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A Survey of Routing Protocols for Underwater Wireless Sensor Networks: Classification, Performance, and Future Directions

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ABSTRACT
This paper comprehensively reviews the research progress of routing protocols for Underwater Wireless Sensor Networks (UWSNs). It proposes a classification framework based on design objectives and decision-making mechanisms, categorizing existing protocols into three primary types: energy-aware, data-centric, and geography-aware. The paper provides an in-depth analysis of the typical mechanisms, performance characteristics, and applicable scenarios for each category, highlighting persistent key challenges such as dynamic network topologies, energy imbalance, and localization inaccuracies. Building on this analysis, future research directions are outlined, including cross-layer and cross-domain collaborative optimization, knowledge-driven self-evolving routing, digital-twin platforms for sea trials, and green ultra-cell architectures. The aim is to advance the development of UWSN routing protocols towards highly efficient, intelligent, and practical solutions.
Keywords: *Underwater wireless sensor networks; routing protocols; energy efficiency; performance analysis*

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I. INTRODUCTION

The growing global demand for ocean resource exploitation, environmental monitoring, and disaster warning has positioned Underwater Wireless Sensor Networks (UWSNs) as a critical infrastructure supporting marine intelligent development. Consequently, UWSNs have emerged as a prominent research hotspot garnering significant attention from both academia and industry. By deploying sensor nodes equipped with sensing, computing, and communication capabilities underwater, UWSNs facilitate the real-time collection and transmission of marine environmental parameters—such as temperature, salinity, current velocity, and pressure. Their applications span diverse fields including marine ecological monitoring, seabed resource exploration, pollution tracing, tsunami warning, and military reconnaissance.

However, the complexity and uniqueness of the underwater environment pose numerous formidable challenges for UWSNs in terms of communication mechanisms, network architecture, and energy management, distinctly differentiating them from traditional Terrestrial Wireless Sensor Networks. Firstly, underwater communication primarily relies on acoustic waves for data transmission. Acoustic waves propagate much slower in water than radio waves, resulting in high communication latency, limited bandwidth, and susceptibility to multipath effects, Doppler shift, and ambient noise. These factors severely impact link stability and data transmission reliability. Secondly, underwater nodes typically drift with ocean currents, exhibiting significant three-dimensional mobility. This leads to frequent dynamic changes in network topology and complicates routing path maintenance. Furthermore, underwater nodes are mostly battery-powered and are difficult to replace or recharge once deployed, rendering energy resources extremely limited. Thus, a core challenge in UWSN routing protocol design lies in prolonging the network lifetime while ensuring communication quality.

Routing protocols, serving as the key technology for efficient data transmission from source nodes to the sink node in UWSNs, directly determine the overall network performance in terms of energy efficiency, latency, throughput, and stability. In recent years, researchers have proposed various types of routing protocols tailored to the specific requirements of UWSNs. Based on their design objectives and decision-making mechanisms, existing protocols can be broadly categorized into three types: energy-optimized routing protocols, data-centric routing protocols, and geographic information-based routing protocols. Energy-oriented protocols focus on reducing energy consumption and extending network lifetime through strategies such as cluster head rotation, path optimization, and load balancing. Data-centric protocols emphasize data transmission reliability, integrity, and timeliness, often incorporating mechanisms like data negotiation, opportunistic forwarding, and priority scheduling. Geographic protocols utilize node location information—such as depth, coordinates, or angles—to achieve low-overhead, high-efficiency path selection, adapting to dynamic topology changes.

Although significant progress has been made in UWSN routing protocol research in recent years, numerous critical issues remain unresolved. For instance, frequent routing path breaks caused by node mobility, the "energy hole" problem resulting from unbalanced energy consumption, the routing void phenomenon in sparsely deployed areas, the impact of localization errors on geographic routing performance, and the lack of unified, realistic ocean testing platforms all constrain the practicality and scalability of existing protocols.

