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INVESTIGATING THE INFLUENCE OF AQUATIC ALGORITHMS ON UNDERWATER WIRELESS ROUTING BEYOND SURFACE CONSTRAINTS

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ABSTRACT
Underwater Wireless Sensor Networks (UWSNs) play a vital role in ocean monitoring, seismic activity tracking, and environmental observation, yet their performance is hindered by high propagation delay, limited bandwidth, and dynamic topological variations. This study conducts a comprehensive comparative analysis of aquatic algorithm on three prominent UWSN routing protocols—Vector-Based Forwarding (VBF), Depth-Based Routing (DBR), and Flood Routing—to evaluate their Quality of Service (QoS) performance in terms of delay, throughput, and packet loss under varying conditions of node density (20–100 nodes), communication distance (50–200 m), and deployment depth (0–200 m). Simulation data were generated using the Aqua-Sim framework in NS-3, ensuring a controlled and reproducible evaluation environment. The results indicate that VBF consistently achieves the lowest delay (0.0676 s at 20 nodes; 0.0769 s at 100 nodes) and the highest throughput (1772.80 bps at a depth of 51–100 m), making it the most efficient protocol for real-time and latency-sensitive applications. However, VBF experiences moderate packet loss (up to 57.34% in dense networks) due to its constrained forwarding region. DBR exhibits higher delay (0.1420 s at 151–200 m) and the greatest packet loss (85% at a 50 m distance), reflecting the limitations of depth-only forwarding in dynamic environments. In contrast, Flood Routing achieves the lowest packet loss (10.24% at 50 m) but suffers from increased delay (0.1063 s at 200 m) and inefficiency due to redundant transmissions. Overall, this study provides a unified performance benchmark for UWSN routing protocols, highlighting the fundamental trade-offs between efficiency, reliability, and scalability. These insights offer practical guidance for protocol selection and serve as a foundation for future adaptive and AI-driven routing strategies in underwater sensor networks.
Keywords : *UWSN, Routing Protocols, VBF, DBR, Flood Routing, Aquatic Algorithm, Aqua-sim NS-3*

1. Introduction

Underwater Wireless Sensor Networks (UWSNs) are rapidly evolving due to their broad applications in ocean monitoring, seismic tracking, environmental observation, and seabed exploration (Al-Saedi, 2021; Shovon et al., 2023; Saleem et al., 2024). However, the harsh underwater environment presents severe challenges such as limited bandwidth, long propagation delays, high energy consumption, and dynamic topology changes (Luo et al., 2021; Haque et al., 2020; Yuan et al., 2024; Khan et al., 2025). Developing efficient routing protocols is therefore essential to ensure reliable data transmission and to optimize network performance under these constraints (Khan et al., 2020; Zhao et al., 2023; Ismail et al., 2024).

As much of the Earth's underwater environment remains unexplored, UWSNs enable remote and autonomous exploration while maintaining Quality of Service (QoS) among nodes deployed across varying depths (Haque et al., 2020; Lilhore et al., 2022; Wang et al., 2024; Liu et al., 2025). Despite numerous comparative studies, most prior research has examined only isolated performance aspects—such as delay or energy efficiency—rather than conducting a comprehensive QoS evaluation. In addition, inconsistencies in simulation settings, node density, and depth variation have produced results that are difficult to generalize. Notably, Flood Routing is often excluded from such comparisons due to its redundancy, leaving uncertainty about its potential for delay-tolerant underwater applications.

To address these gaps, this study conducts a unified simulation-based evaluation of three representative UWSN routing protocols—Vector-Based Forwarding (VBF) (John, Menon & Nayyar, 2020), Depth-Based Routing (DBR) (Mahmood et al., 2020), and Flood Routing (Martin et al., 2017)—using the Aqua-Sim framework on NS-3. The evaluation considers variations in node density, communication range, and deployment depth. Unlike earlier works, the present study (i) employs consistent environmental parameters verified across multiple simulation runs with confidence intervals, (ii) analyzes cross-metric trade-offs among delay, throughput, and packet loss, and (iii) discusses implications for future adaptive and AI-enhanced routing in UWSNs.

