A Comprehensive Survey of Routing Protocols for Underwater Wireless Sensor Networks

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Abstract

Underwater Wireless Sensor Networks (UWSNs) have attracted significant research interest due to their broad applications in ocean exploration, environmental monitoring, disaster prevention, and military surveillance. The unique characteristics of the underwater environment—such as high propagation delay, limited bandwidth, node mobility, and energy constraints—pose great challenges for reliable and efficient data delivery. Routing protocols play a crucial role in addressing these challenges by determining optimal paths from underwater nodes to surface sinks. This paper presents a comprehensive survey of recent routing protocols for UWSNs. The protocols are classified into two main categories: localization-based and localization-free protocols. Each category is further subdivided based on the specific problems they address, including node mobility, energy balancing, channel impairment, energy consumption, and void zone handling. For each protocol, we describe its routing strategy, merits, and limitations. In addition, we highlight emerging trends such as hybrid acoustic-optical communication, reinforcement learning-based routing, and multi-objective optimization. Finally, open research challenges and future directions are discussed.

Keywords

Underwater Wireless Sensor Networks; Routing Protocols; Localization-based; Localization-free; Acoustic Communication; Optical Communication; Hybrid Routing; Void Handling; Energy Efficiency.

1. Introduction

Oceans cover more than 70% of the Earth's surface and contain abundant biological and mineral resources. Underwater Wireless Sensor Networks (UWSNs) have emerged as a key technology for exploring and monitoring these underwater environments [1]. Typical applications include oceanographic data collection, pollution monitoring, offshore exploration, disaster warning, and tactical surveillance [2]. In UWSNs, sensor nodes are deployed at different depths to sense physical parameters and transmit data to one or more surface sinks via multi-hop communication.

The underwater communication channel is extremely challenging. Radio frequency (RF) waves suffer from high attenuation in water, limiting their use to very short ranges [3]. Optical waves offer high bandwidth and low latency but are severely affected by absorption and scattering, and require precise alignment [4]. Acoustic waves are the most commonly used medium for underwater communications due to their relatively low attenuation, but they suffer from low propagation speed (≈1500 m/s), limited bandwidth, and high multipath delay [5]. Moreover, sensor nodes are energy-constrained and their batteries are difficult to replace. Node mobility caused by water currents further complicates the network topology [6].

Routing protocols for UWSNs are designed to cope with these challenges. They determine how data packets are forwarded from the seabed to the surface sinks efficiently and reliably. Over the past two decades, numerous routing protocols have been proposed. This survey aims to provide a systematic overview of the state-of-the-art routing protocols for UWSNs, with a focus on recent advances. Unlike existing surveys, we integrate both classical protocols and the latest developments, including hybrid acoustic-optical routing, reinforcement learning-based approaches, and void handling mechanisms.

The remainder of this paper is organized as follows. Section 2 outlines the major challenges in underwater communications. Section 3 presents a taxonomy of routing protocols, divided into localization-based and localization-free categories, with further subdivisions according to the problems addressed. Section 4 highlights recent advances in hybrid and optical routing, as well as intelligent routing schemes. Section 5 provides a comparative discussion. Section 6 concludes the paper and identifies future research directions..

2. Challenges in Underwater Communications

Underwater communications face several intrinsic challenges that directly impact the design of routing protocols:

·High Propagation Delay: The speed of sound in water is about 1500 m/s, five orders of magnitude slower than radio waves. This results in large end-to-end delays and makes handshaking-based protocols inefficient [7].

· Limited Bandwidth: The acoustic channel has a severely limited bandwidth, typically from a few kHz to tens of kHz, which restricts data rates [8].

·High Attenuation and Noise: Acoustic signals experience absorption loss and spreading loss. Ambient noise from shipping, waves, and marine life further degrades signal quality [9].

·Energy Constraints: Sensor nodes are battery-powered and energy replenishment is difficult. Energy-efficient operation is crucial for network longevity [10].

·Node Mobility: Underwater nodes drift with currents, causing dynamic topology changes. Routing protocols must adapt to these changes without excessive overhead [11].

·Void Regions: A void (or hole) occurs when a node has no neighbor closer to the sink, causing packet drops. Void handling is a critical issue in geographic routing [12].

·Mixed Communication Media: Recent research explores hybrid acoustic-optical systems to combine the long range of acoustics with the high bandwidth of optics. This introduces new challenges in media selection and switching [13].