Therefore, this paper aims to systematically review recent advances in UWSN routing protocols, establish a classification framework, and conduct an analysis of the design principles, operational mechanisms, and performance characteristics of various protocol categories. It also identifies shortcomings in current research and highlights existing challenges. Building on this analysis, the paper outlines prospective future research directions. Through this survey, we hope to provide researchers with a clear understanding of the research landscape and technical references, thereby promoting the continued evolution of UWSN routing protocols towards higher efficiency, intelligence, and adaptability to complex underwater environments.

II. Routing Protocol Taxonomy for UWSNs

To systematically organize the research landscape of routing protocols for Underwater Wireless Sensor Networks (UWSNs), this paper proposes a classification framework based on a dual consideration of design objectives and decision-making mechanisms, building upon a synthesis of existing literature. This framework categorizes UWSN routing protocols into three primary classes: Energy-driven, Data-centric, and Geography-aware. Each category addresses specific challenges inherent to the underwater environment, yet exhibits marked differences in optimization goals, information dependencies, and implementation complexity. The following sections elaborate on the core concepts, key design principles, and applicable scenarios for each protocol category.

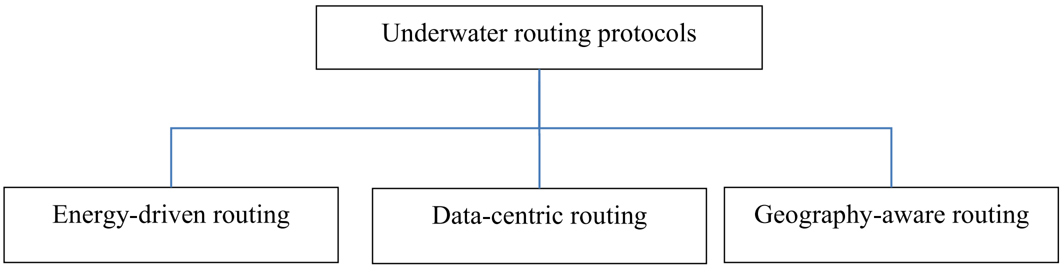

Figure1 The classification of routing protocols for underwater wireless sensor networks

2.1 Energy-driven Routing

Energy-driven protocols prioritize "prolonging network lifetime" as their primary optimization goal. Their fundamental premise is that once deployed, underwater nodes have nearly impossible energy replenishment; thus, every communication event should be treated as an irreversible energy expenditure. To reduce the overall network energy consumption rate, these protocols typically employ strategies such as "hierarchical clustering," "energy gradient awareness," or "multi-hop relaying." These strategies dynamically rotate high-energy-consumption roles (e.g., cluster heads, relays) across temporal or spatial dimensions, thereby preventing premature exhaustion of local nodes.

Typical approaches include: (1) electing cluster heads weighted by residual energy; (2) incorporating an "energy penalty factor" into forwarding decisions, preferentially delegating tasks to nodes with higher energy levels and closer proximity to the water surface; (3) utilizing intelligent algorithms like Ant Colony Optimization or reinforcement learning to offline search for energy-balanced paths. It is noteworthy that while the introduction of intelligent algorithms can enhance energy efficiency, it introduces computational and storage overheads, posing additional challenges for resource-constrained underwater nodes.

In summary, energy-driven protocols perform excellently in long-term, static, or quasi-static monitoring tasks. However, they exhibit limited adaptability to dynamic scenarios involving abrupt topology changes or high-speed node drift. Furthermore, an excessive focus on low power consumption can easily compromise end-to-end delay and data integrity, necessitating co-design with data-centric mechanisms.

2.2 Data-centric Routing

In contrast to the "conserve while transmitting" philosophy of energy-driven protocols, data-centric protocols emphasize "accurate transmission." Their core objective is to ensure high Packet Delivery Ratio (PDR), low redundancy, and differentiated real-time performance for data packets, even within the challenging acoustic channel characterized by high bit error rates, long delays, and frequent voids. To achieve this, the protocol stack typically introduces mechanisms such as "interest-data" negotiation, opportunistic forwarding, or priority scheduling, dynamically allocating network resources to "more valuable" data packets.