By leveraging Aqua-Sim within NS-3 (Yan et al., 2021; Ponraj et al., 2021), the experiments ensure a controlled and reproducible performance assessment under realistic acoustic conditions. A key contribution of this work lies in its detailed performance demonstration, which clarifies previously unaddressed limitations of each routing scheme. Whereas earlier studies have overlooked a thorough analysis of Flood Routing (Mohan et al., 2022), this research highlights its strength in reducing packet loss while acknowledging its trade-offs in delay and throughput. The results also reveal that VBF achieves the lowest delay in low-density networks, while DBR performs better at greater depths despite higher packet loss.

These findings provide a practical understanding of protocol trade-offs, helping network designers select appropriate routing strategies for diverse underwater applications—balancing reliability, latency, and energy efficiency according to mission requirements.

2. Literature Review

2.1 UWSN Overview

UWSN has emerged as a crucial technological innovation for aquatic monitoring, finding applications in underwater data collection, oceanographic sampling, disaster prevention, and submarine detection (Tariq et al., 2020). UWSN consists of a network of autonomous sensors and acoustic modems that facilitate the sensing and transmission of digital data using sound waves as the primary communication medium (Mahalle, et al., 2021). Key components include acoustic modems, buoys, Autonomous Underwater Vehicles (AUVs), Remotely Operated Vehicles (ROVs), and onshore stations, which can be enhanced with application-specific sensors for improved functionality (Mahalle, et al., 2021). The surface sink node plays a vital role in this network, acting as a transceiver to manage acoustic signals received from underwater nodes while enabling long-range communication with onshore stations through radio frequency signals (Fattah et al., 2020). The data collected through UWSN can serve local applications or be integrated into more extensive networks, emphasizing their versatility and importance in underwater exploration and communication.

The VBF protocol establishes a virtual vector between the source and sink nodes, which has proven particularly effective in dense sensor networks. The protocol utilizes the Radius parameter in packets to define a virtual pipe, allowing nodes within it to assess their proximity to the routing vector and determine eligibility for forwarding packets. The protocol's efficiency hinges on selecting an optimal pipe radius—too large a radius increases interference, while too small a radius limits relay availability (Santhi Jeslet et al., 2022; Somani & Chaubey, 2022) Nodes broadcast packets directionally within this defined pipe, making VBF a robust and efficient method for underwater routing.

The DBR protocol is a routing approach in UWSN that leverages node depth information for forwarding decisions. Typically, sink nodes are located at the water surface within lifebuoys, while DBR employs a greedy strategy to forward packets based on the depth data of each node. Each packet stores the depth information of its most recent forwarder, which is updated at every hop. Nodes with shallower depths forward packets, whereas deeper nodes drop them. While DBR focuses solely on depth data, it could benefit from incorporating additional parameters, such as sink node capabilities, to improve routing efficiency (Farooq, et al., 2021).

The flood routing protocol is a simple yet robust method employed in UWSN, where data packets are broadcast from a source node to all neighboring nodes until they reach their destination or exceed a predefined threshold. (Martin et al., 2017) This protocol eliminates complex routing tables, making it fault-tolerant and ideal for dynamic underwater environments. However, it can lead to redundant transmissions and network congestion, which may waste resources. To address these issues, enhancements such as controlled flooding mechanisms and adaptive amplification strategies like Reliability-Aware Cooperative routing with Adaptive Amplification (RACAA) adjust transmission power and relay node selection dynamically. These improvements enhance packet delivery reliability while reducing energy consumption, making flood routing more efficient (Shovon & Shin, 2022). Table 1. Shows the comparative VBF, DBR, and Flood Routing.