These challenges motivate the development of specialized routing protocols for UWSNs..

3. Literature References

Routing protocols for UWSNs can be broadly classified into two categories: localization-based and localization-free protocols. Localization-based protocols require the knowledge of node coordinates (2D or 3D) to make routing decisions, while localization-free protocols rely only on depth information obtained from pressure sensors. Each category is further subdivided according to the primary problem they address: node mobility, energy balancing, channel conditions, energy consumption, or void zone handling.

3.1. Localization-Based Routing Protocols

Localization-based protocols use geographic coordinates of nodes to establish routing paths. They can achieve optimal paths but incur overhead for localization and are sensitive to positioning errors. .

3.1.1. Protocols Addressing Node Mobility

VBF (Vector-Based Forwarding) [14] is a pioneering protocol that defines a virtual pipe from source to sink. Only nodes within the pipe participate in forwarding, which reduces energy consumption and improves scalability. However, nodes inside the pipe are heavily loaded and die quickly, creating energy holes. Moreover, in sparse networks, the pipe may contain no forwarders.

SBR-DLP (Sector-Based Routing with Destination Location Prediction) [15] makes the destination node mobile. Nodes know only their own positions and predict the destination's movement pattern. The source's transmission range is divided into sectors, and nodes in the sector toward the destination are prioritized. This improves throughput but introduces high delay because nodes must wait for the mobile sink.

NEFP (Novel Efficient Forwarding Protocol) [16] combines a forwarding zone, holding time, and Markov chains to estimate forwarding probability. It works well in dense networks but degrades in sparse conditions.

TC-VBF (Topology Control VBF) [17] extends VBF by considering network density for forwarder selection, but it inherits VBF's limitations.

LBDR (Localization-Based Dynamic Routing) [18] divides the network into layers and constructs a routing pipe that adapts to node movement. It achieves high throughput but nodes in the pipe remain overloaded if new nodes do not enter frequently.

3.1.2. Protocols Addressing Energy Balancing

HH-VBF (Hop-by-Hop VBF) [19] creates a separate pipe for each forwarder instead of one global pipe, distributing the load more evenly. However, defining per-hop pipes increases computational delay, and nodes in pipes are still preferred.

REBAR (Reliable and Energy-Balanced Routing) [20] builds an adaptive cylindrical path whose radius decreases near the sink to involve fewer nodes, thus protecting near-sink nodes from early death. It also handles voids via neighbor broadcast. However, position calculation overhead increases with mobility.

BEAR (Balanced Energy Adaptive Routing) [21] divides a hemispherical network into sectors of equal radii. Nodes closer to the sink are assigned more power and higher density to balance energy consumption. The protocol prolongs lifetime but suffers from high interference near the sink.

MDA-SL (Message Dissemination for Storage-Limited UWSNs) [22] forwards packets to nodes with high mobility or residual energy. Throughput is optimized but such nodes die rapidly, creating energy holes.

NGF (New Greedy Forwarding) [23] splits packets among multiple forwarders using the Chinese Remainder Theorem to balance load. This reduces per-node load but increases interference.

3.1.3. Protocols Mitigating Channel Conditions

DFR (Directional Flooding-Based Routing) [24] restricts flooding to a zone defined by the angle among source, forwarder, and sink. It uses link quality to select the best forwarder. Redundant transmissions are a major drawback.

QoSDFR (QoS-Aware DFR) [25] improves DFR by having the sink provide feedback on link quality, eliminating per-node link computation. This saves energy but increases delay due to feedback waiting.

LASR (Location-Aware Source Routing) [26] modifies DSR to incorporate link quality and node position awareness. It selects paths with minimal noise and interference. However, route updates may be delayed due to high propagation delay, leading to stale information.

SMIC (Sink Mobility with Incremental Cooperative Routing) [27] uses amplify-and-forward cooperative communication with a mobile sink. Throughput and lifetime improve, but cooperative transmission doubles energy consumption.

EGRCs (Energy-Efficient Grid Routing Based on 3D Cubes) [28] partitions the network into cubic clusters with cluster heads and relays selected based on residual energy, position, and delay. Performance degrades when cluster heads die.

MMBR (Markov Model-Based Routing) [29] probabilistically selects stable routes with fewer hops. Node mobility causes position errors.

