

An Angle-based Geographic Routing Protocol with Adaptive Information Diffusion for Multi-UUV Networks

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Abstract— With the development of Underwater Acoustic Sensor Networks (UASNs), Unmanned Underwater Vehicles (UUVs) have become essential tools for underwater exploration. The collaboration of multiple unmanned underwater vehicles enables larger-scale missions, which require addressing the inter-vehicle communication challenges. UUVs exhibit high mobility and are energy-constrained, resulting in highly dynamic network topologies. Moreover, such networks cannot afford high-overhead topology maintenance methods. To tackle the issues of high mobility, energy constraints, and unstable links in multi-UUV underwater mobile swarm networks, this paper proposes a geographic routing protocol named APID(Routing Protocol with Adaptive Position Information Diffusion and Angle-based Forwarding). The protocol introduces an adaptive beacon interval mechanism, a self-decision location information diffusion strategy, a forwarder selection method based on confidence and forwarding angle, and a packet buffering mechanism. These features effectively enhance routing stability and energy efficiency in dynamic environments. Simulation results show that compared to GPSR, Improved GPSR, and OLSR, the proposed protocol improves the packet delivery rate by 24.23% and reduces the average energy consumption by 18.89%.

Keywords— Geographic routing protocol, UASNs, Multi-UUV, Angle-based forwarding, Adaptive information diffusion

I. INTRODUCTION

71% of the Earth's surface is covered by oceans. With the increasing exploration and utilization of marine resources, Underwater Acoustic Sensor Networks (UASNs) have played a vital role in environmental monitoring, resource exploration, and seismic surveillance. In recent years, Unmanned Underwater Vehicles (UUVs) have undergone rapid development and been widely deployed for underwater exploration and operations [1][2]. However, a single UUV often suffers from limited detection range, monotonous task types, and difficulties in information transmission. Multi-UUV underwater mobile swarm networks, where multiple UUVs collaborate to complete tasks, offer advantages such as high robustness, good coordination, and improved efficiency.

To meet the communication demands during task allocation, switching, and execution, mobility-supportive underwater routing protocols are of great importance [3].

Unlike terrestrial wireless sensor networks, the unique underwater environment presents challenges for routing protocols in multi-UUV mobile swarm networks. Radio signals attenuate severely underwater, making acoustic waves the primary communication medium. The slow propagation speed of sound in water (1500 m/s), coupled with the asymmetry of the acoustic channel, leads to high latency and low stability in communication links. Since UUVs are typically battery-powered and battery replacement is difficult, Multi-UUV networks face strict energy constraints. UUVs performing different tasks exhibit various mobility patterns [4], and ocean currents can further disturb their positions [5]. For UUVs with multiple task modes, mobility-induced position changes incur high synchronization overhead. The energy-limited underwater environment cannot support large-scale routing updates. In summary, routing protocols for multi-UUV underwater mobile swarm networks must cope with high mobility to discover more stable links in an energy-efficient way.

Routing protocols for UASNs are generally classified into three types: proactive, reactive, and geographic routing protocols. Proactive routing protocols incur excessively high energy consumption, while the route discovery mechanism of reactive protocols cannot adapt well to high mobility and long delays. Neither is suitable for multi-UUV underwater mobile swarm networks. Geographic routing protocols offer low overhead and good scalability, making them more suitable for underwater environments. However, they often suffer from high beacon overhead and difficulty in tracking destination nodes due to their mobility. Moreover, different task modes in multi-UUV networks can lead to uneven node density, making forwarding in sparse areas difficult. Conventional routing protocols also tend to use overly simplistic criteria for forwarder selection, often resulting in poor link quality.

