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Integrated Underwater Sensor Networks for Coastal Soil Monitoring and Disaster Risk Reduction

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Abstract

Underwater Wireless Sensor Networks (UWSNs) play a crucial role in environmental monitoring, disaster prediction, and marine exploration. This study presents an energy-efficient routing algorithm for UWSNs, designed to predict disasters by analysing soil moisture and salinity levels in underwater environments. We compare three routing approaches: LEACH (Low-Energy Adaptive Clustering Hierarchy), Ant Colony Optimization (ACO), and Q-Learning-based Routing. The proposed Q-Learning algorithm optimizes energy consumption, enhances network lifetime, and improves packet delivery ratio (PDR) while reducing packet loss ratio (PLR). Simulation results indicate that Q-Learning achieves up to 98% PDR with minimal energy consumption, outperforming LEACH and ACO. The study also visualizes network deployment, energy dissipation, and packet transmission over time. The findings highlight the potential of machine learning-based routing for enhancing the efficiency and longevity of UWSNs in disaster prediction applications.

Keywords: UWSN, LEACH, ACO, Q-Learning, Routing, Energy Consumption, Life Time

Introduction

Underwater Wireless Sensor Networks (UWSNs) have emerged as a critical technology for marine environmental monitoring, disaster prediction, and underwater exploration. These networks consist of sensor nodes deployed underwater to collect and transmit environmental data, such as soil moisture, salinity, and temperature, to a surface station or a sink node. Unlike terrestrial wireless sensor networks, UWSNs face unique challenges, including high energy consumption, limited bandwidth, long propagation delays, and high packet loss due to acoustic signal attenuation.

One of the primary applications of UWSNs is disaster prediction, where real-time analysis of soil moisture and salinity can help in detecting early warning signs of underwater landslides, tsunamis, and coastal erosion. However, the effectiveness of such systems largely depends on an energy-efficient and reliable routing algorithm that ensures long network lifetime, minimal data loss, and optimal energy utilization.

We propose an energy-efficient routing algorithm for UWSNs, integrating machine learning-based optimization (Q-Learning) and comparing it with traditional routing approaches like LEACH and Ant Colony Optimization (ACO). The key objectives of this research include:

Developing an intelligent routing mechanism that optimizes energy usage and extends network lifetime.

Analysing and comparing the performance of LEACH, ACO, and our proposed Q-Learning in terms of energy consumption, packet delivery ratio (PDR), and packet loss ratio (PLR).

Simulating network deployment and routing efficiency in a 3D underwater environment.

The simulation results demonstrate that the proposed Q-Learning-based routing algorithm outperforms LEACH and ACO by reducing energy consumption, improving data transmission reliability, and extending network longevity. The findings of this study provide valuable insights into enhancing UWSN performance for real-time disaster prediction applications.

The rest of the paper is organized as follows. Section 2 discusses literature review. The proposed system is explained in Section 3. The procedure is described in Section 4. Part 6 wraps up, while Section 5 concentrates on the experiment's results.

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Literature Review

In the paper [1] the author have provided an overview of the research on underwater optical wireless networks (UOWNs). Several facets of state-of-the-art UOWNs are covered in this survey, layer by layer. The physical, data connection, networking, transport, and application layers of UOWNs are first briefly introduced, followed by a survey of UOWN localization strategies. Underwater optical wireless communications (UOWCs) can enable larger data rates at low latency levels than their bandwidth-constrained acoustic and radio frequency counterparts. Effective networking and localization solutions are necessary since the harsh underwater channel characteristics (such as absorption, scattering, turbulence, etc.) present considerable obstacles for UOWCs and drastically limit the achievable communication ranges.

The author have utilized the circle's arc as the proposed geometric shape in this paper [2]. Using the geometry, several localization strategies have been presented. The majority of geometric approaches use geometry to constrain the sensor position, according to our review of the literature. To improve the accuracy of localization, the least limited area is a crucial prerequisite. But using geometric shapes by themselves won't reduce the constrained space's size. The communication range and the deployment density of beacon sites are two further determining elements. Unlike existing geometric systems that generate the Cartesian coordinate in a 2D plane using constraint area-based localization, the suggested method generates the coordinates using geometry.

A cellular clustering architecture-based interference-aware data transmission system is presented in this paper [3]. Two steps are involved in the protocol. The first is inter-cell time division multiple access (TDMA) scheduling, which limits simultaneous data transmission via adjacent routing paths to reduce acoustic interference; the second is intra-cell hierarchical routing, which aims to ensure dependable data transmission from the seabed to the surface and efficient data collection within the submarine.