Based on the granularity of decision-making, these protocols can be further subdivided into three subcategories: (1) Interest-driven protocols suppress blind broadcasting through metadata handshakes, making them suitable for event-triggered sampling. However, the handshake mechanism can be exacerbated by the long propagation delays of acoustic modems, leading to increased end-to-end delay. (2) Opportunistic forwarding protocols leverage the inherent diversity gain of broadcasting, allowing multiple candidate nodes to compete for forwarding. The node that receives the packet first proceeds with broadcasting, while others automatically suppress their transmissions, thereby maintaining high robustness under dynamic topologies. (3) Priority scheduling protocols assign higher MAC layer preemption probabilities to critical data (e.g., tsunami warnings, chemical leaks), achieving "hard real-time" guarantees.

In conclusion, data-centric protocols are indispensable in scenarios highly sensitive to data integrity, such as disaster warning and military reconnaissance. However, their control overhead and computational complexity are generally higher than those of energy-driven protocols. Moreover, frequent channel listening and retransmission operations can accelerate energy depletion. Therefore, they often need to complement energy-driven mechanisms.

2.3 Geography-aware Routing

Geography-aware routing protocols utilize geographically referenced quantities obtainable by nodes—most commonly depth, but extendable to 3D coordinates or angle information—to perform lightweight, stateless routing decisions. Given the severe attenuation of GPS signals underwater, these protocols typically assume that nodes acquire their own depth via pressure sensors, supplemented by acoustic ranging or surface anchor node references to obtain relative coordinates. Their design philosophy is to substitute "geometric attributes" for "topology maintenance," thereby minimizing control overhead while supporting multi-hop forwarding, void avoidance, and mobility adaptation.

Based on the richness of the information used, they can be further classified into two subcategories: (1) Pure depth-based schemes solely utilize the "monotonically decreasing depth" principle for layer-by-layer forwarding. They are simple to implement and have extremely low overhead, suitable for high-density, rapid deployment scenarios. However, shallow nodes are prone to overuse, forming energy holes, and they lack effective remediation mechanisms for sparse regions. (2) Full coordinate-based schemes construct virtual pipelines or conical forwarding regions, restricting forwarding authority within these geometric volumes, which significantly suppresses broadcast redundancy.

The greatest advantage of geography-aware protocols lies in their "plug-and-play" nature: no global routing tables or periodic topology updates are required, and they possess inherent robustness to node mobility. However, their performance heavily depends on localization accuracy. Furthermore, coordinate-based protocols require maintaining neighbor geometry tables, incurring significantly higher storage and computational overhead compared to pure depth-based schemes.

III. Energy-driven Routing Protocols

The non-replenishable energy of underwater nodes makes "minimizing energy consumption" a rigid constraint in routing design. Existing literature commonly categorizes energy-oriented protocols into three types: "Awareness-Balancing," "Clustering-Rotation," and "Intelligent-Optimization." Following this framework, we select six representative mechanisms, focusing on analyzing their decision-making principles, energy models, and inherent limitations, thereby establishing a consistent context for subsequent cross-category comparisons.

3.1 Balancing-aware Representatives

(1) EEDBR (Energy-Efficient Depth-Based Routing)

- **Principle**: Nodes use "shallower depth and higher residual energy" as dual criteria to construct a dynamic candidate set within their neighborhood. It employs passive acknowledgments instead of network-wide flooding; each packet header only needs to carry its own depth and energy level. [1]
- **Advantages**: ① Zero localization overhead, relying solely on pressure sensors; ② Local competition within the candidate set naturally suppresses broadcast storms; ③ The dual constraints of energy and depth can delay the "overutilization of shallow nodes" phenomenon.
- **Disadvantages**: ① The candidate set size increases linearly with node density, raising the probability of conflicts; ② Static criteria respond sluggishly to topological drift, prone to "transient voids" in high-current scenarios; ③ Does not consider link asymmetry; persistent retransmissions over weak channels increase energy consumption.