To address the above issues, this paper proposes the APID routing protocol (Routing Protocol with Adaptive Position Information Diffusion and Angle-based Forwarding), a geographic routing protocol designed for multi-UUV underwater mobile swarm networks. It is capable of identifying more stable transmission links under conditions of high mobility and energy constraints. The main contributions of this paper are as follows:

- To tackle the problems of high overhead and poor adaptability caused by fixed-period beacons in routing protocols, an adaptive beacon interval method based on node state is proposed. The method dynamically calculates the beacon interval by considering the node's own speed, residual energy, and neighbor status. This approach reduces unnecessary beacon overhead and improves the neighbor synchronization efficiency of nodes with high forwarding probability.
- To cope with the high mobility of multi-UUV underwater mobile swarm networks and the difficulty in tracking destination nodes, a low-energy self-decision directional location information diffusion method is proposed. When a node changes its movement state, it sends out an advertisement. Upon receiving the advertisement, each node independently decides whether to forward it based on its own forwarding willingness and the forwarding demand of its neighborhood. This method allows potentially affected areas to obtain the node's movement information in advance, supporting destination node tracking in highly mobile scenarios. At the same time, it reduces the overhead of scoped advertisements and saves energy consumption.
- To address the issue of overly simplistic forwarding criteria in geographic routing protocols, a forwarding method based on confidence and forwarding angle is proposed. This method comprehensively considers the timeliness of collected neighbor information, the relative speed between the node and its neighbors, and the relative position of neighbors to the destination node, in order to select the most suitable forwarder. The constraint of the forwarding angle helps align the direction of multi-hop routing paths, reducing the probability of detours. This method ensures link stability and improves packet delivery rate.
- As a supplement to routine forwarding methods, a routing void optimization method for sparse conditions is proposed. When no suitable forwarder is found among the current neighbors, the node buffers the packet and waits for a suitable forwarder. In high-mobility scenarios, this method effectively improves the delivery rate in sparse environments.

II. RELATED WORK

Routing protocols in Underwater Acoustic Sensor Networks (UASNs) are generally divided into three categories: proactive, reactive, and geographic routing protocols. The mobility of nodes has significant impact on the performance

of these three types of routing protocols [21]. Traditional proactive and reactive protocols encounter many problems when applied to multi-UUV underwater mobile swarm networks.

Proactive protocols, represented by OLSR [6] and DSDV [7], keep global routing tables for all nodes at all times. Whenever the topology changes, an update is triggered regardless of whether there is data to send, leading to enormous routing overhead in highly mobile scenarios. Therefore, proactive protocols are unsuitable for multi-UUV underwater mobile swarm networks.

Reactive protocols, represented by AODV [8] and DSR [9], initiate route discovery only when a packet needs to be transmitted. They flood control packets to explore the path and then start data delivery after the route is established. In the high-delay underwater environment, this approach often causes paths to expire before use, making reactive protocols inappropriate as well.

Geographic routing protocols assume that every node is location-capable and use position information for forwarding decisions. They usually rely on 1-hop beacons to maintain neighbor state. The classic GPSR [10] protocol selects the neighbor closest to the destination as the next hop, but it only knows 1-hop neighbors and cannot cope with a moving destination. LAR [11] also keeps neighbor information and uses location data to narrow the flooding range, yet it still depends on reactive route queries, suffering from timeliness and overhead issues. Other geographic opportunistic protocols include DBR [12] and VBF [13]. DBR is depth-based and thus inappropriate for multi-UUV networks. VBF creates a pipe from source to destination, only nodes inside the pipe forward packets. However, VBF generates excessive redundant transmissions in dense areas and may fail in sparse regions. HH-VBF [14] refines VBF by building the virtual pipe hop-by-hop, but the fundamental problems remain.

Recent studies have focused on improving forwarder selection within geographic protocols. BENGAG et al. [15] proposed DVA-GPSR, which senses local node density and velocity to choose a more reliable next hop. Zhou et al. [16] presented SZLS-GPSR, establishing a communication-safe zone and selecting the most stable relay by jointly considering projection length, cumulative communication duration, and movement direction inside the zone. Although these efforts optimize forwarder choice, they neither simultaneously account for the states of both neighbor and destination nodes nor support destination mobility.

In summary, existing routing protocols cannot effectively handle the challenges in multi-UUV underwater mobile swarm networks. Specifically, UUV movement during task execution and switching causes destination drift, and the randomness of this movement leads to poor link quality. Meanwhile, UUV energy is severely limited. Consequently, the problem addressed in this paper is how to diffuse multi-hop mobility information with minimal overhead and how to select a next hop with better link quality in harsh environments. To this end, the APID routing protocol is proposed. It performs self-decision, multi-hop location

information diffusion within limited energy, employs a forwarding strategy that combines confidence and angle, and supplements this with packet buffering, effectively improving the delivery rate.