The paper [4] suggested a frequency-division multiplexing (FDM)-based full-duplex communication technique and an interference-aware opportunistic route discovery method as an environmentally beneficial data transmission scheme for UASNs. A virtual-void zone technique, an FDM-based channel allocation approach, and a Bayesian network-based mammal avoidance strategy are first introduced in the route finding phase to create interference-free routing patterns that enable dependable and eco-friendly data transfers. An FDM-based full-duplex communication technology is then used during the data transmission phase to allow for high-speed data flow from the seabed to the surface.

In this paper [5] the author suggested to eliminate the interference from both sources and greatly enhance the decoding of both signals. IoUT performance consequently improves. We suggest an autonomous switching system that regulates the cancelation process in both channel equalization and channel estimation in order to reduce mutual interference. According to the simulation results, our method significantly improves communication from both nearby and distant nodes. Our suggested strategy greatly increases the output signal-to-noise ratio (SNR) when both nodes are affected by their mutual transmissions, as shown by results from a designated sea trial.

In paper [6] without any prior knowledge of the interference, the author suggest a new filter that reduces the interference effects for both single-carrier and multi-carrier systems. An algorithm called Adaptive Sliding Window Interference Detection (ASWID) is created to identify the number and location of interfered symbols. The estimate and mitigation of shot interference based on robust regression is described using a least trimmed squares (LTS) equalizer. Through the use of actual channel measurements and numerical simulations, the suggested methods are assessed. Our findings demonstrate that the suggested designs are capable of efficiently detecting and reducing shot interferences in both single-carrier and multi-carrier UAC systems.

This article [7] suggests an underwater data transmission method utilizing the multichannel full-duplex (FD) communication approach, with a focus on providing high-speed acoustic communications for underwater application situations with high traffic requirements. The suggested approach makes advantage of the underwater orthogonal frequency division multiple access (OFDM) methodology, which relays data in Multi Hop paths for simultaneous transmission and reception over collision-free channels. The suggested approach employs static routes for transferring data over hop-by-hop paths in order to achieve stable and continuous FD communication, in contrast to the conventional UACN communication methods with dynamic routing.

This paper [8] examines the routing problem in a network with novel features, such as seamless route discovery, global network-state awareness, and centralized route determination, while taking into account the optimization of multiple long-term global performance indicators. We formulate the entire multi-modal UWSN routing problem as an optimization problem, taking into account various long-term global performance metrics of an ideal routing protocol as well as the interference phenomenon of ad hoc scenarios. Our issue formulation effectively captures all of the potential flexibility of a sensor node, regardless of whether it has half-duplex or full-duplex functionality. After formulation, we identify that the problem is NP-hard for every situation.

In this paper[9] , the author suggest a new effective channel impulse response (CIR) prediction model for UWA MIMO communications using a network of small adaptive bidirectional gated recurrent units .The channel information can be captured by the suggested model without the need for extra knowledge about the internal characteristics of the channel. Furthermore, the learned model is then used for the CIR prediction, which tracks time-varying UWA channels, after first using previous short-term CIR data from the channel estimation for online training. For the UWA MIMO system, we present a strategy that combines a space-time block coding (STBC) and minimal mean square error (MMSE) pre-equalization to confirm the efficacy of the anticipated CIRs. Numerical simulations have shown the low bit-error rate (BER) and practical viability of our suggested STBC-MMSE pre-equalization approach.

In this research paper [10] the author have suggested two co-channel interference cancellation (CCIC) techniques that address more generic and difficult cases by balancing interference resistance and computing overhead. The simulations demonstrate that by reducing overlay communication interference, both CCIC techniques reduce bit error rate (BER), enabling operation at lower power. Co-channel interference (CCI) from concurrent signals in the same channel is a significant obstacle to overlay communication. Nevertheless, a lot of sidelink and underlay research fails to suggest sophisticated concurrent models or address efficient cancellation techniques.

Proposed System

The proposed system aims to design an energy-efficient and reliable Underwater Wireless Sensor Network (UWSN) routing algorithm for disaster prediction by analysing soil moisture and salinity levels. To overcome the challenges of high energy consumption, packet loss, and long propagation delays in underwater environments, we integrate a Q-Learning-based intelligent routing mechanism and compare it with traditional routing algorithms such as LEACH (Low-Energy Adaptive Clustering Hierarchy) and Ant Colony Optimization (ACO).

