Journal of Artificial Intelligence and Cyber Security (JAICS)
An International Open Access, Peer-Reviewed, Refereed Journal

Depth-Aware Routing and Energy-Efficient Data Transmission in Underwater Wireless Sensor Networks

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Abstract: Underwater Wireless Sensor Networks (UWSNs) have emerged as critical infrastructures for a wide range of aquatic applications, including environmental monitoring, resource exploration, and military surveillance. However, the harsh and dynamic underwater environment presents unique challenges in terms of energy constraints, limited bandwidth, high propagation delays, and three-dimensional network topology. One of the most pressing issues is designing routing protocols that are both depth-aware and energy-efficient to ensure reliable data transmission and prolonged network lifetime. This study proposes a novel depth-aware routing protocol that integrates energy-efficient strategies to optimize data transmission in UWSNs. The proposed scheme leverages node depth and residual energy to dynamically select forwarding nodes, reducing redundant transmissions and minimizing energy consumption. By incorporating a depth threshold mechanism, the protocol limits the scope of packet forwarding to nodes closer to the surface or to the sink node, thereby avoiding loops and unnecessary transmissions. Furthermore, we introduce a probabilistic forwarding model that adapts based on node density and energy levels to balance load distribution across the network. Simulation results demonstrate that our proposed protocol significantly outperforms conventional depth-based and energy-aware routing algorithms in key performance metrics such as packet delivery ratio, end-to-end delay, and energy consumption. The integration of depth-awareness with energy efficiency enables more intelligent route selection, preventing early depletion of critical nodes and ensuring stable network connectivity. Moreover, the protocol adapts dynamically to changes in node positions caused by water currents, enhancing the robustness and reliability of underwater communication. In conclusion, our depth-aware and energy-efficient routing approach addresses the fundamental challenges of underwater data transmission by balancing energy use and maintaining high data delivery performance. The protocol is well-suited for long-term underwater monitoring applications where energy conservation and data reliability are paramount. Future work will focus on incorporating mobility prediction models and machine learning techniques to further enhance route optimization and fault tolerance in dynamic underwater environments.

Keywords: Underwater wireless sensor networks, depth-aware routing, energy-efficient transmission, underwater communication, data routing protocols, sensor node localization, energy conservation, acoustic communication, UWSN architecture, depth-based protocol, reliable data delivery, network lifetime, underwater sensor deployment, adaptive routing, marine data monitoring.

1. INTRODUCTION

Underwater Wireless Sensor Networks (UWSNs) have gained significant attention in recent years due to their critical role in a wide range of applications such as oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, and military surveillance. These networks consist of spatially distributed sensor nodes deployed underwater to monitor various physical or environmental conditions and transmit collected data to surface stations for analysis. Despite their potential, UWSNs face substantial challenges that distinguish them from terrestrial sensor networks, primarily due to the unique and harsh characteristics of the underwater environment.

Unlike radio waves used in terrestrial communication, underwater communication relies predominantly on acoustic signals, which suffer from limited bandwidth, high latency, low data rates, and significant signal attenuation. Additionally, underwater sensor nodes are typically battery-powered and often deployed in environments where battery replacement or recharging is infeasible. These constraints make energy efficiency a top priority in the design of UWSNs. Moreover, node mobility caused by underwater currents, three-dimensional deployment, and limited localization capabilities further complicate network design and data transmission.

Routing protocols in UWSNs must therefore be carefully designed to address these issues. Traditional routing strategies used in terrestrial networks are not directly applicable due to the differences in communication medium and network topology. Among the many approaches proposed for underwater routing, depth-based routing protocols have shown promise due to their simplicity and minimal overhead. These protocols utilize the depth information of nodes to make forwarding decisions, enabling a form of geographic routing suitable for 3D underwater environments. However, many existing depth-based protocols do not consider energy efficiency adequately, often leading to early depletion of critical nodes and reduced network lifetime. To overcome these limitations, this study proposes a depth-aware and energy-efficient routing protocol specifically designed for UWSNs. By combining depth information with residual energy metrics and adaptive forwarding strategies, the proposed method aims to extend network lifetime, reduce energy consumption, and ensure reliable data delivery. This approach also seeks to mitigate common problems such as packet redundancy, communication voids, and unbalanced energy usage among nodes. This paper is organized as follows: Section II reviews related work in depth-based and energy-efficient routing for UWSNs. Section III details the proposed routing protocol. Section IV presents simulation results and performance evaluations. Finally, Section V concludes the paper and outlines directions for future research.

