

Article

AODV-Inspired Low-Overhead Routing for Underwater Drone Swarms Using Acoustic Communication

Ozgur Ozkaya ^{1,*}, Jetmir Haxhibeqiri ¹, Jean-Francois Determe ², Jeroen Hoebeke ¹ and Eli De Poorter ¹

¹ IDLab, Department of Information Technology, Ghent University-imec, 9052 Gent, Belgium; jetmir.haxhibeqiri@ugent.be (J.H.); jeroen.hoebeke@ugent.be (J.H.); eli.depoorter@ugent.be (E.D.P.)

² BEAMS-EE, Université Libre de Bruxelles, 1050 Brussels, Belgium; jean-francois.determe@ulb.be

* Correspondence: ozgur.ozkaya@ugent.be

Abstract

Underwater acoustic networks are critical for applications such as environmental monitoring, infrastructure inspection, and autonomous underwater operations. In these scenarios, autonomous underwater vehicles (AUVs) increasingly operate in cooperative swarms, requiring efficient route-discovery and multi-hop communication. However, acoustic underwater communication imposes extremely constrained conditions, including low data rates, long propagation delays, limited bandwidth, and unstable channels. These constraints make routing overhead a dominant factor limiting network performance. In this work, we propose a systematic redesign of the Ad hoc On-Demand Distance Vector Routing (AODV) protocol tailored for ultra-low-rate underwater acoustic networks. The proposed approach combines three complementary design strategies: (i) architectural simplification through a layer-2 AODV variant that eliminates layer-3 overhead, (ii) protocol-level compression using the Static Context Header Compression and Fragmentation (SCHC) standard to minimize packet size, and (iii) acoustic channel-aware parameter tuning to account for long propagation delays and limited channel capacity. The approaches are designed and implemented in ns-3.43 using the underwater acoustic network (UAN) model and evaluated under reachability and scalability scenarios against the default AODV protocol. The results show that the proposed protocols reduce the hello message loss percentage from over 10% to below 3%, decrease route creation time from around 35s to around 15s, and significantly improve the packet delivery ratio under increasing traffic load. In high-load scenarios, the proposed methods consistently outperform default AODV due to reduced channel occupancy and lower collision probability.

Keywords: underwater acoustic network; ad hoc routing; underwater drone swarm; constrained networks



Academic Editors: Ruiqin Zhao and Xiaohong Shen

Received: 19 June 2026

Revised: 10 July 2026

Accepted: 16 July 2026

Published: 20 July 2026

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1. Introduction

Underwater communication is challenging due to the physical characteristics of the propagation medium. Compared to air, an underwater propagation channel is more unstable and unpredictable due to factors such as temperature, salinity, and pressure. Underwater wireless communication can be achieved using acoustic, optical, or electromagnetic/radio-frequency waves [1]. However, electromagnetic/radio-frequency waves experience severe attenuation in seawater due to its high conductivity, especially at higher frequencies. Therefore, traditional wireless technologies, such as radio-frequency (RF) communication, can only be used for low frequencies. Such characteristics limit the

communication range to only a few meters [2]. On one hand, optical communication can support higher data rates, but it is highly sensitive to scattering, turbidity, and alignment constraints. Thus, its deployment is restricted in many underwater scenarios, including high turbidity, dynamic ocean conditions, mobile underwater vehicles, and long-range non-line-of-sight communications [3]. Acoustic communication, on the other hand, is considered the most practical technique for underwater networks due to its ability to cover longer distances. However, underwater acoustic channels have several limitations, including low bandwidth, long propagation delays, high bit error rates, and significant energy consumption [4]. These constraints make the design of efficient and reliable networking protocols challenging for underwater acoustic networks (UANs).

Autonomous underwater vehicles (AUVs) are increasingly being used for ocean exploration, environmental monitoring, infrastructure inspection, and defense-related underwater operations [5,6]. In many emerging applications, multiple vehicles operate cooperatively to perform tasks such as seabed mapping, pollution monitoring, pipeline inspection, and search-and-rescue missions [7–10]. These systems often rely on principles from Swarm Robotics [11], where groups of relatively simple agents coordinate their behavior to achieve complex objectives. Compared to single-vehicle deployments, cooperative AUV systems can significantly improve spatial coverage, robustness, and mission efficiency. However, effective coordination between vehicles requires reliable communication for information sharing, task allocation, and collective decision making. In underwater environments, the limitations of acoustic communication make maintaining the network particularly challenging, especially when drones move out of fixed topologies to perform specific tasks.

In many underwater missions, direct communication between all vehicles and a surface station is not always feasible due to limited acoustic transmission range and environmental interference. Multi-hop communication architectures can extend the operational range by allowing intermediate nodes to relay messages across the network. Mesh-based underwater networks enable distributed sensing, cooperative navigation, and collaborative data collection among multiple vehicles operating over large areas. Such architectures are particularly relevant for swarm deployments where vehicles dynamically move and form temporary communication links.

However, efficient routing in underwater mesh networks remains challenging due to limited bandwidth, long propagation delays, and frequent topology changes. Many existing underwater routing protocols are mainly designed for sensor-to-sink communication rather than peer-to-peer swarm communication. In a swarm, nodes may need to communicate directly with each other over multiple hops, which makes routing more demanding. At the same time, traditional ad hoc routing protocols such as Ad hoc On-Demand Distance Vector (AODV) [12] were originally designed for terrestrial wireless networks and may introduce too much overhead for low-rate underwater acoustic channels. This shows the need for a lighter routing approach for underwater swarm networks.

In this work, we address the limitations of routing in underwater acoustic mesh networks by focusing on reducing protocol overhead under extreme communication constraints. To this end, we design and implement two AODV-inspired routing approaches that systematically target different sources of overhead. The first approach introduces an architectural simplification by removing layer-3 functionality, resulting in a lightweight layer-2 AODV variant with significantly reduced packet size. The second approach applies protocol-level compression based on the SCHC standard to minimize header overhead without sacrificing routing functionality. In addition, both approaches incorporate acoustic channel-aware parameter tuning to adapt the protocol behavior to long propagation delays and limited channel capacity.

The main contributions of this work are as follows:

- We introduce a layer-2 AODV-inspired routing scheme for underwater acoustic mesh networks. This scheme removes layer-3 and transport-layer overhead, avoids ARP exchanges, and redesigns AODV control packet formats to minimize on-air packet size (up to 10× for hello messages) while preserving on-demand multi-hop route discovery.
- We propose an AODV variant leveraging SCHC-based header compression, including an optimized embedding of the SCHC rule ID in the MAC header, achieving up to 90% packet size reduction while preserving layer-3 functionality.
- We define acoustic-aware AODV parameter settings for ultra-low-rate underwater acoustic links, including hello interval, Active Route Timeout, Node Traversal Time, RREQ rate limiting, and Next RREQ Delay. These settings account for long propagation delay, low data rate, and the risk of overlapping route-discovery attempts.
- Through ns-3 simulations, we show that the proposed approaches significantly improve network stability, route establishment, and packet delivery ratio compared to default AODV under controlled underwater acoustic mesh scenarios, particularly under high traffic load and varying network densities.