EEIAR (Energy-Efficient Interference-Aware Routing) [30] selects forwarders with the shortest path and fewest neighbors to minimize interference and delay. Nodes near the surface die quickly.

3.1.4. Protocols Addressing Energy Consumption

FBR (Focused Beam Routing) [31] uses a dynamic cone and multiple power levels. The source starts with low power and increases it until a suitable relay is found within the cone. This saves energy but may fail in sparse networks.

MC (Maximum Coverage) [32] uses two mobile sinks moving in circles to collect data. It balances energy and reduces packet loss, but delay is high because sinks do not prioritize nodes with data.

BEEC (Balanced Energy-Efficient Circular Routing) [33] divides a circular network into sectors with two mobile sinks. Throughput is high, but performance suffers in sparse conditions.

MEES (Mobile Energy-Efficient Square Routing) [34] employs two mobile sinks moving linearly. It improves energy efficiency but causes packet drops when sinks are out of range.

LOTUS (Low-Overhead Localization Technique) [35] uses only two reference nodes for localization, aiding sparse networks, but increases positioning error.

GDflood (Geographical Duplicate-Reduction Flooding) [36] combines localization with network coding to reduce duplicates and energy consumption. End-to-end delay increases due to acknowledgments.

DTMR (Direct Transmission or Mobile Relay) [37] chooses between direct transmission and mobile relay to reduce signaling overhead. Direct transmission may lack reliability.

FVBF (Fuzzy Logic VBF) [38] selects forwarders based on valid distance, projection, and battery level using fuzzy logic. It improves energy and delay efficiency but overloads pipe nodes.

3.1.5. Protocols Addressing Void Region

AVN-AHH-VBF (Avoiding Void Node with Adaptive Hop-by-Hop VBF) [39] enhances VBF by checking for void regions before forwarding. It reduces energy consumption but at the cost of packet loss.

OVAR (Opportunistic Void Avoidance Routing) [40] uses opportunistic routing and adjusts the forwarder set based on packet delivery probability and advancement. Throughput improves but energy imbalance persists.

GEDAR (Geographic and Opportunistic Routing with Depth Adjustment) [41] combines greedy forwarding with opportunistic routing and depth adjustment to recover from voids. It selects forwarders based on packet advancement. Energy imbalance near the sink remains an issue.

EHCAR (Energy Hole and Coverage Avoidance Routing) [42] allows nodes with low energy to broadcast their status, prompting high-energy neighbors to move and fill the void. This may cause false position estimates due to delay and mobility.

PAM (Position-Aware Mobility of AUVs) [43] predefines paths for AUVs to avoid voids. It ensures coverage but consumes high energy when AUVs are far apart.

FLMPC (Forward Layered Multipath Power Control) [44] ensures a forwarder has at least two or three hops of neighbors before selection, avoiding voids. Checking neighbor depth increases delay.

VBVA (Vector-Based Void Avoidance) [45] uses vector shift and back-pressure to route along void boundaries. It provides reliable delivery but incurs extra energy and delay.

3.2. Localization-Free Routing Protocols

Localization-free protocols use depth information instead of full coordinates. They are more scalable and simpler to deploy. Table 2 summarizes key localization-free protocols.

3.2.1. Protocols Addressing Node Mobility

DBR (Depth-Based Routing) [46] is the first localization-free protocol. Nodes forward packets only if they have lower depth (closer to surface) than the previous node. It uses holding time to reduce collisions. DBR achieves good PDR but suffers from redundant transmissions and rapid death of near-surface nodes.

DSRP (Distributed Delay-Sensitive Routing Protocol) [47] considers node velocity and position changes under the random waypoint model. It shows that high mobility increases throughput at the cost of higher energy and delay.

3.2.2. Protocols Addressing Energy Balancing

EEDBR (Energy-Efficient Depth-Based Routing) [48] adds residual energy to DBR's forwarder selection. The sender chooses a neighbor with lowest depth and highest energy. This balances energy but does not guarantee reliability as only one copy is sent.

ODBR (Optimized Depth-Based Routing) [49] assigns initial energy proportional to depth (more energy to shallower nodes). This prolongs lifetime but only works in shallow water.

EBECRP (Energy-Efficient and Balanced Energy Consumption Cluster-Based Routing) [50] divides the network into sectors with cluster heads and two mobile sinks. It saves energy but cluster head movement/mortality causes packet loss.