III. ROUTING PROTOCOL DESIGN

This section presents APID, a geographic routing protocol tailored for highly mobile, multi-task, multi-UUV underwater mobile swarm networks. APID enables stable packet delivery among UUVs executing different missions.

We assume that every UUV knows the initial parameters of the swarm and its own task requirements; some nodes may maneuver; the channel is half-duplex and omnidirectional. When the application layer generates a packet, the source is aware of the current position and velocity of the destination.

In APID, nodes obtain information about others through one-hop beacons and multi-hop advertisements. Each node periodically transmits a one-hop beacon. The beacon interval is adaptively adjusted based on the node's own state and surrounding conditions. When a node changes its motion state, it issues an advertisement. Upon receiving this advertisement, other nodes independently decide whether to forward it based on their own forwarding willingness and the forwarding demand of their neighborhood. During data forwarding, a node divides its transmission range into three forwarding regions relative to the destination. It then selects the most appropriate next hop by jointly considering the confidence level of neighbor positions, the forwarding region, and the distance to the destination. If no suitable next hop exists, the packet is buffered until a qualified neighbor appears.

A. Adaptive Beaconing Based on Node State and Surroundings

Beacon overhead is an important component of routing protocol overhead, and its size is highly correlated with the beacon period [20]. Like other geographic routing schemes, APID employs one-hop beacons to learn neighbor positions. A fixed beacon period, however, cannot satisfy nodes in different states or environments. For example, a node with low mobility does not need to advertise its position frequently; an energy-deficient node should reduce beacon frequency to save power; and nodes with either too many or too few neighbors should also lower the beacon rate to avoid unnecessary overhead.

Therefore, the neighbor factor $X_{Neighbor}$ is computed from the surrounding environment as follows.

$$X_{Neighbor} = \frac{-|NeighborNum - \sqrt{N}|}{N} + \frac{\sum |\bar{S}_{node} - \bar{S}_{neighbor}|}{MaxSpeed \cdot NeighborNum} \quad (1)$$

$X_{Neighbor}$ describes the density and variability of a node's neighbors; the higher the value, the greater the quantity and change among neighbors. $NeighborNum$ is the number of neighbors, $\bar{S}_{neighbor}$ is the average speed of the neighbors, $\bar{S}_{node}$ is the node's own speed, $MaxSpeed$ is the

maximum speed in the network, and N is the total number of nodes.

The node factor X_{Node} is calculated from the node's own state as follows.

$$X_{Node} = \frac{E}{E_{Max}} + \frac{|\Delta \bar{S}_{node}|}{MaxSpeed} \quad (2)$$

X_{Node} describes the node's own energy and motion state; a higher value indicates higher energy and mobility. E is the node's current energy, E_{Max} is its initial energy, $\Delta \bar{S}_{node}$ is the change in its speed since the last beacon, and $MaxSpeed$ is the maximum speed in the network.

Taking both the surrounding environment and the node's own state into account, the adaptive beacon period is calculated as follows:

$$T = \frac{T_{Normal}}{Max(a, Min(X_{Neighbor} + X_{Node}, b))} \quad (3)$$

T_{Normal} is the initially configured beacon period; a and b are parameters that bound the variation of T .

The method turns the fixed period T_{Normal} into an adaptive value within $[T_{Normal}/b, T_{Normal}/a]$. The higher the node's residual energy, the higher its own speed, and the higher the average speed of its neighbors, the shorter the resulting beacon period. Every T seconds, the node transmits a one-hop beacon containing its position, velocity, neighbor count, residual energy, and timestamp. Then it recalculates and updates T . This mechanism eliminates unnecessary transmissions, improves energy utilization, and reduces packet collisions.