(2) ER-DBR (Energy-efficient Reliable DBR)

- **Principle**: Builds upon EEDBR by introducing a "Link Quality Indicator (LQI) - Signal-to-Noise Ratio (SNR) - Packet Reception Rate (PRR)" triplet, narrowing the candidate set to "high-reliability, high-energy" frontier nodes. Employs adaptive transmission power, sending at the minimum power level that meets the PRR threshold. [2]
- **Advantages**: ① Filters out poor-quality links using physical layer metrics, reducing retransmission energy costs; ② The power fine-tuning mechanism reduces per-hop energy consumption.
- **Disadvantages**: ① The receiver needs to periodically feedback channel status, incurring additional listening energy consumption; ② Evaluating the triplet requires sampling multiple frames, causing significant delay during the cold-start phase; ③ LQI fluctuates severely in highly dynamic water; overly conservative threshold update strategies shrink the candidate space, potentially causing detours.

3.2 Clustering-Rotation Representatives

(1) MLCEE (Multi-Layer Cluster-based Energy-Efficient)

- **Principle:** Discretizes the 3D water column into iso-depth layers based on "communication range" granularity. Each layer independently executes an improved LEACH protocol, where the cluster head election function considers residual energy, intra-layer node degree, and distance to the layer boundary. Inter-layer data forwarding uses a "single-hop and multi-hop hybrid" uplink strategy. [3]
- **Advantages**: ① Hierarchical isolation confines "hotspots" to a single layer, suppressing global energy holes; ② The cluster head burden is diluted by spatial granularity, allowing shorter rotation cycles and prolonging network lifetime.
- **Disadvantages**: ① Static layer boundaries cannot adapt to sound speed profile changes caused by tides or haloclines; ② Cross-layer data must pass through "layer-boundary relays," where nodes face a high risk of premature exhaustion; ③ The cluster formation phase still requires network-wide broadcasting, with control overhead linearly proportional to the number of layers.

(2) EECMR (Energy-Efficient Clustering Multi-hop Routing)

- **Principle:** Proposes three node roles: "Cluster Head - Cluster Member - Cluster Relay (CH-CM-CR)." Node weight is determined by a linear combination of "depth, residual energy, and historical head duration." The CR role is specifically responsible for cross-layer forwarding, forming a "vertical multi-hop, horizontal clustering" hybrid topology. [4]
- **Advantages**: ① Introducing a "head duration" penalty term can suppress local hotspots caused by repeated cluster head re-election; ② The CR role offloads cross-layer traffic from CHs, achieving better balance than the traditional "layer-boundary relay" model; ③ Weight computation is local, requiring no global synchronization.
- **Disadvantages:** ① CR election relies on the intersection of JOIN messages from two layers; the CR vacancy rate increases in sparse scenarios, leading to broken vertical paths; ② Weight coefficients require offline calibration and are sensitive to different current velocity-node density combinations; ③ Three-state rotation increases state machine complexity; the MCU needs to maintain role timers, which is unfriendly to low-cost nodes.

IV. Data-centric Routing Protocols

Data-centric routing protocols prioritize the objectives of "high fidelity, low redundancy, and fast delivery." Their design logic diverges from the "conserve while transmitting" approach of energy-based protocols, focusing instead on "transmitting effectively." Confronting challenges such as high bit error rates in the acoustic channel, time-varying topologies, and frequent voids, this category of protocols seeks a balance between data integrity, timeliness, and resource overhead through mechanisms like interest negotiation, opportunistic replication, or priority scheduling. Following the storyline of "Interest-driven → Opportunistic Forwarding → Priority Scheduling," representative mechanisms are selected below to dissect their decision-making principles and inherent trade-offs.

