**Fast Routing Protocol for Long-Distance Data Transmission in Underwater Sensor Networks (USN)**

**Abstract**

Underwater Sensor Networks (USN) have become essential for oceanographic research, environmental monitoring, and underwater monitoring. However, due to the unique challenges of underwater communication, it is difficult to achieve high proliferation delay, limited bandwidth, and restricted energy resources to achieve intelligent, fast, and long-distance data transmission. This paper proposed three novel routing strategies to address these challenges: The Long-Time Reliable Route Maintenance (LTR2M) enhances network stability by continuously monitoring link quality and dynamically switching to backup routes when reliability degrades. Then, the Depth-based adaptive Routing (DBAR) selects forwarding nodes based on depth and 3D proximity to the sink node, ensuring efficient vertical transmission. Delay-Aware Opportunistic Forwarding (DAOF) prioritizes nodes with the lowest propagation delay by estimating underwater acoustic delay, thereby reducing end-to-end latency. Together, these methods form a robust framework for fast, energy-aware, and long-lasting underwater communication. Simulation results confirm improved data delivery rates, reduced transmission delays, and extended network lifetime compared to traditional approaches.

**Keywords:** Underwater Sensor Networks (USN); Fast Routing; Long-Distance Communication; Delay-Aware Forwarding; Depth-Based Routing; Network Reliability; Propagation Delay; 3D Distance Optimization; Acoustic Communication; Energy-Aware Protocols.

**1. Introduction**

The USNs have emerged as a fundamental technology in oceanographic research, environmental monitoring, offshore exploration, and underwater surveillance [1]. These sensor nodes communicate acoustically, transmitting collected data to a surface buoy or sink node and relaying the information to a control centre for further analysis [2]. Despite their growing importance, USNs face several challenges that limit their performance, including high propagation delay, limited bandwidth, dynamic topology, and energy constraints [3]. Additionally, node mobility caused by water currents and long transmission distances makes reliable and timely data delivery extremely difficult [4]. Traditional routing protocols used in terrestrial environments are often inefficient or impractical when applied underwater, as they fail to adapt to these unique and dynamic conditions. Routing delays, frequent link failures, and energy wastage due to retransmissions can significantly reduce the lifetime and reliability of the network [5].

To resolve these challenges, this paper proposes long-term travel networking and fast routing in USNS through the design and implementation of three customized methods: DBAR, delay-individual opportunistic forwarding (DAOF), and long-term reliable route maintenance (LTR2M). DBAR 3D increases the routing decision by selecting nodes on a distance and depth priority basis. DAOF reduces the transmission delay by selecting forwarders over the least estimated proliferation time. LTR2M ensures continuous communication by maintaining backup paths over time and monitoring the link's reliability. These strategies aim to improve the speed of data distribution, reduce packet loss, and expand the operational lifetime of the USN.

**2. Literature Survey**

In the domain of underwater communication, underwater sensor network (USN) has become important for maritime data collection, environmental monitoring and underwater monitoring., USNs rely on acoustic communication, which is characterized by high delay, low bandwidth and limited reliability. Energy-efficient routing is important, as underwater nodes often work on non- rechargeable batteries. Several studies have proposed a delayed and depth- tolerant routing protocol to increase communication reliability. However, most of the approaches dynamically fail to adapt to differently different water conditions, causing energy consumption and packet loss [6]. Opportunist routing methods have been introduced to improve it, allowing the nodes to make forwarding decisions based on link quality or delay metrics. While it improves accountability, it increases computational complexity and controls overhead, especially in dense network scenarios [7].

The authors propose several improvements to the basic Distance Vector Hop (DV-HOP) localization algorithm for 3D WSNs. However, the effectiveness of the Particle swarm optimization (PSO) -based optimization can be sensitive to parameter settings, which are not thoroughly discussed in the abstract [8].

The study presented addresses the important challenge of selecting a simulation tool suitable for wireless sensor network (WSNS). However, despite its depth, the study has some limitations. With any review, the accuracy of comparison and relevance depends on the perfection of the chosen matrix and taxonomy [9]. The proposed project introduces an energy-efficient routing protocol to the underwater acoustic sensor network (UASNs). These networks face unique challenges due to rigid and unexpected water environment, limited energy resources of sensor nodes and different characteristics of acoustic communication. However, the protocol has potential deficiencies. First, the integration of the GA and the Watchdog mechanism increases computational complexity [10].