B. Self-Decision Location Information Diffusion Based on Forwarding Willingness and Forwarding Demand

Through one-hop beacons, a node learns the state of its neighbors. However, when the destination moves, a packet in transit cannot promptly refresh the location change. To address this problem, a node that alters its motion issues a location advertisement carrying its current position, intended position, velocity and timestamp. Blind flooding of such advertisements would incur huge routing overhead, and not every node needs the data. To conserve energy and target the most needy nodes, we propose a self-decision diffusion method driven by forwarding willingness and forwarding demand.

The method combines node state, neighborhood state and information state, introducing the concepts of forwarding willingness and forwarding demand.

Forwarding willingness is determined by the node's own state, the freshness of the advertisement and the number of duplicates already received. The higher the residual energy and the newer the timestamp, the higher the willingness; duplicate receptions reduce it. The forwarding willingness is computed as follows:

$$F_{will} = \frac{E}{E_{Max}} - \frac{T_{now} - T_{stamp}}{MaxHop \cdot T_{overtime}} - N_{duplicate} \quad (4)$$

Where $N_{duplicate}$ is the number of duplicate advertisements received, E is the node's current energy, E_{Max} is its initial energy, T_{now} is the current time, T_{stamp} is the timestamp of the advertisement, $T_{overtime}$ is the neighbor timeout value, and $MaxHop$ is a parameter that limits the advertisement hop count.

Forwarding demand is determined by the impact of the advertisement source's movement on neighbor nodes. Specifically, a neighbor is defined as a demand node if it is farther from the advertisement source than the current node. For each such node i , its demand degree is defined as the direction change of the advertisement source node before and after its movement relative to i . The specific calculation formula is as follows:

$$Weight_{demand} = \frac{\arccos\left(\frac{(P_{before} - P_{neighbor}) \cdot (P_{after} - P_{neighbor})}{|P_{before} - P_{neighbor}| \cdot |P_{after} - P_{neighbor}|}\right)}{\pi} \quad (5)$$

Where P_{before} is the position of the advertisement source when the movement starts, P_{after} is the position of the advertisement source when the movement ends, and $P_{neighbor}$ is the position of demand node i .

After computing the demand degree for every demand node in the neighborhood, the forwarding demand is obtained by first mapping each demand degree into the interval (0,1) with the Sigmoid function and then summing the results. The calculation formula is as follows:

$$F_{demand} = \sum \left(\frac{1}{1 + e^{-Weight_{demand}}} - \frac{1}{2} \right) \quad (6)$$

Based on its own forwarding willingness and the forwarding demand of its neighborhood, a node independently decides whether to continue forwarding the advertisement packet. The decision criterion is as follows:

$$\begin{cases} \lambda \cdot F_{will} + \mu \cdot F_{demand} \geq 1; \text{Forward} \\ \lambda \cdot F_{will} + \mu \cdot F_{demand} < 1; \text{Drop} \end{cases} \quad (7)$$

Where λ and μ are parameters in (0,1) that adjust the weight between forwarding willingness and forwarding demand.

This method integrates the node's own state with the neighborhood's need for the information, allowing each node to autonomously decide whether to forward the location advertisement. It reduces routing overhead while achieving effective multi-hop location information diffusion.

Figure 1 illustrates the core decision mechanism of the diffusion method. A moving node moves from *Before* to *After*, and sends a location advertisement. Upon receiving the location advertisement, each neighbor (N_1, N_2 and N_3) decides whether to forward the advertisement based on its forwarding willingness and forwarding demand. N_1 's forwarding demand is the sum of demand degree of N_1 's neighbors. Each N_1 's neighbor computes its demand degree as the angular change (θ) of the moving node's trajectory relative to itself. In the figure, θ_1 , θ_2 , and θ_3 are large, indicating that these nodes are greatly affected by this motion and have high demand degree. By contrast, θ_4 is very small, indicating that this motion has little impact on the node. Large θ values result in large

forwarding demand. As a result, two neighbors with large forwarding demand (N_1, N_2) proceed to forward the packet, while one with small forwarding demand (N_3) suppresses forwarding. This result demonstrates the method's ability to selectively propagate information based on topological impact.