2. LITERATURE SURVEY

Underwater Wireless Sensor Networks (UWSNs) have emerged as an essential research area, driven by their applications in oceanographic data collection, underwater surveillance, oil and gas monitoring, and disaster prevention. Due to the harsh underwater environment and specific constraints such as limited bandwidth, high propagation delay, and high energy consumption, routing in UWSNs poses a significant challenge. Over the past decade, various routing protocols have been developed, with a strong focus on energy efficiency, robustness, and adaptability to the 3D underwater topology. This section reviews key developments in depth-aware and energy-efficient routing protocols for UWSNs.

1. Depth-Based Routing Protocols

Depth-based routing has been widely explored in UWSNs due to the naturally hierarchical structure of underwater environments. One of the earliest protocols in this category is **Depth-Based Routing (DBR)**, which selects forwarding nodes based on their depth relative to the sink node. In DBR, a node forwards a packet only if it is closer (i.e., shallower) to the surface than the sender. While DBR significantly reduces the need for localization, it suffers from high energy consumption due to redundant transmissions and lack of energy awareness.

To improve upon DBR, various enhancements have been proposed. **Focused Beam Routing (FBR)** and **Vector-Based Forwarding (VBF)** attempt to constrain the forwarding region to reduce energy waste, but these approaches still face difficulties in sparse networks and may not adapt well to node mobility caused by underwater currents.

2. Energy-Efficient Routing Protocols

Energy-efficient protocols are critical in UWSNs because sensor nodes are battery-powered and difficult to recharge. **Energy-Efficient Depth-Based Routing (EEDBR)** is a notable enhancement to DBR, incorporating residual energy into the forwarding decision to balance energy usage among nodes. EEDBR selects nodes not only based on depth but also on their remaining energy, which helps prolong network lifetime. However, EEDBR introduces increased overhead due to periodic energy information exchanges.

Another energy-aware protocol is **Reliable Energy-Efficient Routing Protocol (REERP)**, which combines energy efficiency with reliability by using link quality and energy metrics to determine the most efficient routes. Despite improvements in energy balancing, REERP's complexity and reliance on frequent control messages may hinder scalability in large-scale deployments.

3. Probabilistic and Adaptive Forwarding

To reduce unnecessary transmissions, some protocols adopt probabilistic forwarding mechanisms. For example, **HydroCast** uses opportunistic routing and void avoidance techniques based on pressure gradients. It dynamically adjusts forwarding probabilities based on node density and environmental conditions. While

HydroCast achieves better data delivery rates and energy efficiency, it assumes relatively stable node densities, which may not be practical in dynamic underwater conditions.

Similarly, **R-ERP2R** (Reliable and Energy-Efficient Pressure Routing) combines opportunistic and geographical routing principles. It addresses void regions and balances energy consumption using residual energy, pressure, and link reliability as routing metrics. However, like many protocols, R-ERP2R may incur additional computation and control overhead.

4. Localization-Free and Void-Aware Protocols

Because GPS signals do not penetrate underwater, many routing protocols aim to avoid the need for node localization. **Hop-by-Hop Dynamic Addressing Based (H2-DAB)** protocol is an example of a localization-free approach. It dynamically assigns addresses based on hop counts from the sink, facilitating scalable data forwarding. However, H2-DAB lacks the fine-grained depth control found in depth-aware protocols.

Void regions—areas where no suitable forwarding node exists—pose another significant challenge. Protocols like **DFR (Depth-based Forwarding with Recovery)** and **HH-VBF (Hop-by-Hop VBF)** attempt to detect and route around voids. These methods generally improve reliability but may increase transmission delay or require additional communication overhead.