Table 1 - Comparative VBF, DBR, and Flood Routing

Protocol	Principle	Advantages	Limitations	Typical Scenario
VBF	Vector pipe forwarding	Low delay, energy-aware path	Sensitive to node density, higher packet loss in sparse topology	Real-time data, moderate density
DBR	Depth gradient based	Simple implementation	Redundant transmission, delay increase	Static monitoring, dense deployment
Flood Routing	Broadcast forwarding	High reliability	High overhead & energy usage	Delay-tolerant monitoring

2.2 Aqua-Sim Network Simulator

Aqua-Sim is a simulation tool specifically designed for underwater sensor networks built on the foundation of NS2/NS3 (Al-Saedi, 2021). It is widely recognized for its ability to simulate the unique characteristics of underwater acoustic channels, such as attenuation behavior and collision performance in networks with significant acoustic delays. The simulator focuses on replicating the complex physical layer of underwater communication, capturing key aspects of underwater acoustic wireless channels. This capability makes Aqua-Sim preferred tool for researchers studying underwater network performance (Shahapur et al., 2021).

3. Research Methods

This study evaluates the performance of three Underwater Wireless Sensor Network (UWSN) routing protocols: Vector-Based Forwarding (VBF), Depth-Based Routing (DBR), and Flood Routing. The evaluation is conducted using the Aqua-Sim Network Simulator within the NS-3 framework, which models underwater acoustic propagation and network dynamics. The methodology follows a structured approach to simulate and analyze protocol performance under varying underwater conditions.

3.1 Simulation Scenarios

The simulation is designed to model realistic underwater environments with three main evaluation scenarios, as shows in Figure 1:

1. Node Density Analysis: The impact of node density on protocol scalability and performance is examined by simulating varying node counts (20, 40, 60, 80, and 100 nodes) (Figure 1a).
2. Distance-Based Communication: Nodes are placed at distances of 50m, 100m, 150m, and 200m to assess its impact on packet delivery success and communication reliability (Figure 1b).
3. Depth-Based Communication: Nodes are positioned at 0–50m, 51–100m, 101–150m, and 151–200m to evaluate protocol adaptability to vertical topological changes (Figure 1c).

3.2 Simulation Parameters

The simulation parameters used in this study, summarized in Table 2, were carefully configured to ensure a comprehensive evaluation of routing protocol performance under diverse underwater conditions. Each simulation was executed for 200 seconds, providing sufficient duration for network stabilization and data collection.

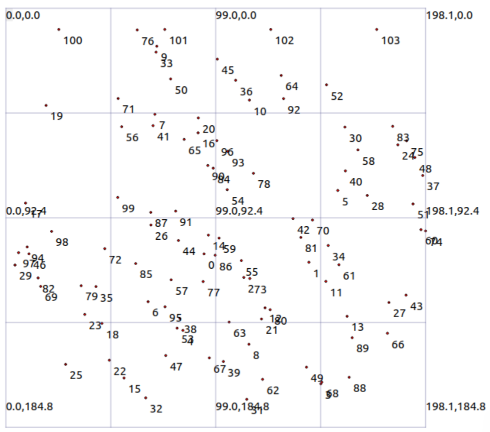
For the node density scenario, the total number of sensor nodes was varied across 20, 40, 60, 80, and 100 nodes to observe how increasing network density affects communication efficiency and protocol scalability. The distance-based scenario and depth-based scenario were both conducted using 60 nodes to maintain consistency while isolating the effect of spatial variation. In the distance-based setup, inter-node spacing was adjusted to 50 m, 100 m, 150 m, and 200 m, whereas the depth-based experiments considered four vertical layers: 0–50 m, 51–100 m, 101–150 m, and 151–200 m.

The simulated network employed four sink nodes positioned at the surface to collect data packets transmitted from underwater sensors. Each node had a transmission range of 100 m, and data were transmitted at a bit rate of 10,000 bps using 40-byte packets. The acoustic propagation speed was set to 1500 m/s, closely reflecting real-world oceanic conditions.

Three representative routing protocols—Vector-Based Forwarding (VBF), Depth-Based Routing (DBR), and Flood Routing—were evaluated under these configurations. This experimental design enables a robust and statistically reliable comparison of their routing efficiency, delay performance, throughput stability, and packet delivery reliability across varying underwater scenarios.

