and (10) to calculate the remaining energy and energy consumption of a node.

$$E_{remain} = E_{init} - E_{consum} \quad (9)$$

$$E_{consum} = E_{trans} + E_{reciev} \quad (10)$$

Here,  $E_{trans}/E_{reciev}$  represents the energy consumed by a node when transmitting/receiving  $l$  bits of data, calculated using Equations (11) and (12).

$$E_{trans} = P_{Tx} * Trans\_time \quad (11)$$

$$E_{reciev} = P_{Rx} * Receive\_time \quad (12)$$

Figure 3.a compares energy consumption among the RBCDD, CIDP, GEDAR, and ECDAR protocols. It can be observed that ECDAR demonstrates superior performance in energy efficiency, particularly as the number of network nodes increases. Specifically, at 600 nodes, ECDAR exhibits the lowest energy consumption, whereas other protocols, such as RBCDD and CIDP, consume

significantly more energy. This indicates that ECDAR optimizes network resource utilization effectively, minimizing energy wastage through mechanisms such as intelligent routing, load balancing, and redundant packet reduction.

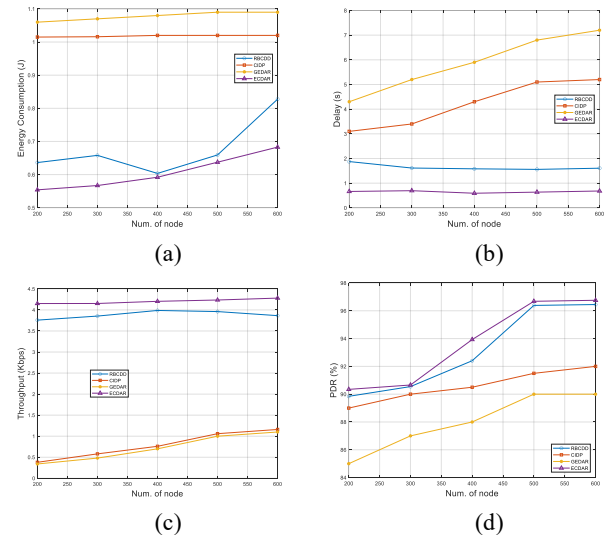
## 4.3 End to End Delay

End-to-end (E2E) delay in underwater wireless sensor networks (UWSNs) refers to the total time required for a data packet to travel from the source node to the destination node, encompassing four primary components: transmission delay, propagation delay, processing delay, and queuing delay. As noted in [15], E2E delay in underwater wireless sensor networks is influenced by the latency of acoustic wave propagation, channel access delays, and the effective data rate. Moreover, it is further constrained by transmission range, ambient noise levels, and channel bandwidth limitations.

As illustrated in Figure 3.b, ECDAR maintains consistently low latency even when the network scales up to 600 nodes. In contrast, other protocols such as GEDAR and CIDP exhibit significant delay escalation as the network expands. This demonstrates ECDAR's superior capability in path optimization and congestion mitigation.

## 4.4 Throughput

Throughput in UWSNs is defined as the rate at which data packets are successfully transmitted from a source node to a destination node within a given time interval and is typically expressed in bits per second (bps). UWSNs face numerous challenges that degrade throughput performance, including limited bandwidth, high latency due to slow acoustic wave propagation, packet loss from noise interference, and multipath effects. As a critical performance metric, throughput significantly impacts the overall system efficiency.



**Figure 3: Simulation results for: (a) Energy consumption, (b) End-to-End delay, (c) Throughput, and (d) Packet Delivery Ratio (PDR).**

The proposed ECDAR protocol maintains stable data transmission performance through optimized routing mechanisms and efficient

resource management. This is clearly demonstrated in Figure 3.c, where ECDAR achieves superior throughput (approximately 4.5 Kbps) compared to RBCDD, CIDP, and GEDAR protocols.

#### 4.5 Packet Delivery Ration

As a reliability metric, Packet Delivery Ratio (PDR) reflects the ratio of successfully received packets to those transmitted and is commonly used to evaluate the performance of UWSNs. This ratio quantitatively measures transmission efficiency by calculating the proportion of successfully received packets relative to the total packets transmitted. In underwater environments, PDR performance is significantly affected by several factors, including Path loss attenuation, Multipath interference, Doppler fading, and Packet collisions, caused by the unique physical properties of acoustic wave propagation.

The results in Figure 3.d show the Packet Delivery Ratio (PDR) and demonstrate that ECDAR delivers superior performance while maintaining stable efficiency when the number of nodes ranges from 500 to 600. This result confirms ECDAR's outstanding advantage in ensuring data transmission reliability. This performance can be attributed to three key design factors of ECDAR: first, the intelligent adaptive routing mechanism helps avoid congested nodes and unstable transmission paths. Second, the efficient error detection and correction algorithm minimizes packet loss. Finally, the optimal load-balancing strategy prevents local overloads.

#### 4 CONCLUSIONS

ECDAR fully embodies the characteristics of a complete network protocol, particularly suitable for large-scale UWSN systems that simultaneously demand high reliability, stable performance, and energy efficiency. This is achieved through its outstanding features, such as: leveraging the advantages of the K-means clustering algorithm for bottom-layer nodes; a dynamic transmission range adjustment mechanism based on each node's remaining energy, optimizing network performance under all operating conditions; integrating an intelligent redundancy mechanism when no forwarder node is found within the standard range, ensuring service continuity even in non-ideal network conditions; and selecting forwarder nodes based on both distance and remaining energy to prevent local overload at specific nodes.

Although ECDAR demonstrates significant advantages over traditional protocols, it still has some limitations that need improvement. For instance, when the emergency transmission mechanism is activated, nodes must increase their transmission power, leading to a sudden spike in energy consumption and reducing node lifespan. Additionally, while ECDAR maintains lower latency compared to other protocols, multi-hop transmission can still result in cumulative delays, affecting real-time applications. These issues can be mitigated through solutions such as employing machine learning algorithms to determine optimal paths based on environmental factors, which also represents a direction for our future research.

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