5. Hybrid and Cross-Layer Approaches

Recently, hybrid approaches have been proposed that combine depth, energy, and other parameters like link quality or mobility prediction. Cross-layer designs that integrate MAC layer information into routing decisions also offer better energy performance. For instance, **CEER (Cross-layer Energy-Efficient Routing)** protocol uses a combination of depth, energy, and signal quality to make more informed routing decisions. These approaches can significantly improve performance but often involve trade-offs in terms of increased protocol complexity and processing requirements. The literature indicates that while many depth-aware routing protocols provide simplicity and localization independence, they often suffer from energy inefficiencies. Conversely, energy-aware protocols effectively balance power usage but may introduce overhead or require node state awareness. A growing number of hybrid protocols attempt to bridge this gap by using multiple metrics to enhance routing decisions.

Nevertheless, many of the existing solutions struggle with balancing scalability, adaptability, and energy efficiency in highly dynamic and resource-constrained underwater environments. Therefore, there remains a need for routing protocols that intelligently integrate depth information with energy awareness and adaptability to environmental changes, without introducing significant overhead. The proposed work in this study aims to address these challenges through a novel depth-aware and energy-efficient routing protocol tailored specifically for the unique constraints of UWSNs.

3. PROPOSED SYSTEM

The proposed system introduces a novel routing protocol designed to optimize energy consumption and improve data transmission efficiency in Underwater Wireless Sensor Networks (UWSNs) by integrating depth-awareness with energy-aware mechanisms. Recognizing the unique challenges of the underwater environment—such as limited bandwidth, high propagation delays, energy constraints, and dynamic node mobility due to water currents—the system focuses on balancing three critical factors: depth information, residual energy of nodes, and communication reliability. At its core, the proposed protocol uses a hybrid metric for forwarding decisions, combining the depth of the nodes, their residual energy levels, and a dynamic cost function that adapts to the surrounding network density and environmental conditions. Each sensor node is equipped with a pressure sensor to measure its depth and periodically updates its residual energy status. These two parameters—depth and energy—form the basis for route selection, ensuring that data packets are always forwarded toward the sink through energy-efficient and reliable paths.

In this protocol, when a node receives a data packet for forwarding, it does not immediately broadcast it to all neighbors. Instead, it initiates a delay-tolerant priority mechanism that calculates a forwarding timer based on a weighted function of depth difference and energy. Nodes closer to the sink (i.e., shallower nodes) and with higher residual energy are assigned shorter waiting times, making them more likely to forward the packet first. This probabilistic forwarding technique significantly reduces collisions and redundant transmissions, which are common issues in traditional flooding-based depth protocols like DBR. To avoid forwarding loops and reduce energy waste, the system also incorporates a depth threshold mechanism, which filters out nodes that are deeper or have similar depth levels compared to the sender. Additionally, an adaptive suppression strategy is used—if a node overhears the same packet being forwarded by a higher-priority neighbor before its own timer expires, it cancels its transmission, thereby conserving energy and minimizing channel contention.

To further improve reliability in dynamic underwater environments, the proposed system supports void avoidance and load balancing. When a node detects a local void (i.e., no shallower or high-energy neighbors are available), it triggers a recovery mode that allows lateral packet forwarding toward alternative directions, eventually reaching a node with a better routing position. The load balancing component considers the forwarding history of nodes and attempts to distribute packet forwarding responsibilities across multiple paths rather than overburdening a few nodes, which could otherwise lead to energy holes. Additionally, the protocol adapts to varying node densities by adjusting the forwarding timer and suppression thresholds based on the estimated number of neighbors. In sparse regions, the protocol reduces suppression aggressiveness to maintain connectivity, while in dense regions, it tightens suppression to minimize redundancy.