Hydrocast [51] uses pressure information for opportunistic forwarding and includes a dead-recovery method. It achieves energy balance but struggles in sparse conditions.

OMR (Optimal Multimodal Routing) [52] combines acoustic and RF, selecting the appropriate mode to avoid bottlenecks. Throughput is high but RF is unsuitable for long range.

3.2.3. Protocols Mitigating Channel Conditions

DEAC (Depth- and Energy-Aware Cooperative Routing) [53] uses cooperative communication with an adaptive depth threshold. It improves reliability but consumes more energy.

DBR-NC [54] adds network coding to DBR to improve reliability and energy efficiency. It assumes an ideal MAC layer, limiting practicality.

QERP [55] employs a genetic algorithm to form clusters and select routes based on QoS metrics. It improves PDR and delay but cluster heads die early.

RIAR (Reliable and Interference-Aware Routing) [56] selects a relay based on hop count, neighbor count, and distance. It works well in sparse nets but near-surface nodes die quickly.

EEIRA (Energy-Efficient Interference- and Route-Aware Routing) [57] chooses forwarders with lowest depth and fewest neighbors to reduce interference. Performance drops in sparse nets.

ECOR (Energy-Efficient Cooperative Opportunistic Routing) [58] uses fuzzy logic to select forwarder sets in cooperative opportunistic routing. It enhances reliability but adds delay.

RRSS (Routing Based on Received Signal Strength) [59] uses beacon signal strength to select forwarders within a vector. It improves energy and delay but overloads vector nodes.

3.2.4. Protocols Addressing Energy Consumption

DRADS (Depth- and Reliability-Aware Delay-Sensitive Routing) [60] combines depth and link state in opportunistic routing. It reduces energy but low-depth nodes die early.

DBR-MAC [61] prioritizes low-depth nodes for channel access based on angle, depth, and overhead. This improves throughput but unbalances energy.

E-CARP [62] is an enhanced version of CARP that is localization-free and forwards packets greedily when conditions are stable. It saves energy but increases delay.

SOR (Self-Organized Routing) [63] forms strings from nodes to the gateway in a radial network. It reduces unnecessary forwarding and delay, but a node death in a string causes packet loss.

DVRP (Diagonal and Vertical Routing Protocol) [64] uses an adjustable angle to limit forwarders, reducing energy consumption. Performance degrades when sink count increases.

DUCS (Distributed Underwater Clustering Scheme) [65] forms clusters with cluster heads for data aggregation and forwarding. It saves energy but cluster heads are overloaded and mobility disrupts clusters.

UMDR (Underwater Multi-Path Routing with Directional Antenna) [66] divides the network into sectors using directional antennas to reduce interference and broadcast. It requires frequent next-hop and antenna information, increasing complexity.

3.2.5. Protocols Addressing Void Region

EBPR (Energy Balanced Pressure Routing) [67] uses beacon feedback and residual energy to avoid voids. It extends lifetime but beaconing is ineffective in sparse nets.

CARP [68] is channel-aware and uses transmission history and power control to avoid voids and shadow zones. It performs well but delay increases in dense nets due to history checking.

LF-IEHM [69] combines variable transmission range and unique holding time to avoid energy holes and interference. It achieves high throughput at the cost of high energy.

3.3. Optical Routing with Multi-Objective Optimization

Pure optical routing is attractive for high-rate applications but faces challenges due to directional beams and limited range.

DS (Distributed Sector-based Routing) [70] selects forwarders within a sector based on minimal BER. It has low delay but few candidates in sparse nets.

DSS (Distributed Sweeping-and-Sector-based Routing) [70] adds a sweeping mechanism to increase candidates, improving PDR at the cost of higher BER.

DEEB (Energy-Efficient Routing for Underwater Wireless Optical Sensor Networks) [71] selects relays with minimal virtual power consumption, balancing energy.

DMRL (Multi-Agent Reinforcement Learning for Optical Routing) [72] uses distributed Q-learning with global reward to optimize lifetime and adaptability.

SectOR (Sector-based Opportunistic Routing) [73] develops candidate selection and prioritization based on distance progress, achieving near-optimal performance.

DHTA (Dual-Hop Topology-Aware Routing) [74] reduces void probability by considering available distance and direction deviation.