4.1 Interest-driven Representatives

(1) SPIN (Sensor Protocol for Information via Negotiation)

- **Principle:** Before sending data, a node first broadcasts an ADV message containing a metadata summary of the data. It enters the DATA transmission phase only after receiving a REQ reply from a neighbor, forming a "hop-by-hop negotiation" chain of semantic handshakes. [5]

- **Advantages**: ① Replaces raw data with metadata, potentially pruning irrelevant copies, with a theoretical lower bound for redundancy of around 5%; ② Negotiation occurs per hop, avoiding network-wide flooding; control overhead scales linearly rather than quadratically with node degree.
- Disadvantages: ① The REQ/ADV round trip requires a two-way handshake; the long propagation delay of acoustic modems is amplified, causing end-to-end delay to accumulate linearly with hop count; ② Lacks native repair mechanisms for voids; if a REQ is lost, it triggers "negotiation deadlock," relying on upper-layer retries; ③ Semantic summaries depend on application-layer prior knowledge, limiting generality.

(2) DD (Directed Diffusion)

- **Principle:** The sink node first broadcasts an "interest," establishing a multi-path reverse tree throughout the network based on a gradient field. Data sources send events along the path with the highest gradient. Intermediate nodes dynamically prune paths using "reinforcement" and "negative reinforcement" mechanisms, eventually converging to a low-latency, high-SNR backbone path. [6]
- **Advantages:** ① The gradient field naturally supports multi-source data fusion, making it suitable for event-driven scenarios; ② The reinforcement mechanism allows adaptive adjustment based on channel quality drift, providing a certain self-healing capability.
- **Disadvantages:** ① The interest flooding phase generates control traffic approximately 1.7 times the data traffic, which is difficult for energy-constrained networks to sustain long-term; ② Gradient calculation relies on periodic Beacons, easily leading to "false gradient" detours; ③ Negative reinforcement depends on ACKs, which are easily lost underwater, making it difficult to promptly prune redundant paths.

4.2 Opportunistic Forwarding Representatives

(1) EBOR (Energy-Balanced Opportunistic Routing)

- **Principle:** The sending node embeds a triplet of "depth + residual energy + packet sequence number" into the packet. Neighboring nodes receiving the packet calculate their own priority. Only the node with the highest local priority and an idle channel proceeds to forward; other nodes automatically suppress their transmissions, forming a "winner-takes-all" opportunistic competition. [7]
- **Advantages:** ① Broadcast diversity gain improves the instantaneous packet reception probability, offering high tolerance to topological jitter; ② The priority function explicitly includes an energy term, which can delay the overutilization of shallow nodes.
- **Disadvantages:** ① The candidate set size increases linearly with node density, raising the probability of contention window collisions and requiring extra backoff timers, offsetting some gains; ② The "first-priority forwards" strategy in sparse areas can lead to "opportunistic voids" due to a lack of candidates; ③ Packet sequence numbers must be globally unique, incurring maintenance overhead proportional to node mobility.

(2) DQELR (Deep Q-Learning based Energy- and Latency-aware Routing)

- Principle: Models the "state-action-reward" relationship as a mapping from local observations (residual energy, depth difference, link SNR) to forwarding decisions. A pre-trained Q-network resides on the nodes. During the online phase, it outputs the candidate set and holding time, enabling "learn-while-forwarding."
- Advantages: ① The reward function can explicitly weight energy and delay, allowing the network to autonomously learn multi-objective trade-offs; ② The experience replay mechanism acts as a low-pass filter against sudden channel fluctuations, reducing jitter. [8]
- Disadvantages: ① The exploration phase requires 200-300 rounds for convergence, with initial PDR fluctuation amplitudes potentially reaching 15%; ② The Q-table or network weights require 3-5 kB of memory, which is unfriendly to low-end acoustic modems; ③ If the training scenario mismatches the actual sea trial environment, transfer errors may cause policy degradation.