The rest of the paper is structured as follows: Section 2 presents related works. Section 3 provides the system and protocol background. Section 4 describes the proposed routing schemes and protocol optimizations. Section 5 presents the simulation setup, including the PHY data rate, communication range, inter-node spacing, packet size, and propagation model, test scenarios, and performance results. Finally, Section 6 concludes the paper and discusses future work.

Dual-Use Consideration

Underwater acoustic networking and AUV swarm communication can be relevant to both civilian and defense-related applications. The technologies studied in this work may therefore have a general dual-use context. However, this manuscript focuses only on routing protocol design and simulation-based performance evaluation for constrained underwater acoustic mesh networks. The proposed methods aim to reduce communication overhead and improve network reliability under low-data-rate acoustic conditions. The work does not address weapon systems, offensive missions, target detection or tracking, classified operational procedures, or tactical deployment strategies. The presented results should therefore be interpreted as a communication-networking study for constrained underwater systems, with potential applications in environmental monitoring, infrastructure inspection, search-and-rescue, and other non-offensive underwater operations.

2. Related Work

This section discusses related work on mesh networks in the context of underwater routing for mesh/sensor/swarm scenarios. Pros and cons of these works are presented, discussed, and compared with our proposed routing protocol.

Ad hoc on-demand distance vector (AODV) is a reactive routing protocol for ad hoc networks. Routes are established when needed. It uses Route Request (RREQ), Route Reply (RREP), and Route Error (RERR) messages for route discovery and maintenance. Sequence numbers in these packets are used to ensure loop-free and up-to-date paths. AODV is efficient in dynamic environments with frequent topology changes, but it may introduce latency during route discovery and suffer from flooding overhead in dense networks. In contrast, our approach explicitly redesigns AODV to reduce control overhead, making it suitable for ultra-low-rate acoustic channels.

LOADng (The Lightweight On-demand Ad hoc Distance-vector Routing Protocol—Next Generation) [13] is a lightweight derivative of AODV, designed for low-power networks such as IoT and wireless sensor networks. Like AODV, it uses RREQ, RREP, and

RERR messages but removes sequence numbers and simplifies operations to minimize control overhead and memory use. That makes it better suited for resource-constrained devices. While it offers efficiency and simplicity in mostly static or slowly changing networks, it sacrifices robustness and freshness guarantees compared to AODV, which is problematic when supporting dynamic drone missions.

Depth-Based Routing (DBR) [14] is a localization-free routing protocol that forwards data packets to the water surface by using nodes' depth information. Each node knows its own depth and includes it in the packet headers. When a node receives a packet, it forwards it only if its depth is shallower (closer to the surface) than the sender's, ensuring progress toward the sink. However, DBR is limited to sink-oriented communication, whereas our approach supports peer-to-peer routing required for swarm coordination.

Vector-Based Forwarding (VBF) [15] is a geographic routing protocol designed for underwater wireless sensor networks. Instead of maintaining full routing tables, it forwards packets along a routing vector from the source to the sink. Any node within a predefined routing pipe (a virtual cylinder around the vector) is eligible to forward the packet. In contrast, our method does not require location information and is specifically designed for underwater swarm communication with reduced routing overhead.

CTP (the Collection Tree Protocol) [16] is a reactive routing protocol designed for wireless sensor networks. It is a tree-based routing protocol, used for topologies where the traffic is supposed to go to a single or multiple sinks. Some nodes advertise themselves as tree roots, and the nodes are forming routing trees to these roots. It uses the link quality metric named expected transmission count (ETX) as its routing metric. Each node shares its ETX with its neighbors by beacons, and routes are created by selecting the lowest ETX through the root. The Trickle algorithm [17] is used to manage the frequency of these beacons. Unlike CTP, which is primarily optimized for data collection to a sink, our approach enables efficient multi-hop peer-to-peer communication between swarm nodes.

CTP sparsity-conscious energy efficient clustering (CTP-SEEC) [18] is a modified version of CTP for underwater sensor networks. The authors integrate three strategies: adaptive transmission power control, clustering in dense regions, and mobile sink assistance in sparse regions. By dynamically adjusting transmission power levels based on distance and RSSI thresholds, the protocol minimizes unnecessary energy use and interference. Clustering balances load and reduces packet duplication, while mobile sinks act as mobile collectors in sparse areas to prevent energy holes and extend network life. While CTP-SEEC improves energy efficiency in sensor networks, it does not address routing overhead in peer-to-peer swarm communication as targeted in this work.

RPL (IPv6 Routing Protocol for Low-Power and Lossy Networks) [19] is a routing protocol designed for constrained networks with limited energy and unreliable links. It builds a tree-like structure toward a sink node, and packets are forwarded through selected parent nodes. To reduce unnecessary control overhead, RPL uses the Trickle algorithm for controlling the dissemination of routing control messages. In contrast, our approach avoids tree-based structures and supports fully decentralized routing, which is more suitable for dynamic underwater swarms.

UWRPL [20] is an underwater adaptation of RPL for acoustic networks. It extends the original protocol by considering additional routing metrics such as link quality, energy, and depth information. This way, it aims to improve routing reliability and efficiency under the high-delay and lossy conditions of underwater acoustic channels. However, UWRPL still relies on structured routing topologies, whereas our approach focuses on lightweight, on-demand routing with minimal overhead for underwater swarm networks.

Existing underwater routing protocols and lightweight AODV derivatives address important aspects of constrained communication; however, they are generally designed

under assumptions that differ from those considered in this work. Among AODV-derived protocols, LOADng is the closest to our objective, since it also aims to reduce routing overhead in constrained networks. Nevertheless, LOADng mainly focuses on simplifying AODV operation for low-power and lossy networks, rather than specifically addressing underwater acoustic constraints such as very low data rates, long propagation delays, large packet airtime, and the need for acoustic-aware timer adaptation. In addition, LOADng does not update any default timers of the AODV, as it does not consider cases with long-propagation delays. In our case, we have updated such parameters (e.g., Node Traversal Time, hello interval, etc.) to comply with the long propagation delays of the underwater environment. DBR and VBF are primarily designed for sink-oriented or geographic forwarding. DBR forwards packets based on depth information toward the surface, whereas VBF forwards packets along a geographic routing vector. These assumptions are suitable for many underwater sensor-network scenarios, but they are less suitable for peer-to-peer mesh communication among AUVs, where any node may need to communicate with any other node without relying on a fixed sink, depth-based forwarding, or accurate localization. Similarly, CTP and CTP-SEEC focus on data collection and tree- or clustering-based structures, which are not directly aligned with non-hierarchical swarm communication. RPL and UWRPL provide structured routing for low-power and lossy networks, and UWRPL further incorporates underwater acoustic routing metrics. However, these protocols still rely on root-oriented or structured topologies, whereas the target scenario in this work requires lightweight on-demand routing in a peer-to-peer underwater mesh. Therefore, the proposed schemes in this study do not aim to replace all lightweight or underwater routing protocols. Instead, they address a specific gap: reducing the overhead of AODV-style peer-to-peer communication under ultra-low-rate acoustic-channel constraints.