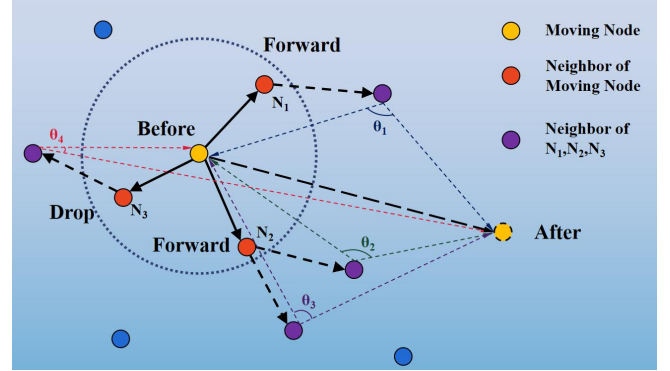


Figure 1. Principle diagram of the self-decision location information diffusion method

C. Forwarder Selection Algorithm Based on Confidence and Forwarding Angle

In conventional geographic routing protocols, a node usually chooses its next hop based only on the neighbor's geometric closeness to the destination, ignoring other influencing factors. In this paper, nodes obtain the positions of surrounding nodes through one-hop location beacons and multi-hop location information diffusion, and then compute a confidence value for each neighbor.

The confidence in a neighbor is determined by the freshness of its timestamp, the relative speed between the two nodes, and the neighbor's residual energy: the newer the timestamp, the lower the relative speed, and the more residual energy, the higher the confidence. The calculation is as follows:

$$Confidence = \text{Max} \left(0, 1 - \frac{T_{now} - T_{stamp}}{T_{overtime}} \right) - \frac{|\vec{S}_{node} - \vec{S}_{neighbor}|}{MaxSpeed} + \frac{E}{E_{Max}} \quad (8)$$

Confidence represents the reliability level that a node assigns to a neighbor's position information. T_{now} is the current time, T_{stamp} is the timestamp carried by the neighbor's most recent advertisement, $T_{overtime}$ is the neighbor timeout value, $\vec{S}_{node}$ is the node's own speed, $\vec{S}_{neighbor}$ is the neighbor's speed, and $MaxSpeed$ is the maximum speed in the network.

Based on the forwarding angle toward the destination, the node's transmission range is divided into three regions: non-forwarding, low-efficiency forwarding, and high-efficiency forwarding. The forwarding angle θ is defined as follows:

$$\theta = \arccos \left(\frac{(P_{dst} - P_{node}) \cdot (P_{neighbor} - P_{node})}{|P_{dst} - P_{node}| \cdot |P_{neighbor} - P_{node}|} \right) \quad (9)$$

When $\theta \in [0, \alpha]$, the neighbor lies in the high-efficiency forwarding zone; when $\theta \in (\alpha, \beta]$, it lies in the low-efficiency forwarding zone; when $\theta > \beta$, it lies in the non-forwarding zone.

Depending on the zone, the neighbor's weight is computed with distinct formulas:

$$Weight = \begin{cases} 2Confidence - \frac{Distance(Neighbor, Dst)}{Distance(Node, Dst)}; \theta \leq \alpha \\ Confidence - \frac{Distance(Neighbor, Dst)}{Distance(Node, Dst)}; \alpha < \theta \leq \beta \\ 0; \theta > \beta \end{cases} \quad (10)$$

Among all neighbors, the node with the highest weight excluding the previous hop is selected as the next hop.

The forwarder selection method based on confidence and forwarding angle is illustrated in Figure 2. Based on the relative position of the current node *Src* to the destination *Dst*, the transmission range of *Src* is divided into three distinct forwarding regions. Each neighboring node is classified into one of these regions according to its relative forwarding angle, and its color represents its confidence value. The optimal forwarder is chosen by jointly considering the neighbor's confidence and the region it belongs to. This joint consideration balances geographic progress with topological stability, leading to more reliable routing.