4.3 Priority Scheduling Representatives

(1) PBR (Priority-Based Routing)

- Principle: The application layer marks data packets with "urgent/normal" priority labels. The MAC layer employs differentiated backoff windows (e.g., minimum contention window can be as low as 2 for high priority). Simultaneously, the routing layer preferentially selects nodes with "low depth + high link quality," forming a "cross-layer preemption" chain. [9]
- Advantages: ① The average delay for warning packets during event bursts can be compressed to around 0.38s, meeting hard real-time requirements like tsunami monitoring; ② The preemption mechanism only locally adjusts backoff without modifying the path structure, allowing orthogonal combination with existing geographic protocols.

- Disadvantages: ① Low-priority packets experience "starvation" under prolonged high-load scenarios, with their delay variance potentially up to 6 times that of high-priority packets; ② The priority field requires cross-layer passing and modification of the frame format, leading to poor compatibility with commercial acoustic modem stacks.

(2) DVOR (Delay-sensitive Void-aware Opportunistic Routing)

- **Principle:** Nodes maintain a history of forwarding failures. When the estimated void probability exceeds a threshold θ, the "angular detour mode" is activated: the next-hop search sector is deflected by 15°–30°, and the transmission power is simultaneously increased by 3–5 dB to bridge the void region. [10]
- **Advantages:** ① Void-induced packet loss rate can be reduced from 21% to 7% without requiring additional beacons; ② Joint optimization of deflection angle and power achieves a Pareto improvement between energy cost and detour length.
- **Disadvantages:** ① The θ threshold is sensitive to traffic load and requires offline calibration; misconfiguration can lead to "excessive detouring," increasing energy consumption by 8-10%; ② Power increase causes new interference to neighboring nodes, necessitating coupling with the MAC layer power control protocol; otherwise, secondary conflicts may arise.

V. Geographic--aware Routing Protocols

In underwater wireless sensor networks (UWSNs), geographic information (such as depth, coordinates, angles, etc.) provides an intuitive and efficient basis for routing decisions. Geography-aware routing protocols leverage the spatial attributes of nodes to enable rapid forwarding without requiring global topology information, significantly reducing control overhead and, to some extent, mitigating broadcast storms and the void hole problem. Based on the decision dimensions and information requirements, existing protocols can be categorized into "Depth-driven Schemes" and "Geography-aware Schemes". The former relies solely on one-dimensional depth information obtained from pressure sensors, while the latter requires the construction of multi-dimensional spatial references using acoustic positioning or angle estimation. The following sections elaborate on these categories from three aspects: operational principles, advantages and disadvantages, and evolutionary context.

5.1 Depth-driven Schemes

(1) DBR (Depth-Based Routing)

- Principle: Nodes construct a "layer-by-layer ascending" path based on the depth difference between themselves and their upstream neighbors. The packet header carries only the sender's depth. A receiving node automatically becomes a candidate forwarder if it has a shallower depth, and the next hop is selected through local competition. [11]
- Advantages: ① Requires no positioning infrastructure; operation is supported by a single pressure sensor per node. ② Extremely simple control fields result in very low per-packet overhead. ③ Forwarding decisions are entirely local, eliminating routing reconstruction delays during topology changes.
- Disadvantages: ① Shallower nodes are consistently selected, leading to an "inverted pyramid" energy consumption distribution, which easily forms permanent energy holes near the surface. ② The broadcast competition mechanism causes severe collisions in high-density scenarios, resulting in a high redundant copy rate. ③ Lacks a strategy to avoid "local depth minima"; if currents cause temporary voids, packets may loop locally until their TTL expires.

(2) EEDBR (Energy-Efficient DBR)

- **Principle:** Introduces a "residual energy" threshold alongside DBR's single depth criterion. A candidate node enters the forwarding competition only if its depth is shallower and its energy is higher than the neighborhood average. Neighbor energy levels are acquired via passive listening, eliminating the need for additional signaling.
- **Advantages:** ① The energy threshold effectively delays the over-utilization of shallow nodes, significantly extending network lifetime compared to DBR. ② Maintains zero dependency on positioning, with no increase in hardware cost. ③ The competition window is inversely correlated with energy level, causing weaker nodes to automatically back off, reducing collision probability.
- **Disadvantages:** ① Static thresholds cannot adapt to varying current speeds; nodes in high-flow areas might be selected as forwarders due to high energy, but their rapid positional drift can lead to link breaks. ② Fixed energy listening periods lead to sluggish responses to bursty traffic, easily causing buffer overflow. ③ Does not account for acoustic channel asymmetry; poor reverse link quality can cause ACK loss, triggering unnecessary retransmissions.