Table 1 compares the routing protocols based on the main requirements of underwater swarm communication. The comparison includes the communication model, non-hierarchical operation, acoustic-aware parameter tuning, packet size reduction, and the use of periodic control packets. These criteria are important because AUV swarms require direct peer-to-peer communication and should not depend on a fixed sink or root. At the same time, the routing protocol must work under acoustic-channel limitations such as low data rate, long propagation delay, and limited channel capacity. As shown in the table, our method(s) is the only one that combines P2P communication, non-hierarchical operation, acoustic-aware tuning, and packet size reduction.

Table 1. Comparison of routing protocols.

Protocol Name	Comm. Model	Non-Hierarchical	Acoustic-Aware Design		Periodic Control Packet
			Parameter Tuning	Packet Size Reduction	
AODV	P2P	Yes	No	No	Yes
LOADng	P2P	Yes	No	Partial	No
DBR	Sink	Partial	Yes	No	No
VBF	Sink	Partial	Yes	No	No
CTP	Sink	No	No	No	Yes
CTP-SEEC	Sink	No	Yes	No	Yes
RPL	Hybrid	No	No	No	Yes
UWRPL	Hybrid	No	Yes	No	Yes
Our Method	P2P	Yes	Yes	Yes	Yes

3. System and Protocol Background

This section explains and discusses the technologies used in this research paper. Starting from the underwater network MAC layer that utilizes ALOHA, towards the network layer, explaining the AODV routing protocol. Finally, SCHC compression is explained before moving on to the newly designed routing protocols presented in this paper.

3.1. Underwater MAC Layer: ALOHA

Unlike terrestrial networks, the underwater acoustic environment is not stable, harsh, and generally has low data rates. All of these should be considered while designing or choosing which MAC protocol to use in an underwater wireless network [21]. Acoustic signals propagate underwater at approximately 1500 m/s, which is much slower than electromagnetic-wave propagation, leading to significantly higher propagation delays. This physical limitation severely degrades the performance of CSMA-like MAC protocols. Even if a node senses the channel as idle for a certain period, it cannot be guaranteed that no transmission has already been initiated elsewhere in the network. To overcome this, one might think of increasing the channel sensing time in the range of the propagation delay for the physical distances that the network is supposed to cover. In that case, much of the time will be spent in channel sensing before any actual transmission can happen, thus reducing the actual throughput. However, longer channel sensing time will not ensure collision-free transmission.

Besides long propagation time, data rate is another issue for underwater acoustic networks. Due to the utilization of relatively low bandwidths (just a few kHz), at low frequency ranges between 10 Hz and 1 MHz, data rates of acoustic modems are limited [3]. Consequently, packet transmission times are relatively long, increasing the likelihood of collisions and channel contention.

Considering both limitations, long propagation time as well as low transmission data rate, the utilized MAC protocol should be simple and incur low overhead. Hence, in this work, we select one of the simplest and most lightweight MAC protocols, namely pure ALOHA [22].

Pure ALOHA is one of the oldest channel access mechanisms in communication technology. However, it is, or its variants are still used in today's underwater networks and underwater sensor networks [23,24]. In pure ALOHA, a node sends its packet whenever it is ready to send, without any time spent on sensing or channel activity detection. This results in a lower overall performance compared to today's wireless MAC protocols in use for RF communication: pure ALOHA has a maximum efficiency of about 18.4% [25].

3.2. Network Layer: AODV Routing Protocol

Routing protocols are an essential part of multi-hop ad hoc networks, be it swarm networks or wireless sensor networks. They are responsible for creating and maintaining the routes in a network, which are then used to transfer the actual data. In our work, we use the AODV routing protocol for its reactive nature and basic design.

AODV [26] is a reactive routing protocol, meaning that routes are created when needed and maintained as long as they are actively being used. Other than that, only neighbor information is held by the nodes, obtained via periodic hello messages. It utilizes three control messages: Route Request (RREQ) to dynamically discover a path to a destination node when no active route is known, Route Reply (RREP) to notify the source node that a valid path to the destination has been successfully found, and Route Error (RERR) to notify surrounding nodes when destinations become unreachable due to a link break.

When a source node needs to send data but lacks a route, it broadcasts an RREQ across the network. As this request floods throughout the network, intermediate relay nodes record the path leading back to the source. When the target destination or a node with

a fresh path receives the request, it generates a Route Reply (RREP) message. This reply travels back to the source along the recorded path, meanwhile establishing the forward path to the destination. The end result is an active route over which data transmissions can begin. The packet format of an RREQ message is given in Figure 1. A RREQ message is 24 bytes long and contains information such as IP addresses and sequence numbers of both the originator and the destination.

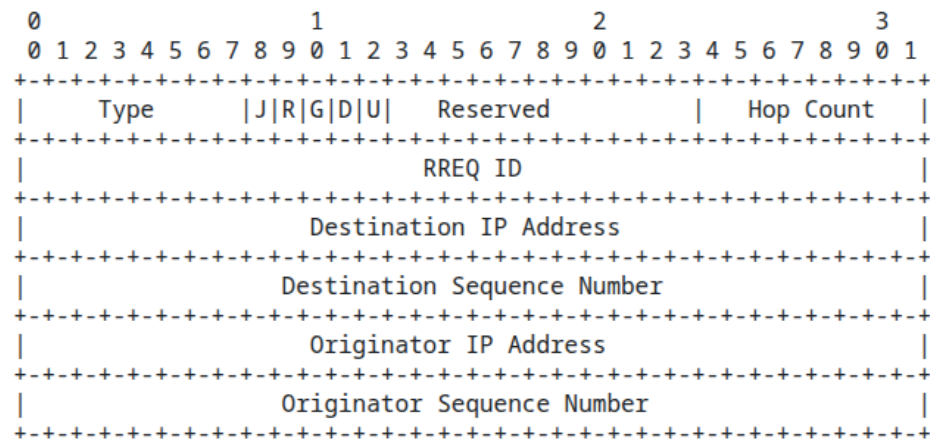


Figure 1. RREQ Message Format [12].

RREP packets are not only used to reply to RREQs but also for hello messages. A hello message is simply an RREP packet with the originator and source fields equal to the sender. As such, an RREP used as a hello message is not routable in the network and is used only in a single link. By using hello messages, nodes create a neighbor table to be used for further routing operations, such as route maintenance. A RREP message contains 20 bytes of information, and its fields are provided in Figure 2.