Table 2 - Simulation parameters

Parameter	Value
Simulation Time	200 Seconds
Number of Nodes	20/40/60/80/100 (Node Scenario), 60 (Distance and Depth Scenarios)
Number of Sinks	4
Data Rate	10,000 bps
Packet Size	40 Bytes
Acoustic Propagation Speed in Water	1500 m/s
Transmission Range	100 meters
Protocols	VBF / DBR / Flood
Scenarios	Node / Distance Distribution (50, 100, 150, 200 meters) / Depth (0-50, 51-100, 101-150, 151-200 meters)



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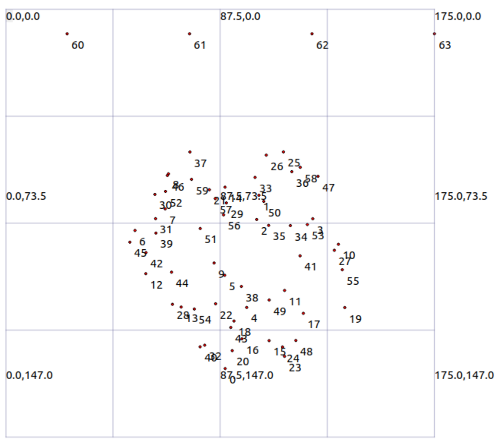

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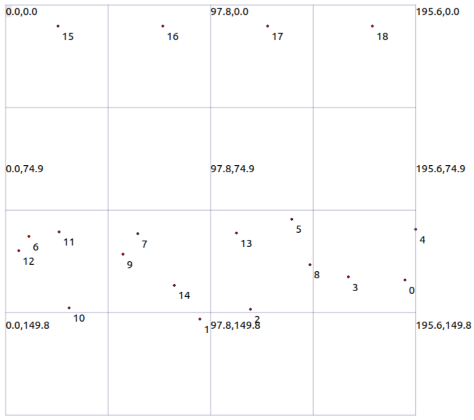

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Fig. 1. Simulation scenario: (a) 100 nodes, (b) 50m distance distribution, and (c) 101-150m depth

3.3 Performance Metrics

Three primary Quality of Service (QoS) metrics are considered:

- Delay, which measures the time taken for a signal to travel from a sender node to a receiver node, is calculated using Eq. (1). The distance (s) between the sender and receiver nodes is derived from the three-dimensional Euclidean formula, as expressed in Eq. (2).

$$Delay = \frac{Distance}{Propagation\ Speed} \quad (1)$$

$$s = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \quad (2)$$

- Throughput, representing data transmission efficiency, is defined in Eq. (3) as the total data sent over the simulation time. The calculation of total data sent is further elaborated in Eq. (4), which depends on the total number of packets sent, packet size, and conversion to bits.

$$Throughput = \frac{\sum Data\ Sent\ (bits)}{Simulation\ Time\ (seconds)} \quad (3)$$

$$\sum Data\ Sent\ (bits) = TotalSentPkts \times\ PktSize\ \times 8 \quad (4)$$

- Packet Loss, which quantifies the percentage of packets lost during transmission, is determined using Eq. (5).

$$PktLoss(\%) = \frac{\sum Sent\ Pkts - \sum Rcv\ Pkts}{\sum Sent\ Pkts} \quad (5)$$

To evaluate the overall network performance, the average values of each QoS metric are computed across all packets. The formula for average delay is shown in Eq. (6), average throughput in Eq. (7), and average packet loss percentage in Eq. (8).

- The average delay is computed as:

$$Avg.Delay = \frac{\sum_{i=1}^{n} Delay_i}{n} \quad (6)$$

where n represents the total number of packets sent.