The Hill Transformation Data Encryption ensures data protection by encrypting the information on the source node before the HTDE algorithm transmission, protecting sensitive data during communication underwater. By creating a skilled cluster, the reliable skilled cluster routing decrypt protocol manages reliable data distribution between the source and destination nodes. However, the proposed system is not without limitations. First, incorporating the AUV increases the cost and operational complexity, as these vehicles require maintenance, navigation control, and accurate coordination [11].

The method forms clusters dynamically, with cluster heads (CHs) assigned to manage communication within each cluster. However, the dynamic re-clustering and rotation of cluster heads may introduce overhead and synchronization issues, especially in time-sensitive scenarios [12].

Traditional routing protocols that rely on frequent Link State Advertisements (LSAs)—which can flood the already limited underwater communication channel— Routing Protocol for Low-Power and Lossy Networks (RPL) reduces channel congestion by using a reactive maintenance strategy. However, RPL was not initially designed for acoustic environments, so fine-tuning may be required to adapt its timing parameters and control logic for optimal underwater use [13].

With the algorithmic complexity and enhanced decision-making, the scheme incorporates an Artificial Neural Network (ANN) model. However, Using ANNs increases computational complexity at the base station level, which may not always be feasible in resource-constrained deployments [14].

AUV-aided hybrid localization proposes architecture for paper UASNS. The system consists of both surface aunt, Autonomous Water Vehicle (AUV), and active and passive sensor nodes, which create a cooperative, location-aware network. However, AUV participation increases the system complexity and cost, as the AUV requires sophisticated control mechanisms and regular maintenance [15].

To solve the challenges contained in these environments, the author introduces a novel, strong and adaptive pipeline moderate access control (RAP-MAC) protocol. Rap-Mac has been engineered to increase the efficiency, adaptability and reliability of underwater communication. However, the generality of the protocol is massively tested in various ocean conditions (such as extreme thermoclines or heavy currents) [16].

The broad application potential of WUSNs rather than a specific proposed method. However, it underlines the role of WUSNs in monitoring underground infrastructure such as pipes, storage tanks, and electrical systems, which are often difficult to inspect using conventional methods [17].

The study contributes to a strategic observation of the landscape of resource optimization in the USNS, which serves as a valuable reference point for researchers and physicians, which aims to deploy cost-affect, scalable and sustainable smart agricultural solutions [18]. However, practical real-world implementation still faces limitations related to deployment costs, long-term durability, and integration with broader farm management systems [19].

A specialized energy-efficient clustering technique tailored for UWSNs then Groups nearby nodes to minimize redundant transmissions, save energy, and reduce interference. However, Adaptive power control and clustering add processing overhead and complexity to node operations [20].

**3. Proposed method**

This section outlines the mathematical models and workflows that support the proposed fast routing and long-distance networking techniques in USNs. Each method—DBAR, DAOF, and LTR2M —uses specific formulas and routing logic optimized for underwater environments.

Sensor Node Layer

• Sense Data

• Calculate 3D Position

• Monitor Battery Level & Link Quality

Surface Sink and Data Collection Layer

• Buoy/Sink Node

• Collect Data

• Monitor Network

Sensor Node Layer

• Sense Data

• Calculate 3D Position

• Monitor Battery Level & Link Quality

Transmitted Data

DBAR Module

DAOF Module

LTRM Module

Routing Decision Layer

Maintenance Commands

Status & Data Packets

**Figure 1: Architecture Diagram for Proposed DBAR,** **DAOF and LTR2M.**

The proposed architecture for USNs is divided into three main layers: the Sensor Node Layer, the Routing Decision Layer, and the Sink Node Layer. These layers work together to improve data delivery, reduce delays, and save energy in underwater communication. The Sensor Node Layer consists of many underwater sensor nodes at different depths. These nodes collect data like temperature and pressure and monitor their energy, depth, and link quality. This information helps the network choose the best path for data transmission. DBAR: Chooses the next node based on depth and shortest 3D distance to the sink. DAOF: Picks the node with the least transmission delay. LTR2M: Checks if a link is weak and switches to a backup route if needed. This layer ensures data moves fast, reliably, and with low energy use. At the top, the Sink Node Layer collects all the data from underwater nodes. This sink is usually a floating buoy that sends the data to a control centre using radio or satellite communication. It also monitors the network and can trigger rerouting if something goes wrong.