5.2 Geography-aware Schemes

(1) VBF (Vector-Based Forwarding)

- **Principle:** The source node writes its own and the sink's 3D coordinates into the packet header, defining a virtual linear vector. Downstream nodes calculate their perpendicular distance (i.e., "projection distance") to this vector. If this distance is less than a preset radius R, they enter the candidate pipeline and compete for forwarding based on the principle of maximizing the "advance distance" towards the sink. [12]
- **Advantages:** ① Explicitly controls the number of forwarding nodes via the pipeline radius R, theoretically bounding the number of packet copies. ② Projection calculation requires only basic arithmetic, resulting in low computational complexity. ③ Inherently robust to node mobility, as nodes drifting outside the pipeline automatically drop out, eliminating the need for explicit neighbor table maintenance.
- **Disadvantages:** ① The radius R requires offline calibration; if too large, redundancy increases dramatically; if too small, insufficient nodes within the pipeline can cause "virtual voids". ② The projection distance is highly sensitive to positioning errors; even small coordinate deviations can lead to misjudgment. ③ Sink coordinates need to be flooded network-wide, incurring non-negligible initial control overhead.

(2) RPSOR (Reliable Path Selection and Opportunistic Routing)

- **Principle:** Utilizes a Mobile Sink that periodically cruises the area. Nodes compute their forwarding priority based on the "shortest expected meeting time" with the sink's predicted trajectory. During the expected meeting window, opportunistic broadcasting is used to deliver packets to the Sink. A "Reliability Index" is introduced to evaluate link stability, and paths with an index below a threshold are temporarily blocked. [13]
- **Advantages:** ① The Mobile Sink balances spatial traffic load, significantly alleviating energy hotspots near the shore. ② The meeting-time-driven mechanism reduces ineffective forwarding, noticeably lowering end-to-end delay. ③ The dynamic Reliability Index screens out poor-quality links, significantly improving the Packet Delivery Ratio (PDR).
- **Disadvantages:** ① Relies on GPS-based trajectory broadcasts from the Sink; the long delays in the underwater acoustic channel cause cumulative errors in trajectory prediction. ② The Reliability Index requires periodic probing, and the additional probe frames increase energy consumption. ③ Sensitive to Sink failure; if the cruise is interrupted, the network can instantly become partitioned.

VI. Challenges and Future Directions

Despite significant progress in the algorithm design and performance optimization of Underwater Wireless Sensor Network (UWSN) routing protocols in recent years, this field still faces a series of unresolved key challenges due to the characteristics of the underwater acoustic channel, node resource constraints, and the highly dynamic nature of the marine environment.

6.1 Theoretical Challenges

(1) Dynamic Topology and Void Hole Coupling Effect

Most existing protocols construct routing metrics based on a "quasi-static" assumption. However, under actual sea conditions, ocean currents with speeds of 1–3 m/s can cause coupled spatiotemporal variations in node displacement and link quality, leading to alternating occurrences of transient voids and energy holes. Future work needs to establish a joint model of stochastic geometry and fluid dynamics to quantify the theoretical limits between the void evolution rate and routing convergence delay.

(2) Lack of Metrics for Energy Balance

Most protocols use the "First Node Dies" time as the criterion for network lifetime, ignoring the impact of the variance and skewness of the energy distribution on subsequent data collection phases. It is imperative to propose a joint "Energy-Service" utility function that incorporates energy distribution entropy, data distortion rate, and remaining service duration into a unified framework.