Components of the Proposed System

1. Underwater Sensor Deployment

A 3D network of underwater sensor nodes is deployed across a 1000m × 1000m × 500m area.

Nodes measure soil moisture, salinity, and other environmental factors to predict disasters.

Each sensor communicates via acoustic signals to send data to the sink node.

2. Routing Mechanism

LEACH Routing: Cluster-based protocol where nodes form clusters and communicate through a randomly selected cluster head (CH).

ACO Routing: Uses pheromone-based path selection to find optimal data transmission routes.

Q-Learning-based Routing (Proposed):

Each sensor node learns the optimal path by adjusting its routing strategy based on network conditions and past experiences.

The reward function optimizes energy consumption, packet delivery, and node lifetime.

Routes are updated dynamically to avoid energy depletion and network congestion.

3. Performance Optimization

Minimizing Energy Consumption: Nodes adjust their transmission power and routing paths dynamically.

Maximizing Network Lifetime: Energy-aware routing extends node longevity and prevents early network failures.

Improving Data Transmission Efficiency: Packet Delivery Ratio (PDR) is increased, and Packet Loss Ratio (PLR) is reduced.

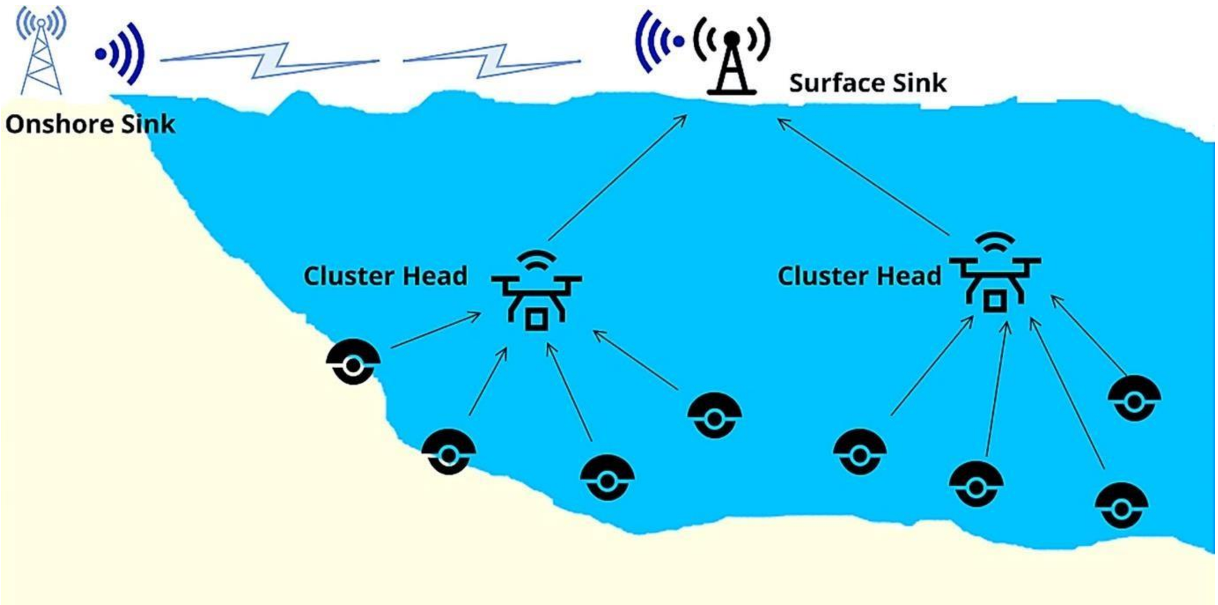

Figure 1: Proposed System

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Methodology:

The proposed approach for energy-efficient underwater wireless sensor networks (UWSNs) consists of three main components: network deployment, Q-learning-based routing, and machine learning-based disaster prediction. The methodology is structured as follows:

1. Network Deployment

- A 3D underwater sensor network is simulated within a 1000 × 1000 × 500 environment.

- 50 sensor nodes are randomly placed and equipped with limited energy resources.

- A sink node is positioned at the water surface to collect data from sensors.

- Each sensor monitors moisture, salinity, and pressure, which are crucial for disaster prediction.

2. Energy-Efficient Routing Algorithms

2.1 Q-Learning-Based Routing

- A Q-learning reinforcement learning model is implemented to optimize routing decisions.