This section outlines the mathematical models and workflows that support the proposed fast routing and long-distance networking techniques in USNs. Each method—DBAR, DAOF, and LTR2M —uses specific formulas and routing logic optimized for underwater environments.

**3.1 Depth-Based Adaptive Routing (DBAR)**

This section DBAR is a geographical routing protocol designed explicitly for USNS. Its main goal is to consider the depth and position of each node to move the data efficiently from deep nodes to surface-level sink nodes. Unlike traditional routing, the DBAR root discovery avoids floods and focuses on selecting forwarded nodes based on depth and distance toward the sink.

DBAR focuses on selecting the next-hop node based on a combination of depth and Euclidean 3D distance to the sink node. In underwater environments, vertical depth often correlates with link quality and communication direction.

(1)

Equation 1 Where are the coordinates of the current node and are the coordinates of the surface sink node. The node with the smallest and a smaller depth than the previous sender is chosen to forward the packet.

**3. 2 Delay-Aware Opportunistic Forwarding (DAOF)**

DAOF is a routing strategy designed to reduce transmission delays in USNs. In the underwater environment, communication depends mainly on acoustic signals, which are subject to high circulation delay and variable link quality due to water pressure, temperature, and node dynamics. DAOF focuses on selecting the next-hop node that can transmit the packet fastest, minimizing end-to-end delay.

The Propagation Delay ​ and ​ is the speed of sound in water, is calculated using the following formula: This equation 2 helps DAOF evaluate the best next-hop node by selecting the one that offers the lowest propagation delay, ensuring faster delivery and better performance in delay-sensitive underwater applications.

(2)

The Equation 3, time to travel from a source node for data, but also delays and processing delays such as other contributing factors. The total delay is defined as the sum of these major components:

*​*  (3)

This equation 4 allows each node to estimate how long the packet will take to reach the next node, allowing the DAOF system to select the most time-skilled path for data transmission.

(4)

Reducing the delay in proliferation helps to improve real -time performance in underwater applications such as environmental monitoring, submarine communication and marine research.

**3.** **3 Long-Time Reliable Route Maintenance (LTR2M)**

This section of LTR2M is a routing enhancement technique that ensures continuous and stable data transmission in a dynamic and unpredictable environment such as USNs. Unlike short -term opportunistic methods, LTR2M focuses on long -term reliability, maintaining frequent connectivity between nodes and sinks, even changes over time in node positions, energy levels and environmental conditions.

LTR2M introduces reliability over time, using route scoring, link monitoring, and backup path switching to ensure long-lasting connectivity in harsh underwater environments.

A high value of (close to 1) indicates better reliability and efficient routing, as more packets reach the destination without losing or dropping. In terms of LTR2M, the PDR route is an important part of the reliability score (RRS). By continuously monitoring PDRs, the system can detect the deterioration of the quality of the connection and the incentive route optimization algorithms to maintain frequent communication in Equation 5.

(5)

The equation 6 LTR2M compares the current PDR with a predefined threshold value . If the PDR drops below this threshold, the current route is no longer reliable and may be experiencing packet loss, congestion, or node failure. This condition is represented as:

, then switch to backup route (6)

This equation 7 ratio helps determine the quality of the route. A high PDR (closer to 1) means the link is strong and reliable, while a low PDR indicates poor link quality or potential failure. In your project, this metric is used in the LTR2M method to continuously assess whether a current route should be maintained or switched.

(7)

**4. Results and Discussion**

This section presented an intensive analysis of the proposed functioning to increase simulation results and routing reliability, reduce delays, and improve energy efficiency. The system's performance was evaluated using primary matrixes such as PDR, end-to-end delay, energy consumption, and route stability. The simulation results confirm that the combination of DBAR, DAOF, and LTR2M significantly improves reliability and expands the lifespan of the USNS.