(3) Error Propagation from Positioning Inaccuracy to Routing Decisions

Geographic protocols generally assume that depth or coordinate errors follow a Gaussian distribution. However, underwater acoustic refraction causes errors to exhibit spatiotemporal non-stationarity. Future research needs to introduce error propagation graph models, formally embedding the uncertainty principle into the routing optimization objectives.

6.2 Future Research Directions

(1) Cross-Layer and Cross-Domain Collaborative Optimization

Breaking away from the traditional "layered and domain-separated" design paradigm, a holistic framework should be constructed that integrates vertical "Physical-Network-Application" collaboration and horizontal "UAV-AUV-Shore-based" collaboration. For instance, employing AUVs as "mobile edge nodes" to collect Channel Impulse Response (CIR) in real-time and feed it back to the network layer for path reselection; simultaneously, utilizing air-water millimeter-wave links for second-level topology updates, reducing routing convergence time from hundreds of seconds to tens of seconds.

(2) Knowledge-Driven Self-Evolving Routing

Integrating knowledge graphs and reinforcement learning to build an "Environment-Network-Task" ternary knowledge base, endowing protocols with self-explanatory and self-evolving capabilities. Nodes can use Graph Neural Networks (GNNs) to mine high-order correlations among "ocean currents - link quality - energy status," generating routing strategies online. Leveraging meta-learning to achieve "train once, adapt to multiple domains," ensuring the same model maintains ≥90% optimal performance across different scenarios like thermoclines, abyssal plains, and coastal coral reefs.

(3) Digital-twin Sea Trial Platform

Establishing a closed-loop "Algorithm-Model-Data" digital-twin system that maps real-sea trials and virtual simulations in real-time. The digital-twin can predict the performance evolution of a protocol over the next 24 hours, triggering parameter self-adjustment in advance. Transfer learning can be used to feed the results from the twin back into laboratory simulations, forming a "Simulation-Sea Trial-Re-simulation" spiral iterative process, ultimately achieving the goal of "zero-shot" deployment for new protocols.

(4) Green Hyper-Cellular Architecture

Drawing on the terrestrial "hyper-cellular" concept, the UWSN can be partitioned into three levels of virtual clusters: "Macro-Micro-Pico." Macro-clusters, centered around mobile sinks, are responsible for large-scale data aggregation. Micro-clusters, anchored by AUVs, achieve regional energy balance. Pico-clusters, self-organized by static nodes, provide high-density sensing. Through cross-cluster power control and sleep scheduling, network-level energy efficiency can be improved by over 30%, while simultaneously meeting long-term (e.g., yearly) deployment requirements.

VII. Conclusion

This paper reviews the research landscape of routing protocols for Underwater Wireless Sensor Networks. Moving beyond the traditional fragmented narrative framework of "Energy-Data-Location," it proposes re-examining UWSN routing design through the coupled lens of "Environment-Constraints-Mechanisms." Through a comparative analysis of representative protocols, it identifies that energy-sensitive strategies significantly extend network lifetime in static monitoring scenarios but incur increased end-to-end delay. Data-centric mechanisms maintain high packet delivery rates in event-driven scenarios through interest negotiation and opportunistic forwarding, albeit at the cost of additional control overhead. Geography-aware schemes exhibit inherent robustness to topological disturbances in environments with water currents, yet their performance boundaries are significantly constrained by depth errors. Furthermore, the paper distills three common bottlenecks: the tripartite coupling of "Topology-Energy Consumption-Void Holes," the nonlinear amplification of "Positioning Error-Performance" effects, and the "Simulation-Sea Trial" gap. Future research should focus on constructing cross-layer collaborative frameworks that integrate AUV mobility, Channel Impulse Response, and energy entropy into unified optimization objectives. Leveraging meta-learning-driven lightweight reinforcement learning can enable multi-domain adaptation. Finally, utilizing digital-twin sea trial platforms for closed-loop "Algorithm-Model-Data" verification is crucial to propel UWSN routing protocols towards efficient, intelligent, and practical evolution.

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