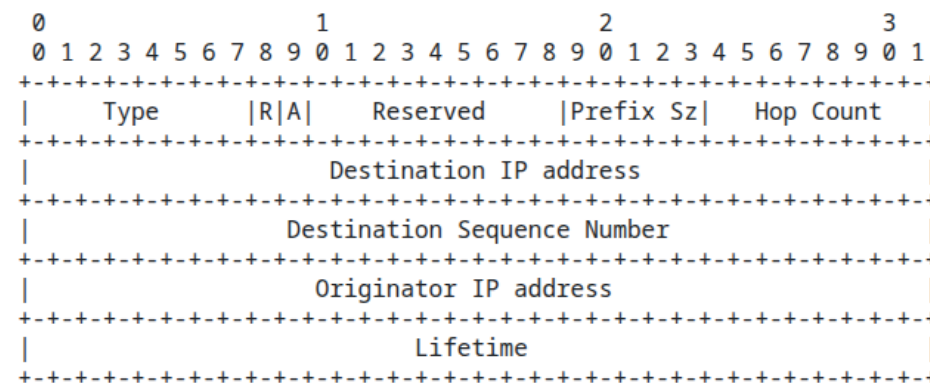


Figure 2. RREP message format [12].

Route maintenance is responsible for keeping routes valid and handling link failures. In AODV, routes are maintained while they are in use and monitored through periodic hello messages exchanged between neighbors, although link-layer acknowledgments are also commonly used. If a node no longer receives hello messages from a neighbor, it assumes that the link is broken. When a link failure is detected, a Route Error (RERR) message is generated to inform other nodes that certain destinations previously reachable via the broken link are no longer reachable. Nodes receiving the RERR message invalidate the affected routing entries and further propagate the RERR message until all affected nodes have been notified. If communication is still needed, a new route discovery process is initiated. RERR is the only message type with a dynamic size, depending on the number of

unreachable destinations via the broken link. The fields of an RERR message are presented in Figure 3.

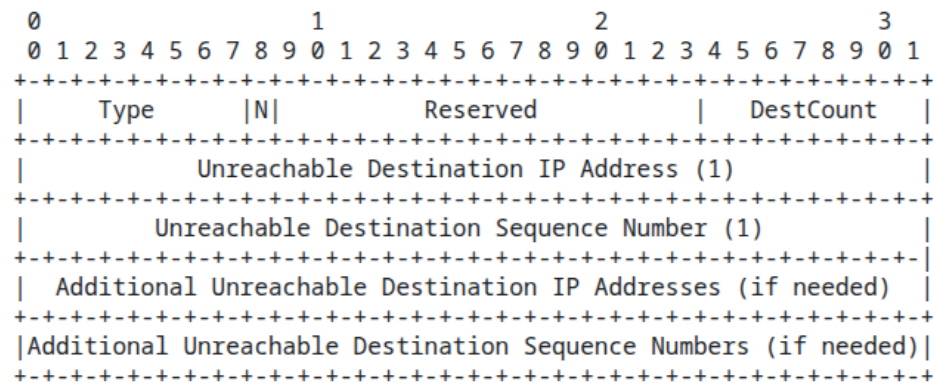


Figure 3. RERR message format [12].

3.3. Static Context Header Compression (SCHC)

Underwater acoustic networks operate at extremely low data rates, typically ranging from a few bytes per second to several kilobytes per second. As a result, packet size has a direct impact on transmission time, which in turn increases the likelihood of collisions and interference. Reducing packet size is therefore a key factor in improving overall network performance.

One approach to achieve this is the use of Static Context Header Compression (SCHC) [27], an IETF standard originally developed for low-power wide-area networks (LPWANs). SCHC reduces header overhead by exploiting the fact that many packet header fields remain constant or change predictably within a given network context. It operates using pre-shared rules between communicating devices, allowing header fields to be fully omitted or partially transmitted. Importantly, SCHC also supports partial field transmission. For example, instead of sending full address fields, only the least significant bytes (e.g., the lower 8 bits) may be transmitted if the upper bits are known from the shared context. This further reduces packet size while preserving the ability to uniquely identify nodes within the network. In addition to header compression, SCHC provides fragmentation mechanisms that enable efficient transmission of packets over highly constrained links, making it well-suited for underwater acoustic communication environments.

3.4. Encryption Overhead Consideration

Security is an important but often overlooked aspect of underwater swarm communication, as these systems may operate in mission-critical environments such as infrastructure inspection, defense, or environmental monitoring. In such scenarios, ensuring the confidentiality and integrity of exchanged data is essential, but must be carefully balanced against the severe resource constraints of the underwater acoustic network.

The Advanced Encryption Standard (AES) [28] is a symmetric encryption algorithm widely used to provide confidentiality in communication systems. In constrained networks, AES-128 is commonly preferred because it provides a good balance between security and computational cost [29].

AES is a symmetric cipher that can be used in two different modes: as a block cipher (e.g., CBC) or as a stream-like cipher (e.g., CTR mode). In its block cipher form, AES operates on fixed-size 128-bit blocks and may require padding when packet payloads are smaller than the block size. This introduces data overhead in the form of padding and optional authentication tags, increasing packet size and transmission time. When used in counter (CTR) mode, AES effectively behaves as a stream cipher, encrypting data byte-

by-byte without requiring padding. In this case, it introduces no inherent data expansion, apart from optional integrity fields (e.g., MAC), but requires synchronization information (such as nonces or counters), which introduces a small amount of control overhead at deployment time.

In underwater acoustic networks, even minimal increases in packet size significantly affect channel occupancy and collision probability. Therefore, an AES-based encrypted configuration is simulated and evaluated in this work to quantify the impact of encryption-related packet-size overhead on routing performance. For stream-mode configurations, where encryption does not inherently increase the payload size, no additional packet-size overhead is assumed (see Section 5).

4. Routing Design Strategies for Ultra-Constrained Acoustic Networks

In ultra-low-rate acoustic networks, routing overhead affects not only protocol efficiency but also channel occupancy, collision probability, and route discovery reliability. Therefore, this work investigates three complementary design strategies for adapting AODV to underwater swarm communication: reducing protocol layers, compressing headers, and tuning timing parameters according to acoustic channel constraints. All designed protocols will be benchmarked against the default AODV implementation.

4.1. Layer-2 AODV Routing Protocol Design

The network layer (Layer-3) in the Open Systems Interconnection (OSI) model plays a big role in scalability and flexibility. However, in specific areas where the network resources (e.g., data rate) are limited, this layer can be removed to reduce the packet size with a trade-off of losing IP compatibility. Underwater acoustic networks can be one of these areas, as they are often low-data rate networks deployed outside of existing IP networks. Limiting packet size as much as possible is a big step towards a stable underwater network. Thus, we implemented a layer-2 AODV to see its effect and removed layer-3 features completely.

Layer-2 AODV is an AODV variation that runs on top of layer-2. It uses the same route discovery, route maintenance, and hello messages, but with the benefit of a smaller packet size. By removing the layer-3 header, 20 bytes of the layer-3 header, and 8 bytes of the transport (UDP) header, at least 28 bytes are removed from every packet. Furthermore, modifications in the AODV headers reduce packet size even more than just removing IP and UDP headers.