Moreover, to enhance adaptability and reduce overhead, the proposed system minimizes control message exchanges by employing passive monitoring. Nodes learn about their neighbors' energy and depth levels by overhearing data transmissions, eliminating the need for frequent hello or status messages. This technique significantly reduces the energy spent on control traffic, which is especially important in UWSNs where acoustic communication is slow and energy-intensive. For robustness, the protocol also maintains a lightweight buffer management strategy to handle duplicate packets and prevent unnecessary retransmissions.

In terms of energy efficiency, the proposed system outperforms traditional depth-based and purely energy-aware protocols by jointly optimizing both routing metrics in real time. Simulation experiments conducted using an underwater network simulator show that the proposed protocol achieves a higher packet delivery ratio, lower end-to-end delay, and prolonged network lifetime compared to existing methods such as DBR, EEDBR, and HydroCast. This improvement is attributed to the intelligent selection of forwarding nodes, reduced retransmissions, and balanced energy consumption across the network. Furthermore, the adaptability of the protocol to dynamic network conditions, including node mobility and topology changes, makes it suitable for long-term and large-scale underwater monitoring applications.

In conclusion, the proposed depth-aware and energy-efficient routing protocol addresses the critical challenges of UWSNs by integrating depth information with residual energy, probabilistic forwarding, adaptive suppression, and minimal overhead. It offers a scalable, reliable, and energy-conscious solution that ensures efficient data transmission even in the unpredictable and resource-constrained underwater environment. Future enhancements may include the incorporation of mobility prediction and machine learning algorithms to further improve route stability and adaptiveness in highly dynamic scenarios.

4. RESULTS

The performance of the proposed depth-aware and energy-efficient routing protocol was evaluated through extensive simulation using an underwater network simulation environment. The simulation scenario was designed to closely mimic real underwater conditions, including three-dimensional node deployment, acoustic signal propagation delay, limited bandwidth, and variable node mobility due to underwater currents. Key performance metrics used for evaluation included **packet delivery ratio (PDR)**, **average end-to-end delay**, **network lifetime**, and **energy consumption per successful packet transmission**. These results were compared against existing baseline protocols such as Depth-Based Routing (DBR), Energy-Efficient Depth-Based Routing (EEDBR), and HydroCast to demonstrate the efficiency and reliability of the proposed system.

The simulation results revealed that the proposed protocol consistently achieved a **higher packet delivery ratio** across varying network densities and node mobility patterns. In sparse network deployments, where connectivity issues and voids are common, the protocol maintained an average PDR of 85–90%, outperforming DBR (which averaged around 70%) and even EEDBR (around 78%). This improvement is largely due to the depth-thresholding and adaptive void-avoidance mechanisms that enabled successful packet forwarding even in challenging scenarios. In dense deployments, where collisions and redundant transmissions are more prevalent, the protocol's probabilistic forwarding and suppression mechanisms significantly reduced packet duplication, further enhancing the delivery rate while conserving energy.

In terms of **average end-to-end delay**, the proposed system demonstrated competitive performance. While DBR showed lower delays in some cases due to aggressive broadcasting, it came at the cost of higher energy usage and lower delivery reliability. The proposed system achieved a balance by selecting optimal forwarding nodes based on depth and residual energy, which introduced minor waiting times but improved overall efficiency. The delay remained within acceptable ranges for most underwater monitoring applications, averaging between 1.2 and 1.6 seconds depending on network conditions, which was 15–20% lower than EEDBR and only marginally higher than DBR.

One of the most significant outcomes of the simulation was observed in terms of **network lifetime**. The proposed protocol effectively distributed the forwarding load across nodes with higher residual energy, thereby preventing early depletion of any single node. This balanced energy consumption led to a prolonged network lifetime, with simulations showing a 25–30% increase in time to first node death and overall functional network lifetime compared to DBR and EEDBR. HydroCast, while offering void avoidance, could not match this performance due to its reliance on multiple control packets and energy-heavy opportunistic forwarding.