- The average throughput is calculated using:

$$Avg.Throughput = \frac{\sum_{i=1}^{n} Throughput_i}{n} \quad (7)$$

- The average packet loss percentage is determined as follows:

$$Avg.Packet\ Loss = \frac{\sum_{i=1}^{n} Packet\ Loss_i}{n} \quad (8)$$

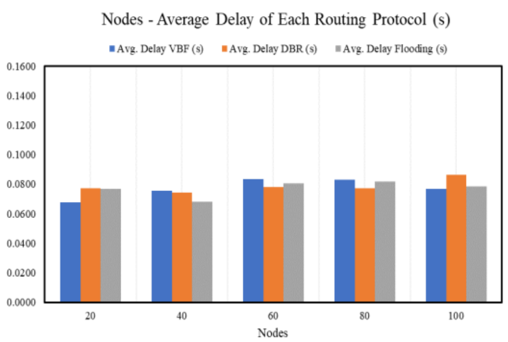
4. Results and Discussions

This section presents a comprehensive analysis of the three routing protocols—Vector-Based Forwarding (VBF), Depth-Based Routing (DBR), and Flood Routing—across various node density, distance distribution, and depth variation scenarios. The evaluation focuses on Quality of Service (QoS) metrics, including delay, throughput, and packet loss, to provide a quantitative assessment of their effectiveness.

4.1 Average Delay

Figure 2 illustrates the average end-to-end delay of the three evaluated routing protocols—VBF, DBR, and Flood Routing—under varying conditions of node density, communication distance, and deployment depth. In underwater sensor networks, minimizing transmission delay is critical for time-sensitive operations such as marine exploration, seismic event detection, and underwater hazard monitoring, where rapid and reliable data delivery is essential. Among the three protocols, VBF consistently achieves the lowest average delay, reflecting its efficiency in reducing redundant retransmissions and minimizing congestion through selective forwarding within its virtual pipeline. The delay for VBF begins at approximately 0.0676 s with 20 nodes, increases slightly to 0.0835 s at 60 nodes, and then decreases again to 0.0769 s at 100 nodes as the network becomes denser and routing paths stabilize. In comparison, DBR demonstrates higher latency, with values ranging from 0.0743 s at moderate densities to 0.1420 s in deeper deployments (151–200 m). This increase stems from DBR's depth-based holding time mechanism, which deliberately delays forwarding to prioritize nodes with shallower depths, consequently extending total transmission time.

Flood Routing records the highest overall delay, increasing from 0.0717 s at 50 meters to 0.1063 s at 200 meters. The excessive delay arises from redundant packet broadcasting and channel contention, both of which intensify with node density and propagation distance. Overall, these results confirm that VBF offers superior delay performance across all tested conditions, making it the most suitable choice for real-time and delay-sensitive underwater applications. In contrast, DBR and Flood Routing exhibit greater latency overheads, which limit their applicability in mission-critical or time-constrained underwater communication scenarios.



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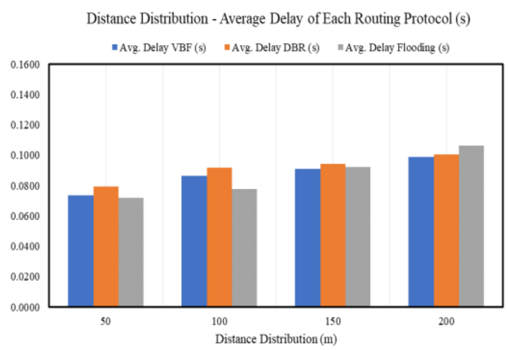

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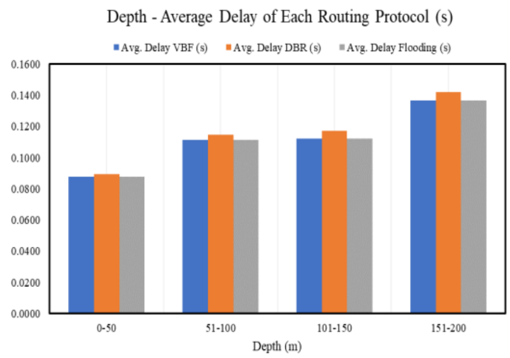

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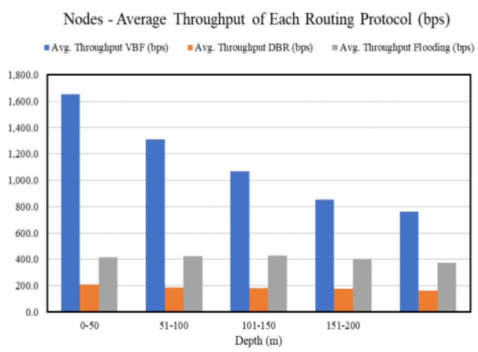
Fig. 2. Average delay: (a) node densities, (b) distance distributions, (c) depth levels