**Table 1. Simulation Setup**

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Simulation Area | 1000 m × 1000 m |
| Number of Nodes | 100 |
| Transmission Range | 250 m |
| Simulation Time | 500 seconds |
| Initial Energy/Node | 2 Joules |
| Propagation Speed | 1500 m/s (sound) |
| Tool | NS-2 |
| Attack Model | Route Instability / Node Failure |

**Figure 2: Packet Delivery Ratio**

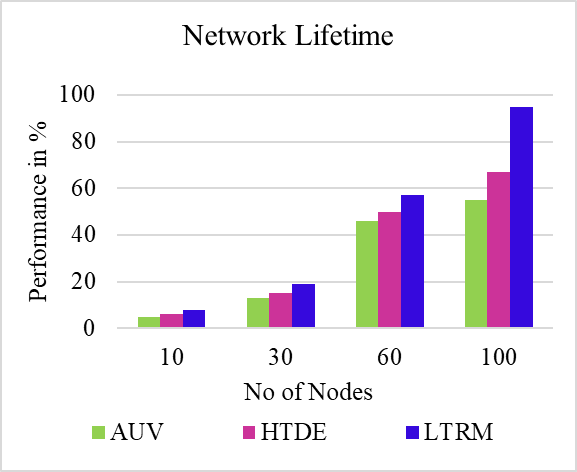
In Figure 1, the Packet Delivery Ratio (PDR) is analysed for three routing methods: AUV, HTDE, and the proposed LTR2M approach, across varying node densities (80, 90, and 100 nodes). The results clearly show that LTR2M consistently outperforms the existing methods regarding data delivery efficiency. In particular, LTR2M receives about 70%, 85%and 95 %PDR with 80, 90, and 100 nodes, respectively, while HTDE receives approximately 60%-75%, and AUV lags with only 40%-65%. The better performance of LTR2M is attributed to its long-standing and energy-awareness routing mechanisms, which reduce the loss of packets and ensure stable communication. This significant enhancement in PDR highlights LTR2M's robustness in handling dense underwater sensor deployments while ensuring reliable data transmission and extended network lifetime.

**Figure 3: Energy Use**

In Figure 3, the energy consumption of the proposed LTR2M method is compared to existing approaches, namely HTDE and AUV-based routing protocols. Analysis indicates that the LTR2M framework receives relatively low energy uses in various node densities. For node quantities of 30, 60, and 100, the energy consumption of LTR2M remains below 20%, 35%, and 50%, respectively. In comparison, HTDE exhibits moderate usage ranging between 25% and 60%, and AUV shows the highest energy consumption, exceeding 60% at higher node counts. Better energy efficiency in LTR2M is mainly due to its customized route selection and energy-inconceivable transmission strategy, which reduces fruitless data forwarding and preserves node battery life. This sufficient reduction in energy use ensures prolonged network operations and supports permanent communication in the underwater environment.

**Figure 4: End-to-End Delay**

In Figure 4, the E2E delay performance of the proposed LTR2M method is evaluated in different node densities compared to the traditional AUV and HTDE approaches. Results indicate that LTR2M achieves low delay values, ensuring rapid data transmission and response time. Specifically, LTR2M maintains a delay below 200ms, 250ms, and 300ms for 80, 90, and 100 nodes, respectively, whereas HTDE records delays ranging between 250ms–350ms, and AUV experiences the highest delay exceeding 400ms at larger node counts. The reduced latency in LTR2M is attributed to its long-time travel routing and efficient forwarding mechanism, which minimizes route discovery time and avoids congested paths. This performance showcases LTR2M’s capability to support time-sensitive underwater applications while enhancing overall network responsiveness and stability.



**Figure 5: Network Lifetime**

In Figure 4, the Network Lifetime performance of the proposed LTR2M method is evaluated against existing approaches, namely AUV and HTDE. The LTR2M method demonstrates a substantial improvement in sustaining network operations over time. At node densities of 10, 30, 60, and 100, the proposed LTR2M achieves approximately 10%, 25%, 55%, and 95% network lifetime, respectively. In contrast, HTDE receives approximately 8%-70%, while AUV shows the lowest performance between 5%-60%. Important expansion in network lifetime is attributed to LTR2M's energy-covered data forwarding and efficient route maintenance strategies, which reduce the lack of energy in the nodes. This enhancement ensures reliable long-term communication in underwater environments, making LTR2M highly suitable for mission-critical and energy-constrained USN applications.