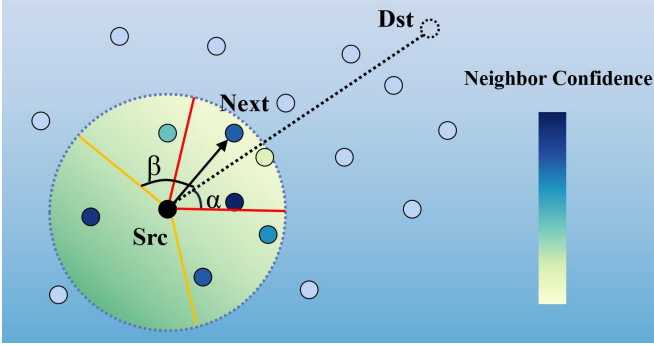


Figure 2. Forwarder Selection Algorithm Based on Confidence and Forwarding Angle

D. Routing Void Optimization Method Based on Packet Buffering

If the maximum weight among all neighbors is below 0, no qualified forwarder exists and the node has entered a routing void. To handle the void, the packet is buffered at the current node until a suitable forwarder appears.

As the waiting time t increases, the angular thresholds α and β are enlarged. Their variation with t is given by:

$$\begin{cases} \alpha' = \text{Min} \left(\frac{\pi}{2}, \alpha \left(\frac{2}{1 + e^{-\frac{t}{100}}} \right) \right) \\ \beta' = \text{Min} \left(\pi, \beta \left(\frac{2}{1 + e^{-\frac{t}{100}}} \right) \right) \end{cases} \quad (11)$$

Whenever the node detects a new neighbor or transmits a one-hop beacon, it re-executes the forwarder selection algorithm. If a qualified neighbor exists, the buffered packet is forwarded, otherwise the node keeps waiting. When the angular limits α and β reach their upper bounds, the weight threshold is removed and the neighbor with the highest weight is chosen as the forwarder.

IV. SIMULATION AND RESULTS

To evaluate the performance of the proposed routing protocol, we conduct experiments on the NS-3 simulator using Aqua-sim-ng [17] and compare APID with GPSR, OLSR and Improved GPSR [18]. GPSR is a classic geographic routing protocol, OLSR is the representative proactive topology-based protocol, and Improved GPSR is an enhanced GPSR that maintains a two-hop neighbor table in sparse regions to improve performance.

In the simulation scenario UUVs are randomly placed at the beginning; when the simulation starts some UUVs move randomly inside the area while the rest remain stationary.

The simulation parameters are listed in the table below.

TABLE 1. SIMULATION PARAMETERS

Simulation Parameter	Value
Simulation Tool	NS-3
Number of Nodes	10~100
Simulation Area	5km × 5km × 4km
Rx Power	0.75W
Tx Power	2W
Initial Energy	10000J
MAC Protocol	Aloha
Node Speed	3~20 knots
Transmitter Data Rate	3kbps
Simulation Time	5000s

This paper adopts PDR and AEC to evaluate protocol performance.

Packet Delivery Rate (PDR) is defined as the rate of successfully received distinct packets to the total packets sent. It reflects the overall reliability of the network. The formula is:

$$PDR = \frac{N_{receive}}{N_{send}} \quad (12)$$

where $N_{receive}$ is the total number of successfully received packets and N_{send} is the total number of sent packets.

Average Energy Consumption (AEC) is defined as the energy consumed per packet transmission per node, reflecting energy efficiency [19]. The formula is:

$$AEC = \frac{E_{total}}{N_{receive} \times NodeNum} \quad (13)$$

where E_{total} is the total energy consumed during the simulation and $NodeNum$ is the total number of nodes.

A. PDR

To evaluate the reliability of APID, we examine how node density and the fraction of mobile nodes affect delivery rate. When not acting as a variable, the number of nodes is 50, and the mobile node rate is 0.5.