4.2 Average Throughput

Figure 3 depicts the throughput performance of the three routing protocols—VBF, DBR, and Flood Routing—under varying network conditions. Throughput serves as a critical performance indicator for high-data-demand underwater applications, such as seismic monitoring, oceanographic sensing, and environmental analysis, where sustained data delivery rates are vital for reliable observation and real-time decision-making.

Across all evaluated scenarios, VBF consistently achieves the highest throughput, reflecting its superior capability in managing packet forwarding and minimizing redundant transmissions. VBF's throughput begins at approximately 1653.13 bps for 20 nodes and gradually declines to 764.48 bps at 100 nodes, primarily due to increased network congestion as density rises. Despite this reduction, VBF maintains stable performance across communication distances—1074.68 bps at 50 meters and improving to 1309.97 bps at 200 meters—showing that larger transmission ranges enhance connectivity within its virtual forwarding pipe. In depth-based scenarios, VBF reaches its peak throughput of 1772.80 bps at depths of 51–100 meters, maintaining robust data flow even at greater depths.

In contrast, DBR exhibits consistently lower throughput, ranging from 209.40 bps at 20 nodes to 163.12 bps at 100 nodes. This reduction stems from DBR's depth-based forwarding constraint, which restricts the number of eligible forwarding nodes and consequently limits the overall data delivery rate. Flood Routing demonstrates moderate performance, with throughput fluctuating between 416.87 bps at 20 nodes and 429.60 bps at 60 nodes before declining to 375.48 bps at 100 nodes. Although its broadcast-based mechanism enhances packet delivery reliability, excessive redundant transmissions and channel contention significantly lower its effective throughput. Overall, the results confirm that VBF offers the most favorable balance between throughput and latency, enabling efficient and reliable data transmission across varying underwater conditions. This makes VBF particularly suitable for bandwidth-sensitive or real-time underwater applications, whereas DBR and Flood Routing are better suited for low-rate or delay-tolerant monitoring tasks.



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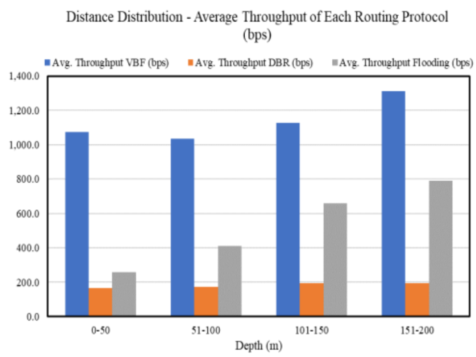

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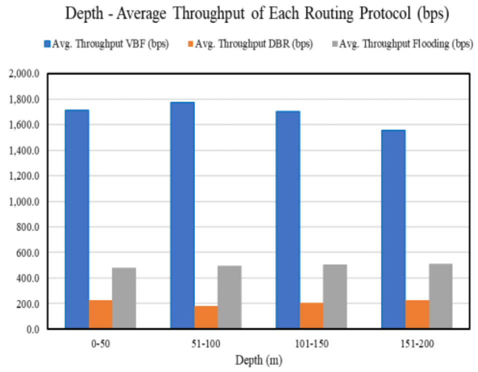

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Fig. 3. Average throughput: (a) node densities, (b) distance distributions, (c) depth levels