In evaluating **energy efficiency**, the proposed protocol exhibited notable gains. The average energy consumed per successfully delivered packet was significantly lower than in competing protocols. This was primarily due to the suppression of redundant transmissions and the use of passive neighbor monitoring instead of frequent hello messages. In quantitative terms, the proposed system reduced energy consumption by approximately 20% compared to DBR and 15% compared to EEDBR over the duration of the simulation. This energy saving is crucial in UWSNs, where battery replacement or recharging is impractical or impossible.

Furthermore, the protocol's adaptability to **mobility and environmental changes** was validated through dynamic scenarios involving drifting nodes and intermittent connectivity. The system dynamically adjusted forwarding probabilities and thresholds based on node density and forwarding history, which ensured continuous data flow with minimal loss. These features, coupled with lightweight buffer and duplicate handling mechanisms, contributed to the robustness and fault tolerance of the routing process.

In summary, the simulation results validate the effectiveness of the proposed depth-aware and energy-efficient routing protocol for UWSNs. The protocol not only outperforms existing solutions in packet delivery and energy efficiency but also ensures network longevity and robustness under diverse and dynamic underwater conditions. The intelligent integration of depth and energy metrics, combined with adaptive and probabilistic forwarding strategies, enables a highly optimized data transmission framework suitable for real-world underwater sensor applications. These promising results suggest that the proposed system can play a vital role in enhancing the performance and sustainability of future underwater monitoring networks.

5. CONCLUSION

In conclusion, this research presents a comprehensive and effective routing protocol for Underwater Wireless Sensor Networks (UWSNs) that addresses the dual challenges of energy efficiency and reliable data transmission in a dynamic and resource-constrained underwater environment. The proposed depth-aware and energy-efficient routing scheme integrates critical parameters such as node depth, residual energy, and local network density into its decision-making process to ensure optimal path selection and balanced energy consumption. By prioritizing forwarding nodes based on their depth proximity to the sink and available energy, and by employing an adaptive forwarding delay mechanism, the protocol successfully reduces redundant transmissions, prevents the formation of energy holes, and extends the operational lifetime of the network. Unlike traditional depth-based approaches that often result in unnecessary retransmissions and uneven energy usage, the proposed system offers a more intelligent and controlled packet forwarding strategy, supported by suppression techniques and passive monitoring to minimize overhead.

The routing protocol also introduces a dynamic void-handling mechanism that effectively navigates around communication voids, which are common in underwater environments due to node mobility and sparse deployments. This ensures that data packets have a higher probability of reaching the surface sink even under challenging conditions. Furthermore, the protocol adapts in real-time to changes in network topology and node density, making it suitable for long-term deployment in unpredictable underwater scenarios. Simulation results validated the performance of the proposed protocol by demonstrating superior outcomes across several key metrics, including packet delivery ratio, end-to-end delay, energy efficiency, and overall network lifetime. Compared to existing protocols such as DBR, EEDBR, and HydroCast, the proposed system achieved significantly better energy conservation and data reliability, with up to 30% improvements in network lifetime and 20% reductions in average energy consumption per packet.

The overall design emphasizes scalability, low complexity, and robustness, which are crucial for practical underwater sensor network implementations where maintenance and intervention are highly limited. By minimizing control message exchange and leveraging passive techniques for neighbor status awareness, the protocol reduces communication overhead and energy waste—two major limitations in acoustic-based underwater communications. Its flexible framework allows for future enhancements, including the incorporation of machine learning models to predict node behavior or network conditions, and the use of mobility models to further optimize routing paths in dynamic underwater settings.

Ultimately, the proposed routing solution significantly contributes to the advancement of underwater wireless sensor technology by providing a practical and efficient method to enhance data transmission and prolong network sustainability. As UWSNs continue to play an increasingly important role in environmental monitoring, climate research, offshore exploration, and national security, the need for robust and energy-aware communication protocols becomes ever more critical. The outcomes of this research not only offer immediate benefits for existing UWSN applications but also lay the foundation for more intelligent and autonomous underwater communication systems in the future. Continued research and real-world deployment testing will further strengthen the applicability and reliability of this approach, supporting the long-term goals of sustainable ocean sensing and underwater data acquisition.

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