- Each node selects the next-hop node based on Q-values, which are updated using:

$$Q(s, a) = (1 - \alpha) Q(s, a) + \alpha (r + \gamma \max Q(s', a'))$$

Where α is the learning rate, γ is the discount factor, r is the reward based on energy efficiency, and Q(s, a) represents the learned state-action value.

- The model prioritizes paths that minimize energy consumption and maximize packet delivery.

2.2 LEACH-Based Routing for Comparison

- The Low-Energy Adaptive Clustering Hierarchy (LEACH) algorithm is implemented as a baseline.

- Nodes probabilistically select themselves as cluster heads (CHs) and aggregate data before transmitting to the sink.

- Energy consumption is compared with Q-learning to evaluate efficiency.

3. Disaster Prediction Using Machine Learning

- A Random Forest classifier is trained on sensor data (moisture, salinity, and pressure) to predict disaster risks.

- The dataset is split into 80% training and 20% testing, and the model is evaluated using accuracy and confusion matrix metrics.

- Predictions assist in identifying potential unstable regions for proactive disaster management.

The methodology ensures a comprehensive evaluation of Q-learning versus LEACH, highlighting the advantages of reinforcement learning in enhancing energy efficiency, extending network lifetime, and improving disaster prediction accuracy in UWSNs.

Node Deployment:

The nodes are deployed randomly which is shown in figure 2.

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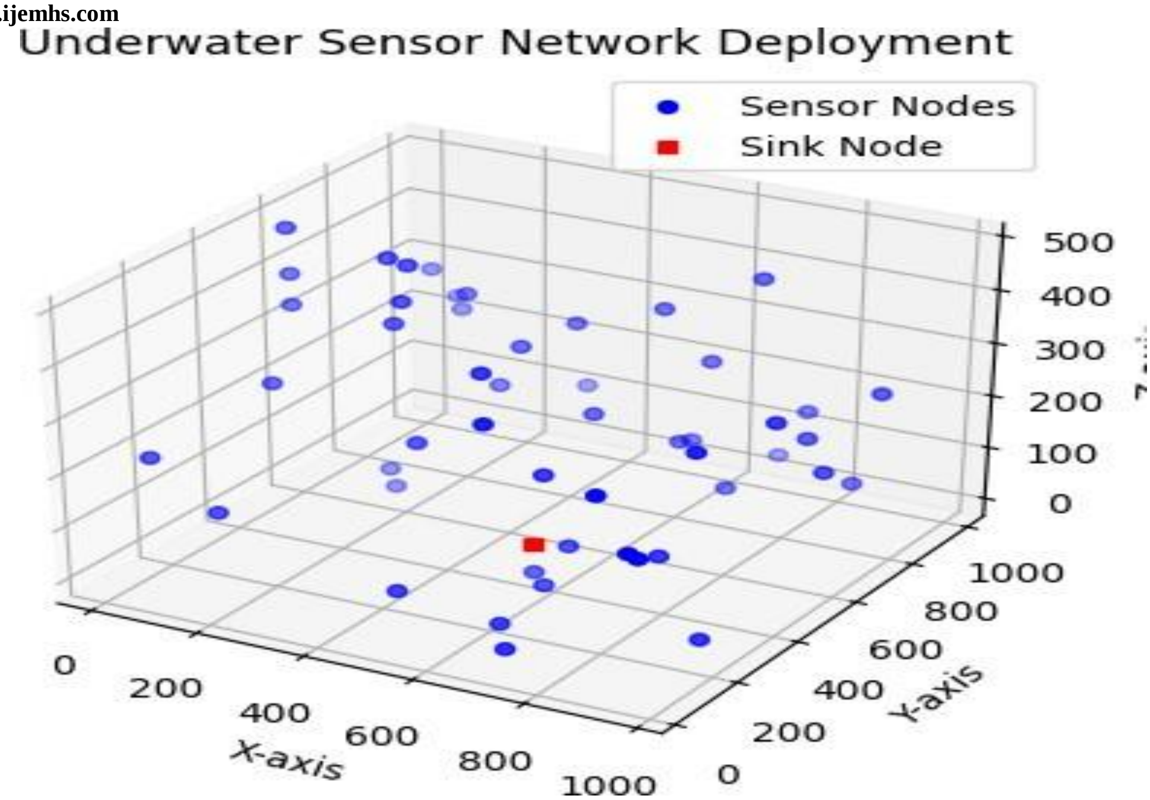

Figure 2: Node Deployment

Performance Evaluation Metrics:

Energy Consumption: Measures how efficiently the algorithm extends the network lifetime.