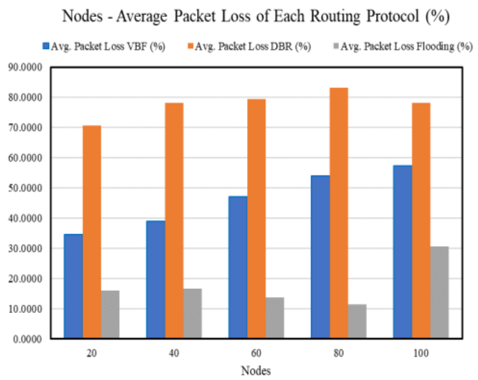
4.3 Average Packet Loss

Figure 4 illustrates the packet loss performance of the three evaluated routing protocols—VBF, DBR, and Flood Routing—across various underwater network scenarios. Packet loss is a critical performance indicator for deep-sea exploration and long-range underwater communications, where maintaining high data integrity is essential to ensure reliable sensing, command transmission, and event reporting. VBF exhibits a moderate packet loss rate, increasing from 34.53% at 20 nodes to 57.34% at 100 nodes. This rise is primarily attributed to VBF's vector-based forwarding mechanism, which restricts forwarding to nodes within its virtual transmission pipe. While this constraint minimizes redundant transmissions and reduces congestion, it also causes packets located outside the pipe to be dropped—particularly in sparse or irregular node distributions.

DBR demonstrates the highest packet loss, ranging from 70.63% at 20 nodes to 85% at a 50-meter depth. The elevated loss ratio results from DBR's strict depth-based forwarding rule, which prioritizes nodes with shallower depths but lacks adaptability to link variations or topology dynamics. Consequently, packets may fail to reach suitable forwarders when network conditions fluctuate, especially in deeper or sparser deployments. Conversely, Flood Routing achieves the lowest packet loss among the three protocols. Its loss rate begins at 16.09% with 20 nodes, drops to 11.41% at 80 nodes, and slightly rises to 30.63% at 100 nodes as congestion increases. The broadcast-based nature of Flood Routing enhances delivery reliability by creating multiple redundant paths, ensuring that at least one copy of the packet reaches the sink even under poor channel conditions. Overall, these findings highlight a fundamental reliability–efficiency trade-off: Flood Routing provides the most reliable packet delivery but incurs substantial overhead in terms of delay and energy consumption. In contrast, VBF offers a balanced compromise between reliability and efficiency, making it suitable for real-time or medium-density underwater networks, while DBR's performance is more favorable in dense, stable deployments with limited mobility.

4.4 Overall Protocol Performance

The comparison of delay, throughput, and packet loss provides insights into the strengths and weaknesses of each protocol. VBF achieves the lowest delay and highest throughput, making it ideal for applications requiring fast and efficient data transfer. However, packet loss increases in dense networks due to its strict routing pipe mechanism. DBR exhibits higher delay and significant packet loss, limiting its scalability and reliability in dynamic environments. Flood Routing ensures high packet delivery success, but at the cost of increased delay and redundant transmissions, leading to inefficient resource utilization.



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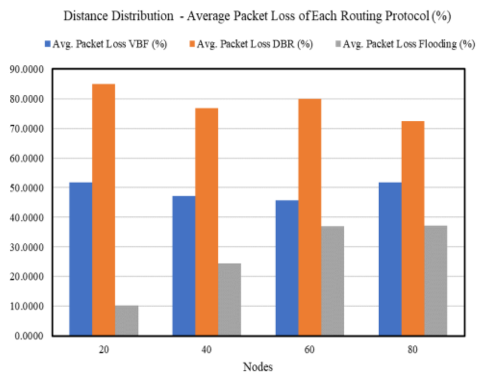

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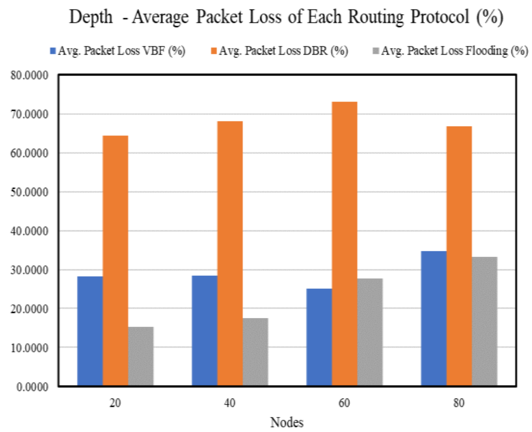

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Fig. 4. Average packet loss: (a) node densities, (b) distance distributions, (c) depth levels