Hello messages are used to monitor neighbors and link breaks. Since there is no ACK in both UAN ALOHA MAC and in the custom data application for layer-2, hello messages are the only option left.

As the main purpose of hello messages is to detect neighbors and possibly link breaks (in their absence), they need to have a small size to be efficient. Reusing RREP packets as hello messages, as is the case in normal AODV, where many of its fields are not utilized for hello messages, will waste much of scarce channel airtime. As such, for layer-2 AODV, we create a separate packet format for hello messages that is 10 times smaller than a regular AODV hello message. The hello message format is presented in Figure 4. Compared to default AODV, layer-2 AODV uses a header of only 2 bytes for a hello message instead of 20 bytes. The first byte is used for the header type, and the second one is used for the source address. To make it compatible with the ns-3 UAN model, the source address is saved as an 8-bit address (*Mac8Address*). That information is sufficient to maintain a neighboring table.

where P is the packet size in bytes and N is the number of unreachable destinations. Equation (1) is not a theoretical model, but follows directly from the layer-2 AODV RERR packet format. The first 4 bytes are fixed as *Type*, *Flags*, *Reserved*, and *Number of Unreachable Destination* parameters, 1 byte for each, while the rest is the dynamic part of an RERR message.

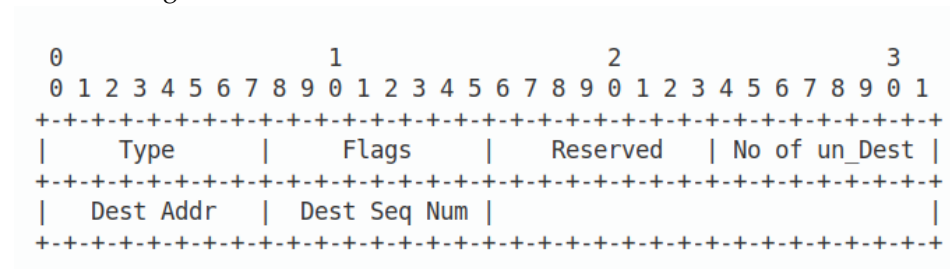


Figure 7. Layer-2 AODV RERR message format.

This approach substantially reduces protocol overhead by removing layer-3 and transport-layer headers, while also avoiding ARP-related exchanges. As a result, it is best suited for closed underwater swarm deployments where all nodes use the same custom protocol stack, while interoperability with IP-based systems becomes more limited.

4.2. AODV with SCHC: Compression Design

An alternative way to reduce the packet size is to utilize compression of the whole packet, rather than removing certain layer overhead. In this section, we utilize SCHC in every node in the network to perform packet compression. A static context is defined and shared between nodes beforehand, containing predefined compression rules. These rules are used to compress not only IPv4/UDP headers but also AODV control packet headers based on known and fixed field values. During packet transmission, nodes apply the corresponding rule and send only the Rule ID and compression residue instead of the full header information. Compression and decompression operations are handled locally at each node using an existing SCHC library [30] that is integrated with the ns-3 simulator. Figure 8 illustrates the basic SCHC compression and decompression process used in this work. Before transmission, the original protocol stack contains the MAC, IP, UDP, AODV, and data fields. SCHC removes or compresses the fields that can be reconstructed from the shared static context and only sends the remaining compressed information together with the Rule ID. At the receiver side, the same shared context is used to reconstruct the original headers before the packet is processed further.



Figure 8. An illustration of the SCHC process.

Even though SCHC is a static and rule-based compression system, it is flexible in defining the rules. Multiple rules can be defined, depending on the size of the rule ID field, ranging from very strict rules to quite flexible ones. The SCHC rules define how each header field is processed during compression using two key components: a matching operator and an action. The matching operator determines how the value of a field is

compared to the predefined rule context. For example, ‘equal’ indicates that the field must match a predefined value exactly and can therefore be omitted in transmission, while ‘ignore’ allows any value and requires the field (or part of it) to be sent. More advanced operators, such as ‘MSB’ and ‘LSB’, enable partial matching, where only the most or least significant bits of a field are compared or transmitted. The associated action specifies how the field is handled in the compressed packet. The ‘not-sent’ action indicates that the field is fully reconstructible from the shared context and does not need to be transmitted. The ‘value-sent’ action transmits the field explicitly, typically when it changes dynamically or cannot be inferred. In the case of partial matching (e.g., MSB/LSB), only a subset of the field is transmitted (e.g., the least significant bytes).

For compatibility with (above-sea) IP networks, applying a rule is not mandatory. It is also possible to disable SCHC compression for certain packet types. Finally, it is possible to update the SCHC rules dynamically.

We apply SCHC to AODV control packets (hello messages, RREQ messages, RREP messages, RERR messages) and data packets. In this study, we do not consider compressing ARP packets since the ARP packets do not have IP and UDP headers, and they are quite small in size. IP header compression is fairly straightforward. Most of the fields of an IPv4 header are fixed or can be ignored for such a control packet. The two main parts of this header are the sender and the receiver IP addresses. Even those can be compressed based on the network subnet size. In our work, we assume that the network size will not exceed 254 nodes; thus, we only consider the last byte of the IP address of a node. Also, the other header fields can be used to distinguish to which rule the packet belongs. In some cases, we considered using TTL or packet length as an indicator if a packet falls into a rule or not. Tables 2–6 provides an overview of all five of the rules that have been defined.

Fields not listed in the tables are matched using the *ignore* operator, and the information is not sent because they are not required by the receiver and can be reconstructed from the shared static context. In this study, we use only five rules, meaning that we can use less than 1 byte for the rule ID field. While that limits our number of rules, it also enables us to utilize less space. As a final optimization, we decreased the rule ID field’s length to 4 bits and encoded it into the MAC header next protocol field, saving another byte.

Compared to the layer-2 approach, SCHC preserves layer-3 operation and is therefore more compatible with IP-based networking. However, it relies on pre-shared compression rules and assumes that addressing and packet formats remain consistent with the shared context.

Table 2. SCHC hello rule.

Header	Field	Matching Operator	Action
IPv4	IP4_V	equal	not-sent
IPv4	IP4_LEN	equal	not-sent
IPv4	IP4_DEVADDR	MSB	LSB
IPv4	IP4_APPADDR	equal	not-sent
UDP	UDP_DEV	equal	not-sent
UDP	UDP_APP	equal	not-sent
UDP	UDP_LEN	equal	not-sent
AODV	AODV_TYPE	equal	not-sent
AODV	AODV_LIFETIME	equal	not-sent

Table 3. SCHC RREQ rule.