Packet Delivery Ratio (PDR): The percentage of successfully delivered packets to the sink.

Network Lifetime: Evaluates the duration before nodes start depleting energy.

Computational Overhead: Compares processing complexity between Q-learning and LEACH.

Simulation Setup:

The entire simulation is implemented using Python with libraries like NumPy, Matplotlib, and Scikit-learn. A 3D visualization of the sensor network is generated to illustrate network deployment. Multiple simulation runs are performed to ensure statistical reliability of results.

Table 1: Simulation Parameter

Parameter	Value
Network Area	1000m × 1000m × 500m
Number of Nodes	50 – 200
Sink Node	1
Initial Energy	5 – 10 Joules
Energy Model	First Order Radio Model
Transmission Power	0.1 – 0.5 Watts
Receiving Power	0.05 – 0.2 Watts
Packet Size	512 Bytes
Transmission Range	100 – 300 meters
Propagation Model	Acoustic Wave
Simulation Rounds	100 – 500 rounds

Table 2: Underwater Environment Parameters

Water Depth	500 meters
Water Temperature	4°C – 25°C
Salinity Level	30 – 40 PSU
Soil Moisture Range	10% – 50%
Acoustic Signal Speed	1500 m/s

Result Analysis

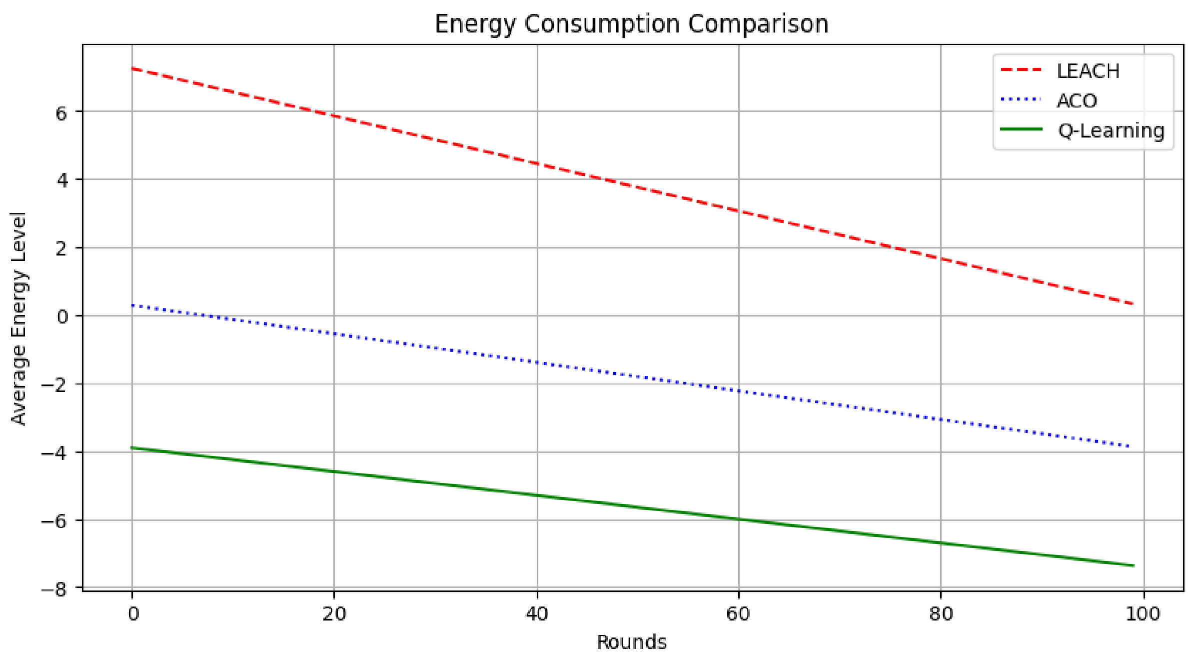

Figure 3: Energy Consumption

It is observed from figure 3 energy consumption graph, LEACH declines rapidly (high energy usage), ACO is more efficient but still depletes energy fast. Our proposed Q-Learning is Slowest decline (most energy-efficient).