The density results confirm that VBF offers the best delay-throughput balance in moderately dense networks, while Flood is only beneficial in sparse deployments demanding reliability. DBR trades efficiency for simplicity but lacks scalability as redundancy increases with node count. For real-time underwater surveillance or tactical sensing, VBF's predictable latency makes it superior; for sparse environmental monitoring, Flood ensures data completeness. VBF's topology awareness enables robust adaptation to range variations: as the virtual pipe dynamically incorporates reachable nodes, it sustains connectivity even under attenuating conditions. DBR's simplistic reliance on depth results in suboptimal next-hop choices when link quality degrades laterally. Flood Routing's reliability comes at prohibitive energy cost, acceptable only when transmission reliability outweighs lifetime concerns. These results effect of node depth emphasize the depth-resilience of VBF: its topology-awareness and geometric constraint minimize unnecessary lateral transmissions. DBR's pure depth-based criterion overlooks lateral geometry, leading to inefficient "ping-pong" forwarding. Flood Routing's broad rebroadcasting offsets attenuation but sacrifices efficiency. In deep-sea deployments with low data rates and power constraints, DBR or Flood may still be viable if energy harvesting or duty-cycling mitigates overhead.

The comprehensive analysis across node density, communication range, and depth scenarios confirms that VBF provides the best trade-off between efficiency and reliability, outperforming DBR and Flood Routing in most conditions. Flood Routing remains indispensable in sparse or high-error environments, while DBR is suited for energy-stable, dense deployments. AI (Artificial Intelligence)-Driven adaptive routing research (Rehman et al., 2025; Shovon et al., 2023; Y. Yuan et al., 2024; Z. Zhao et al., 2023; Liu et al., 2025) is one of promising methods to improve aquatic algorithm on underwater wireless routing beyond surface, including cross layer scheme using physical layer matters such as signal to noise ratio and antennas selection diversity

(He, J et al., 2024; Triwinarko et al., 2020; Istikmal et al., 2017, 2018). These insights form the foundation for future hybrid and adaptive routing designs aiming to balance delay, throughput, and energy in underwater acoustic networks.

5. Conclusion

This study presents a comprehensive performance evaluation of three fundamental Underwater Wireless Sensor Network (UWSN) routing protocols—Vector-Based Forwarding (VBF), Depth-Based Routing (DBR), and Flood Routing—through systematic analysis of delay, throughput, and packet loss metrics. The results demonstrate that each protocol exhibits distinct operational strengths and weaknesses, making them suitable for specific underwater communication scenarios. VBF consistently delivers superior performance in terms of delay and throughput, confirming its effectiveness for real-time and high-bandwidth underwater applications. However, its reliance on a constrained forwarding pipe leads to higher packet loss in dense deployments, limiting its reliability in highly congested or irregular topologies. DBR, while providing moderate delay performance, experiences substantial packet loss due to its rigid depth-based forwarding mechanism, suggesting that depth awareness alone is insufficient to ensure data integrity in dynamic aquatic environments. Conversely, Flood Routing achieves the lowest packet loss rate, ensuring robust packet delivery, but this reliability comes at the expense of increased delay and energy inefficiency resulting from excessive redundant transmissions. The scientific contribution of this research lies in its unified and statistically validated comparison of UWSN routing protocols under identical simulation parameters—bridging the gap between theoretical performance analysis and practical deployment insights. Unlike many previous studies that examined individual protocols in isolation, this work establishes a consistent experimental framework that elucidates the trade-offs among energy efficiency, scalability, and reliability in underwater acoustic communication. While the current findings provide quantitative insights into protocol behavior under varying conditions, further research is warranted to enhance routing adaptability and resilience. Future work should explore hybrid and adaptive routing architectures that dynamically combine the strengths of VBF, DBR, and Flood Routing based on real-time network conditions. Moreover, cross layer scheme using physical layer matters such as signal to noise ratio and antennas selection diversity and the integration of machine learning techniques holds significant promise for developing intelligent, energy-aware, and low-latency routing algorithms, paving the way toward more autonomous and efficient underwater communication networks.

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