Header	Field	Matching Operator	Action
IPv4	IP4_V	equal	not-sent
IPv4	IP4_LEN	equal	not-sent
IPv4	IP4_TTL	ignore	value-sent
IPv4	IP4_DEVADDR	MSB	LSB
IPv4	IP4_APPADDR	MSB	not-sent
UDP	UDP_DEV	equal	not-sent
UDP	UDP_APP	equal	not-sent
UDP	UDP_LEN	equal	not-sent
AODV	AODV_TYPE	equal	not-sent
AODV	AODV_HOPCNT	ignore	value-sent
AODV	AODV_RREQ_ID	MSB	LSB
AODV	AODV_DST_IP	MSB	LSB
AODV	AODV_DST_SEQ	MSB	LSB
AODV	AODV_ORIG_IP	MSB	LSB
AODV	AODV_ORIG_SEQ	MSB	LSB

Table 4. SCHC RREP rule.

Header	Field	Matching Operator	Action
IPv4	IP4_V	equal	not-sent
IPv4	IP4_LEN	equal	not-sent
IPv4	IP4_TTL	ignore	value-sent
IPv4	IP4_DEVADDR	MSB	LSB
IPv4	IP4_APPADDR	MSB	LSB
UDP	UDP_DEV	equal	not-sent
UDP	UDP_APP	equal	not-sent
UDP	UDP_LEN	equal	not-sent
AODV	AODV_TYPE	equal	not-sent
AODV	AODV_HOPCNT	ignore	value-sent
AODV	AODV_DST_IP	MSB	LSB
AODV	AODV_DST_SEQ	MSB	LSB
AODV	AODV_ORIG_IP	MSB	LSB
AODV	AODV_LIFETIME	equal	not-sent

Table 5. SCHC RERR rule.

Header	Field	Matching Operator	Action
IPv4	IP4_V	equal	not-sent
IPv4	IP4_TTL	ignore	value-sent
IPv4	IP4_DEVADDR	MSB	LSB
IPv4	IP4_APPADDR	MSB	LSB
UDP	UDP_DEV	equal	not-sent
UDP	UDP_APP	equal	not-sent
AODV	AODV_TYPE	equal	not-sent
AODV	AODV_NO_DEST	equal	not-sent
AODV	AODV_DST_IP	MSB	LSB
AODV	AODV_DST_SEQ	MSB	LSB

Table 6. SCHC Data Packet rule.

Header	Field	Matching Operator	Action
IPv4	IP4_V	equal	not-sent
IPv4	IP4_TTL	ignore	value-sent
IPv4	IP4_ID	ignore	value-sent
IPv4	IP4_DEVADDR	MSB	LSB
IPv4	IP4_APPADDR	MSB	LSB
UDP	UDP_DEV	equal	not-sent

4.3. Packet Size Comparison

Decreasing the control overhead of AODV by shortening the control packet size is one of the main goals of the proposed protocols. We drop the size of some packets to even 1 byte (AODV hello message). Table 7 shows the comparison of different packet sizes between the default AODV and proposed implementations (both layer-2 AODV and AODV w/ SCHC compression). The values shown consider the MAC header overhead (UAN MAC header) as well. It has a size of 3 bytes, which contains the information of the source, destination, type, and next protocol. The biggest compression is achieved on hello messages for both protocols, reducing the size by 10 to 11 times, respectively.

The LOADng [13] comparison shows that, although LOADng is a lightweight AODV derivative, its control-message encoding does not necessarily minimize on-air packet size under the encapsulation assumptions considered in this work. In contrast, the proposed layer-2 AODV and AODV w/ SCHC schemes explicitly target acoustic-channel occupancy by reducing the actual transmitted packet size. This distinction is important in ultra-low-rate underwater acoustic links, where even small header reductions can noticeably reduce transmission airtime and collision probability.

Table 7. Comparison of packet sizes.

Packet Type	AODV	LOADng	Layer-2 AODV	AODV w/ SCHC
Hello Message	51 Bytes	NaN	5 Bytes	4 Bytes
RREQ	55 Bytes	61 Bytes	11 Bytes	11 Bytes
RREP	51 Bytes	65 Bytes	14 Bytes	10 Bytes
RERR	43 Bytes	61 Bytes	9 Bytes	8 Bytes
DATA (30 Bytes)	61 Bytes	61 Bytes	40 Bytes	37 Bytes

4.4. UAN-Aware AODV Parameter Selection

Since default AODV parameters are designed for terrestrial wireless networks, they cannot be directly applied to underwater acoustic networks, where propagation delay and packet transmission time are much larger. The parameter values used in this work are therefore selected through a constraint-guided tuning process. First, lower bounds are derived from acoustic propagation time, packet transmission time, and AODV protocol requirements. Second, conservative margins are added to account for MAC-layer access delay, forwarding delay, processing delay, and uncertainty in the acoustic channel. Finally, the selected values are evaluated in the considered ns-3 scenarios. Therefore, the modified parameters in Table 8 should be interpreted as scenario-specific acoustic-aware settings, rather than universal optimal constants.

Table 8. AODV parameters tuned for UANs.

Parameter	Default Value	Modified Value
Hello Interval	1 s	15–30–60–90–120
Active Route Timeout	3 s	180 s
Node Traversal Time	40 ms	500 ms
RREQ Rate Limit	10 per s	1 per s
TTL Start	1	3
MAX TTL	35	9
Next RREQ Delay	<1 s	5–11 s

The *Hello Interval* determines how frequently nodes broadcast neighbor-discovery and link-monitoring messages. In underwater acoustic networks, this parameter must be selected carefully because each periodic hello message occupies the channel for a relatively long time. If the interval is too short, the network may spend a significant part of its limited capacity on control traffic only, increasing the probability of collisions. Therefore, the hello interval should first satisfy a channel-occupancy constraint, shown in Equation (2):

$$T_{\text{hello}} \geq \frac{N \cdot T_{\text{tx}}}{C_{\text{max}}} \quad (2)$$

where T_{hello} is the HELLO message interval, N is the number of nodes sharing the channel, T_{tx} is the transmission time of a HELLO packet, and C_{max} is the maximum allowed channel occupancy. Assuming a network of 5 nodes, a data rate of 5000 bps, a default hello message length of 51 bytes and the 18% channel efficiency of ALOHA, the minimum hello interval should be around 2.27 s. However, this is still not realistic as all capacity would then be consumed by the periodic control messages. In the next section, multiple test results are presented and discussed to see the effect of the *hello interval* parameter, leading to the selection of an optimized hello interval parameter of 60 s.

The *Active Route Timeout* determines how long an established route remains valid without recent activity. If the timeout is too short, routes may be invalidated before the protocol has enough time to detect whether a neighbor is still reachable. According to AODV RFC [12], the *Active Route Timeout* must be bigger than $2 \times \text{HelloInterval}$. Since the selected hello interval in this work is 60 s, the *Active Route Timeout* parameter is set as 180 s. This provides an additional safety margin against premature route expiration in the presence of long propagation delays and sparse control-message exchange.