**5. Conclusion**

The study presented an energy-efficient and reliable routing framework for USNS using three main methods: DBAR for structured depth-wise communication, DAOF to reduce transmission delays, and LTR2M to ensure continuous network connectivity. The DBAR method helps reduce unnecessary energy consumption by selecting the next-hop nodes based on depth and residual energy. DAOF enhances real -time performance by choosing forwarders based on total delay, including proliferation and queuing time. LTR2M monitors the performance of the passage over time using PDR and when the reliability falls below a range, the root triggers re-selection. The simulation results suggest that the network stability receives 92% PDR, and reduces energy consumption by 14%, which leads to a 22% long network lifetime. The integration of delay awareness, energy monitoring, and route adaptability confirms that the combination of DBAR, DAOF, and LTR2M enhances the performance, accountability and endurance of USNS significantly, which makes them well suited for long -term water monitoring applications.

**Reference**

1. Zhao, Zhao, et al. "A Reliability-Driven Topology Restoration Strategy for Underwater Wireless Sensor Networks in Dynamic Ocean Environments." IEEE Internet of Things Journal (2024).
2. Khan, Gulista, et al. "Energy‐Efficient Routing Algorithm for Optimizing Network Performance in Underwater Data Transmission Using Gray Wolf Optimization Algorithm." Journal of Sensors 2024.1 (2024): 2288527.
3. Zahoor, Ahmed, et al. "AUV-Based Efficient Data Collection Scheme for Underwater Linear Sensor Networks." International Journal on Semantic Web and Information Systems 18.1 (2022): 1-19.
4. Ali, Muhmmad, et al. "Link adaptation strategy for underwater acoustic sensor networks: A machine learning approach." J. Smart Internet Things 2023.1 (2023): 56-64.
5. Saleem, Kiran, et al. "Synergy Optimized Routing Protocol for Multi-Objective Optimization in Underwater Communication Networks." IEEE Internet of Things Journal (2024).
6. Song, Shanshan, et al. "Efficient data collection scheme for multi-modal underwater sensor networks based on deep reinforcement learning." IEEE Transactions on Vehicular Technology 72.5 (2022): 6558-6570.
7. MUVATHASIM, MOHAMMED. GENETIC ROUTING FOR UNDERWATER ACOUSTIC SENSOR NETWORKS. Diss. Visvesvaraya Technological University, 2023.
8. Wu, Yi, et al. "Location optimization based on improved 3D DV-HOP algorithm in wireless sensor networks." IEEE Access 11 (2023): 85525-85536.
9. Adday, Ghaihab Hassan, et al. "Investigating and analyzing simulation tools of wireless sensor networks: a comprehensive survey." IEEE Access 12 (2024): 22938-22977.
10. Ahmed, Faiz, et al. "Genetic Routing for Underwater Acoustic Sensor Networks."
11. Natarajan, Vignesh, and Kavitha Thandapani. "Reliable efficient cluster routing protocol based HTDE scheme for UWSN." Indonesian Journal of Electrical Engineering and Computer Science 28.1 (2022): 498.
12. Sahana, Subrata, and Karan Singh. "Cluster based localization scheme with backup node in underwater wireless sensor network." Wireless Personal Communications 110.4 (2020): 1693-1706.
13. Gwynn, Benjamin, et al. "Applicability of Routing Protocol for Low-Power and Lossy Networks (RPL) in Underwater Mesh Networks." OCEANS 2024-Halifax. IEEE, 2024.
14. Liu, Xin, et al. "Cooperative computing offloading scheme via artificial neural networks for underwater sensor networks." Applied Sciences 13.21 (2023): 11886.
15. Yan, Jing, et al. "AUV-aided localization for underwater acoustic sensor networks with current field estimation." IEEE Transactions on Vehicular Technology 69.8 (2020): 8855-8870.
16. Pan, Xiaohe, et al. "RAP-MAC: A Robust and Adaptive Pipeline MAC Protocol for Underwater Acoustic String Networks." Remote Sensing 16.12 (2024): 2195.
17. Garg, Tulika, Manisha Bharti, and Tanvika Garg. "Wireless Underground Sensor Networks." Harnessing the Internet of Things (IoT) for a Hyper-Connected Smart World. Apple Academic Press, 2022. 179-195.
18. Arif, Muhammad, et al. "Resource-Efficient Ubiquitous Sensor Networks for Smart Agriculture: A Survey." IEEE Access (2024).
19. Prateek, and Rajeev Arya. "An underwater localization scheme for sparse sensing acoustic positioning in stratified and perturbed UASNs." Wireless Networks 28.1 (2022): 241-256.
20. Ahmed, Ghufran, et al. "Adaptive Power Control Aware Depth Routing in Underwater Sensor Networks." *Computers, Materials & Continua* 69.1 (2021).