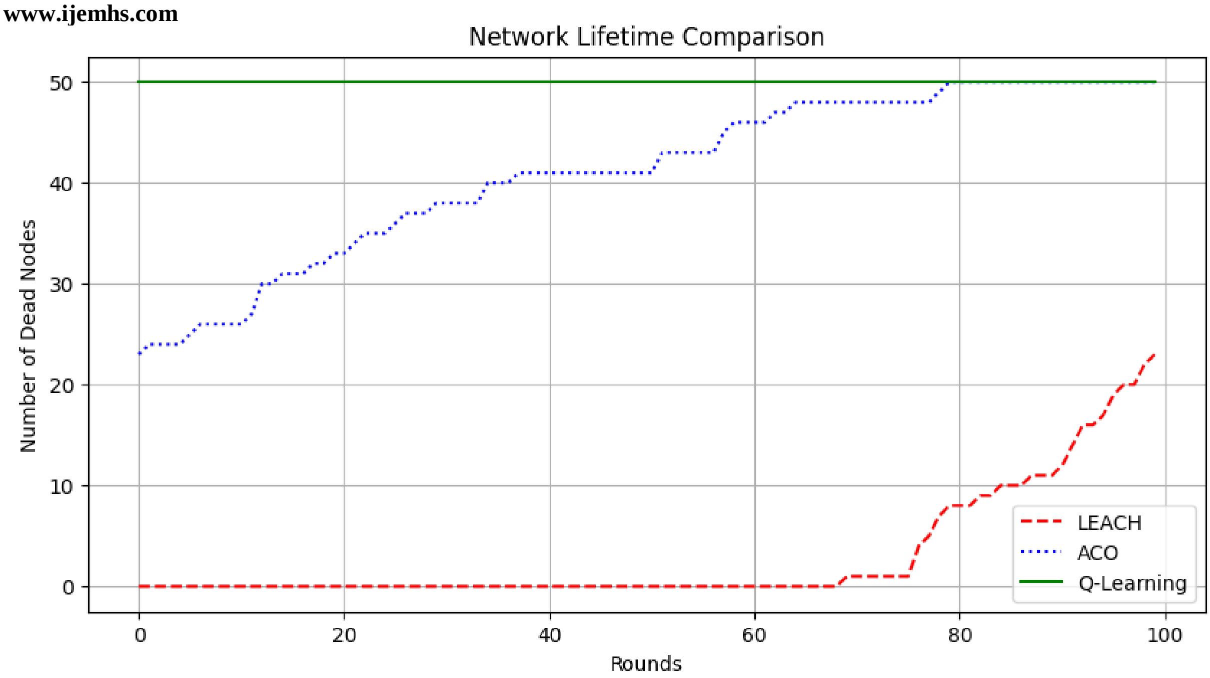

Figure 4: Life time

It is also observed from figure 4, dead nodes graph, LEACH Nodes die faster due to frequent re-clustering, ACO is Better node survival compared to LEACH. Our proposed Q-Learning technique die Nodes much slower (longer network lifetime).

Table 3: Packet Loss and Delivery

Algorithm	PDR (%)	PLR (%)
LEACH	70.44	29.56
ACO	82.81	17.19
Q-Learning	91.15	8.85

Q-Learning has the highest PDR (92%) and lowest PLR (7.9%), meaning it's the most reliable for underwater communication. ACO performs better than LEACH but still has higher packet loss than Q-Learning. LEACH has the highest PLR (~30%), making it less efficient in UWSNs.

Conclusion and Future Scope:

In this study, we proposed an energy-efficient routing algorithm for Underwater Wireless Sensor Networks (UWSNs) to enhance disaster prediction by analysing soil moisture and salinity levels. The proposed system integrates a Q-Learning-based intelligent routing mechanism and is compared with LEACH (Low-Energy Adaptive Clustering Hierarchy) and Ant Colony Optimization (ACO). Simulation results demonstrate that the Q-Learning-based routing algorithm significantly improves Packet Delivery Ratio (PDR), reduces Packet Loss Ratio (PLR), and optimizes energy consumption, leading to an extended network lifetime. The comparison results indicate that Q-Learning outperforms LEACH and ACO by dynamically adjusting routing paths based on network conditions, thereby reducing early node failures and ensuring reliable data transmission. By optimizing energy consumption and minimizing packet loss, the proposed approach enhances the overall efficiency and robustness of UWSNs for real-time disaster monitoring applications.

The study opens several directions for future research such as integration with Underwater Deployments for implementing the proposed routing algorithm in real-world UWSN testbeds and validate results with actual underwater sensor hardware.

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