The *Node Traversal Time* defines the expected time required for a routing packet to progress by one hop. In terrestrial wireless networks, the default value of 40 ms is sufficient because propagation delay is almost negligible. This assumption does not hold in underwater acoustic networks. In this study, the *Node Traversal Time* is selected using a conservative one-hop timing budget as in Equation (3):

$$T_{\text{NTT}} \geq T_{\text{prop}} + T_{\text{tx}} + T_{\text{guard}} \quad (3)$$

Assuming an effective interference range of 400 m and an acoustic propagation speed of approximately 1500 m/s, the propagation delay is about 267 ms. In addition, a 50-byte routing packet at a 5000 bps PHY data rate requires about 80 ms of transmission time. Together, these two values already result in approximately 347 ms. Therefore, the *Node Traversal Time* is set to 500 ms by adding a guard margin of about 150 ms. This margin accounts for common MAC-to-PHY layer delay, processing and forwarding delay, SCHC computational cost and uncertainty in the actual distance between the nodes. As a result, the protocol waits long enough before assuming that a routing packet has failed to progress through the network.

The *RREQ limit rate* is the maximum number of RREQ packets that can be sent by a node per second. It is changed to the minimum value possible, which is 1 per second, to prevent RREQ overload in the network. *TTL start* and *max TTL* parameters are changed according to a small-scale underwater swarm network topology, spanning up to 9 hops. Lastly, the *Next RREQ Delay* is calculated by Equation (4):

$$T_{\text{next-RREQ}} = 2 \cdot T_{\text{NTT}} \cdot (TTL_i + T_{\text{buffer}}) \quad (4)$$

where T_{NTT} denotes the *Node Traversal Time*, TTL_i is the TTL value used in the current expanding ring search attempt, and T_{buffer} is an additional buffer value used to provide extra waiting time. The factor 2 accounts for the forward propagation of the RREQ and the return path of the RREP. This delay is especially significant in underwater acoustic networks, since sending the next RREQ too early can cause multiple route discovery attempts to overlap in the channel. Based on the selected *Node Traversal Time* of 500 ms and the TTL values used in this work, the *Next RREQ Delay* changes between 5 and 11 s.

On top of that, to prevent collisions, packet transmission delay and forwarding delay are added to both AODV and ALOHA MAC protocols. To prevent sending a packet immediately after reception, a fixed 500 μs delay is added to the ALOHA MAC protocol. Furthermore, randomization is added for AODV RREQ transmissions, which is between 0 and 500 ms to prevent collisions and interference due to the flooding nature of the route discovery mechanism.

It is important to note that reducing packet size does not reduce the physical propagation delay of the acoustic signal. Instead, packet-size reduction decreases transmission time and channel occupancy, which lowers the probability of collisions in low-rate acoustic channels. The long propagation delay itself is addressed through acoustic-aware AODV timer settings, especially *Node Traversal Time*, *Active Route Timeout*, and *Next RREQ Delay*, etc. In this way, packet-size reduction and parameter tuning address two different but related underwater acoustic constraints.

5. Simulation Environment and Results

In this section, the test environment, simulation parameters, and results are provided in detail and discussed.

5.1. Simulation Environment

The implementation of the L2 AODV protocol, as well as the SCHC compressed version of AODV, is done in the ns-3 network simulator. Simulations are conducted using ns-3 version 3.43 on the Linux Ubuntu 22.04 operating system.

The evaluation is divided into two parts: reachability and scalability tests. These two test groups are designed to evaluate different aspects of the proposed routing protocols. Reachability tests are used to see whether the network can establish and maintain communication properly under low or no data traffic. In this part, metrics such as the hello message loss percentage and the first route creation time are examined. In addition, the hello message loss percentage is also evaluated under different network topologies in order to observe the effect of network topology on neighbor reachability.

The considered topologies in this study are presented in Figure 9. The three topologies are selected to represent different connectivity patterns that can appear in cooperative AUV operations. Multi-AUV systems are often organized in formation structures for tasks such as search, mapping, monitoring, and inspection, where the relative position of vehicles affects both coordination and communication. The line topology represents a sparse multi-hop chain, which is relevant for survey, transect, or inspection-like missions [31]. The ladder topology represents a denser formation with a higher number of neighbors per

node, allowing us to evaluate the effect of local density and increased collision probability. The V-shaped topology represents a branching formation, which is also considered the in multi-AUV formation planning literature [32]. These topologies are therefore not intended to cover all possible swarm configurations, but to provide controlled cases with different neighbor distributions while keeping the number of nodes fixed.

Scalability tests are used to evaluate the protocol's performance under increasing traffic load. For this purpose, single or multiple simultaneous data transmissions are applied to the network to observe how the protocols behave as the data load increases. In this way, both the basic stability of the network and the protocol performance under heavier load can be evaluated. All of the scenarios are simulated at least 50 times, and the results presented are averaged over all 50 tests. The test environment parameters are given in Table 9.

Table 9. Simulation environment parameters.

Parameter	Value
Number of Nodes	10 Nodes
PHY Data Rate	5000 bps
Node Communication Range	270 m
Inter-Node Distance	100 m
Packet Size	30 Bytes
Simulation Duration	90 min
Number of Tests	50 Runs Each Case
Traffic Type	UDP
Propagation Model	Thorp Propagation Model

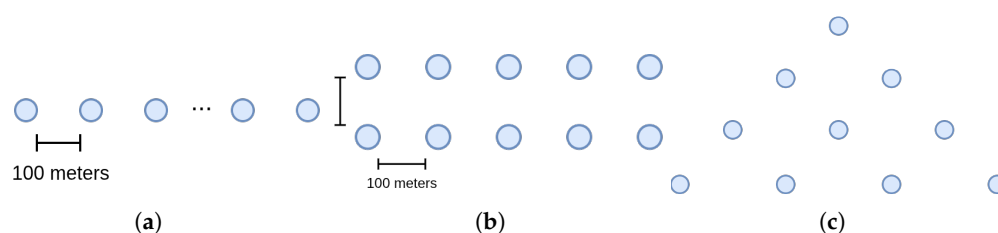


Figure 9. Different topologies for 10 nodes used in the topology test scenarios. (a) Line topology; (b) grid topology; (c) ladder-shaped topology.

The evaluation in this work is based on controlled static topologies. This choice was made to isolate the effect of routing overhead, packet size, and AODV parameter tuning under underwater acoustic constraints. Although the motivating application is cooperative AUV communication, node mobility is not included in the current simulations. Therefore, the results should be interpreted as a controlled evaluation of the proposed routing mechanisms for underwater acoustic mesh networks, rather than as a complete validation of mobile or dynamic swarm behavior. Mobility-aware scenarios, time-varying channels, and experimental validation are left for future work.

The ns-3 UAN model captures important characteristics of underwater acoustic communication, such as low data rate, long propagation delay, and distance-dependent attenuation. However, it does not fully capture all real underwater effects, such as Doppler shifts, rapidly changing multipath, and environmental variations. These effects can further influence routing performance in real deployments. More realistic mobility and channel conditions are therefore left as future work.