3.4. Hybrid Acoustic-Optical Routing

Recent years have witnessed growing interest in hybrid acoustic-optical systems and the application of machine learning to underwater routing.Hybrid routing leverages the complementary strengths of acoustic and optical communications: acoustics provide long range and omni-directionality, while optics offer high bandwidth and low latency. Several hybrid protocols have been proposed:

PHVP (Packet Hierarchy and Void Processing) [75] classifies data packets into important and normal based on historical distribution. Important packets are sent via optical links for low delay, while normal packets use acoustic links. It also introduces a two-level void handling mechanism: first, adjust the optical divergence angle to find more neighbors; if still no forwarder, switch to acoustic mode. This improves PDR and energy efficiency.

MURAO (Multi-level Routing for Acoustic-Optical Hybrid UWSNs) [76] organizes the network into groups with group heads managing routing. It uses Q-learning for adaptive path selection, improving robustness and reducing delay.

CAPTAIN (Data Collection for Underwater Optical-Acoustic Sensor Networks) [77] uses clustering: intra-cluster communication via optics, inter-cluster via acoustics. This reduces energy consumption significantly.

CRPOA (Cooperative Routing Based on Q-Learning for Hybrid Networks) [78] models energy and delay for both media and applies Q-learning to select relays. It balances energy and improves PDR.

PCAQR (Power Control Aided Q-Learning Routing) [79] adds power control to the Q-learning framework, further optimizing energy efficiency.

3.5. Intelligent Routing Based on Reinforcement Learning

Reinforcement learning, especially Q-learning, has been widely adopted in UWSN routing due to its ability to adapt to dynamic environments.DQIR (Deep Q-Network-based Intelligent Routing) [80] applies deep Q-learning to acoustic routing, using reward functions based on residual energy and depth to select next hops.QACR (Q-learning-based Accelerating Convergence Routing) [81] introduces layer-based Q-value initialization and adaptive discount factors to speed up convergence in dynamic UWSNs.These intelligent approaches demonstrate superior adaptability and performance compared to traditional heuristic protocols.

4. Comparison and Discussion

(1)Localization-Based vs. Localization-Free

Localization-based protocols can achieve more optimal paths but require extra energy and hardware for positioning. They are suitable for applications where precise location is needed (e.g., target tracking). Localization-free protocols are simpler, more scalable, and resilient to mobility, making them ideal for large-scale monitoring.

(2)Acoustic vs. Optical vs. Hybrid

Acoustic protocols are mature and reliable for long-range communication but suffer from low data rate and high delay. Optical protocols offer high speed but are limited by range and alignment. Hybrid protocols attempt to get the best of both worlds by switching or combining media based on context. However, they introduce complexity in media selection and coordination.

(3)Void Handling

Void handling is critical for maintaining PDR. Approaches range from backpressure (VBVA) to opportunistic forwarding (OVAR, GEDAR) to adaptive beam adjustment (PHVP). No single solution works best in all scenarios; hybrid methods appear promising.

(4) Energy Efficiency

Most protocols aim to reduce energy consumption through limiting forwarding nodes (VBF, FBR), balancing load (EEDBR, REBAR), or using sleep modes. Reinforcement learning-based protocols optimize energy adaptively.

(5)Intelligent Routing

Reinforcement learning enables nodes to learn optimal policies from experience. However, convergence time and computational overhead remain challenges. Multi-agent and transfer learning may address these issues.

5. Conclusion and Future Directions

This survey has provided a comprehensive overview of routing protocols for UWSNs, covering both classical and recent advances. Protocols are categorized based on localization requirements and the primary problems they address. Emerging trends include hybrid acoustic-optical communication, reinforcement learning-based routing, and multi-objective optimization. Despite significant progress, several open challenges remain:

Accurate channel modeling: Empirical models need refinement; data-driven and machine learning-based models could improve prediction.

Cross-layer design: Combining routing with MAC and physical layer parameters can optimize performance holistically.

Scalability and mobility: Protocols must efficiently handle large-scale deployments and high node mobility.

Energy harvesting: Integrating energy harvesting techniques can extend network lifetime.

Security: Underwater networks are vulnerable to attacks; secure routing protocols are urgently needed.

Real-world experimentation: Most protocols are evaluated only in simulation; field trials are necessary to validate performance.

Future research should focus on developing adaptive, intelligent, and cross-layer optimized routing solutions that can operate effectively in the harsh and dynamic underwater environment.

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