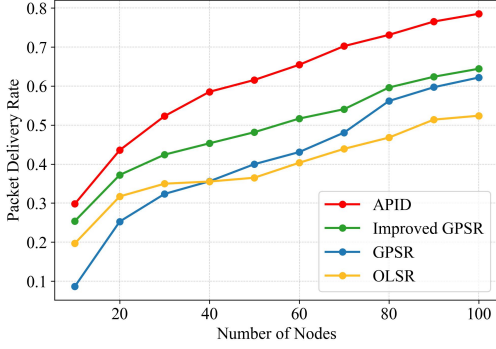


Figure 3. Packet delivery rate versus the number of nodes

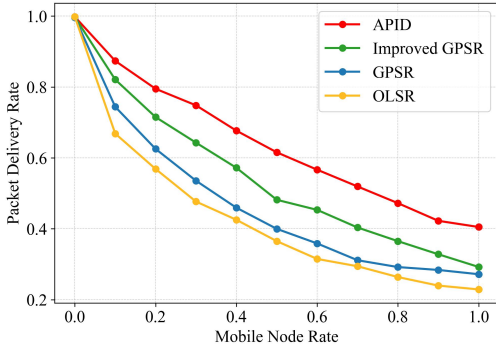


Figure 4. Packet delivery rate versus the mobile node rate

Figure 3 shows the PDR versus the number of nodes. As density grows with network size, all protocols exhibit a positive trend. APID explicitly handles mobility and selects the next hop using multiple metrics, yielding more stable links. Compared with GPSR, Improved GPSR and OLSR, APID raises PDR by 48.32 %, 24.23 % and 55.04 %, respectively. Improved GPSR's two-hop table in sparse regions gives it a large advantage over GPSR at low node counts, while at high density their results converge. OLSR is stable when the network is small, but its control traffic collides with data packets as the number of nodes increases, depressing delivery rate.

Figure 4 shows the PDR versus the mobile node rate. When every node is static, all four protocols achieve near 100 % delivery. As the fraction of mobile nodes rises, OLSR's topology updates lag, producing many invalid routes and a steep decline. GPSR also loses packets because the destination moves. Improved GPSR maintains two-hop topology in sparse areas and tolerates destination motion better than GPSR, but its performance still degrades under high mobility. APID's self-decision directional advertisements and angle-based forwarding track node movement more effectively, giving the highest delivery rate. On average, APID surpasses GPSR by 33.61 % and Improved GPSR by 15.57 %.

B. AEC

To evaluate the energy efficiency of the APID routing protocol, we study the impact of node count on average energy consumption. When not acting as a variable, the mobile node rate is 0.5.

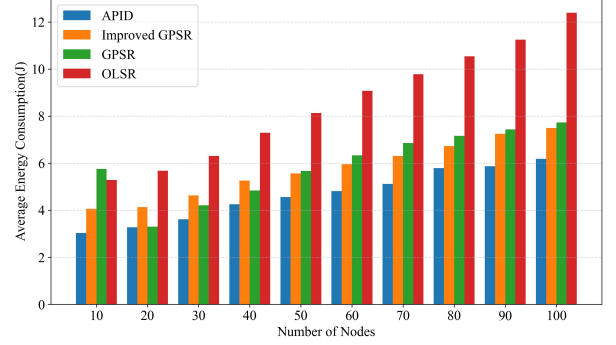


Figure 5. Average energy consumption versus the number of nodes

Figure 5 shows the average energy consumption versus the number of nodes. As the number of nodes increases, GPSR incurs no extra topology overhead, but its lower delivery rate translates into higher average energy expenditure per successful packet. Improved GPSR maintains a two-hop neighbor table in sparse regions, imposing considerable topology overhead, so its average energy cost exceeds that of GPSR when the network is small. OLSR, which keeps global topology, exhibits a sharp rise in average energy as the network scales. Although the total energy consumed by APID also grows with network size, its high delivery rate keeps the average energy per packet the lowest. Compared with GPSR, Improved GPSR and OLSR, APID reduces average energy consumption by 21.45 %, 18.89 % and 45.72 %.

V. CONCLUSIONS

To address the challenges of high mobility, energy constraints, and unstable links in multi-UUV underwater mobile swarm networks, this paper proposes the APID routing protocol, which utilizes self-deciding information diffusion and angle-based forwarding. APID incorporates an adaptive beacon interval mechanism, a directional location information diffusion strategy based on autonomous decisions, and a next-hop selection method that considers both confidence and forwarding angle. These features collectively enable stable routing in highly dynamic environments. Simulation results show that compared to GPSR, Improved GPSR, and OLSR, APID achieves a higher packet delivery rate and lower average energy consumption. The APID protocol demonstrates superior adaptability to underwater environments and is well-suited for multi-UUV mobile swarm networks.

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