5.2. Computational and Memory Considerations

The proposed layer-2 AODV scheme does not introduce additional compression processing; instead, it removes IP/UDP processing and ARP exchanges. Therefore, its computational cost is expected to be comparable to or lower than default AODV, while the routing-table and neighbor-table memory requirements remain of the same order as AODV. The SCHC-based scheme introduces an additional rule-matching and decompression step. However, previous SCHC implementations for constrained LPWAN devices report low processing and memory overhead. For example, Sánchez-Gómez et al. [33] reported SCHC processing times below 8 ms and a memory requirement of 609 bytes per SCHC context on a constrained end device (48 MHz CPU clock). In the underwater acoustic scenarios considered in this work, packet transmission times are much larger than local header-processing times. Therefore, the small computational overhead introduced by SCHC is expected to be outweighed by the reduction in on-air packet size and acoustic channel occupancy.

5.3. Reachability Performance and Topology Tests

Default AODV, AODV w/ SCHC, and its encrypted variation, and layer-2 AODV routing protocols are compared to each other. For reachability tests, the chosen KPIs are hello loss percentage and first route creation time. Hello loss percentage indicates how the network manages itself without any ongoing traffic. Already having a high percentage of hello message losses leads to an even worse performance during ongoing traffic. Route creation time is also an important KPI to measure. Since AODV uses an expanding ring search for routes, optimizing route creation time is important to finish the route discovery process as soon as possible to prevent further RREQ flooding in the network.

Figure 10 shows the hello loss percentage in a line topology for different hello interval values, 30, 60, 90, and 120 s, respectively. Thanks to randomization added in both AODV initiation and hello message intervals, we managed to have a stable network for layer-2 AODV and layer-3 AODV w/ SCHC. Both cases experience less than 3% hello message loss for all tested intervals. On the other hand, the default AODV shows poor performance, with a hello message loss percentage of more than 10% for all tested intervals.

Figure 11 shows the first route creation time in a line topology for all cases, along with the theoretical minimum for each case given a hello message interval. Similar to the previous results on hello message loss, layer-2 AODV and AODV w/ SCHC achieve good results. Lowering the packet size helps with successful data transmission, resulting in better performance for faster route creation time. However, AODV w/ SCHC has slightly worse performance compared to layer-2 AODV, even though they have the same size in RREQ packets. This is due to an extra packet exchange needed by the MAC layer, which is ARP. Since layer-2 AODV does not need to use ARP, it performs better than all of the protocols. In both hello loss percentage and first route creation time tests, the encrypted version of AODV w/ SCHC performs slightly worse than the two protocols. This happens due to the increased packet size caused by the encryption blocks.

Hello loss percentages are also tested using different topologies. The number of neighbors can be different based on the network topology, which may cause better or worse performance depending on the density of the network. We tested three different topologies: line, ladder, and V-shape. Each topology has 10 nodes and the inter-node distance is 100 m (vertical and/or horizontal), as presented in Figure 9. To ensure fairness, we did not change the total number of nodes in the network.

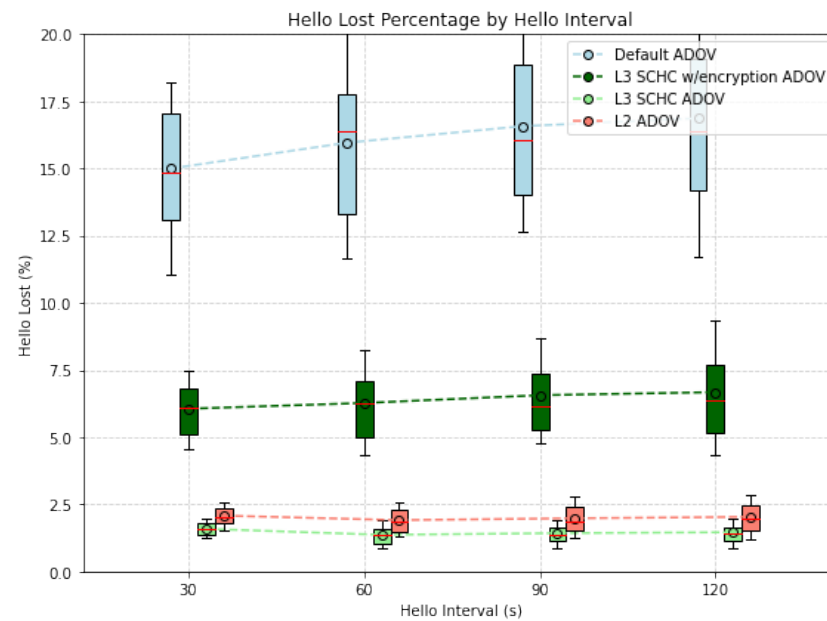


Figure 10. Average of hello lost percentage against hello interval.

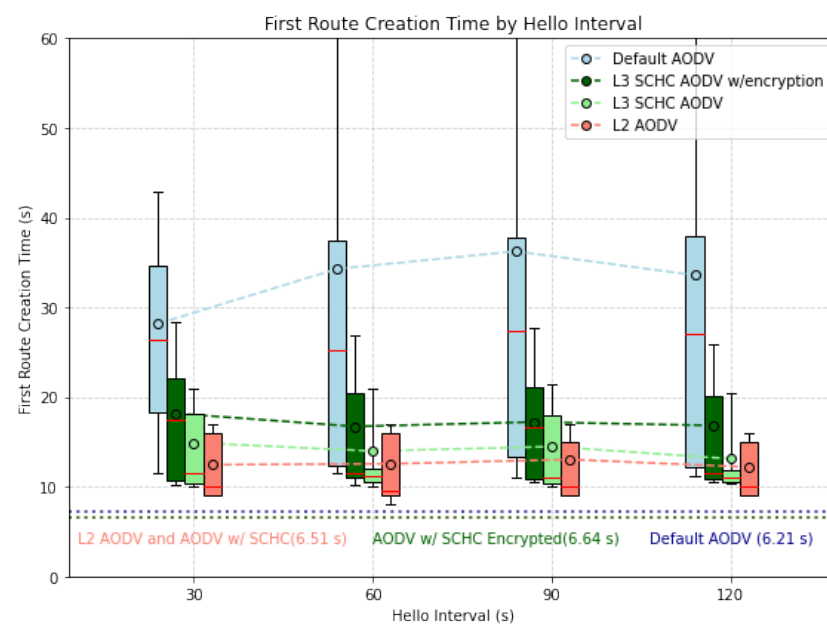


Figure 11. First route creation time by hello interval.

Having the same number of nodes does not ensure the same result across different topologies. Depending on the number of neighbors, signal quality is highly affected due to interference, thus this reflects on the performance of the whole network. It is important to have as few collisions as possible in a constrained network such as UAN. Figure 12 shows the effects of different topologies on hello message loss percentage. The tests are done using the layer-2 AODV protocol for all topologies, and 60 s is chosen as an optimized value for the hello message interval parameter. The ladder topology has the highest average number of neighbors per node; interference and collisions are much higher compared to the line and V-shape. The results show that higher hello message losses are experienced in the denser case, hence for the ladder network topology.

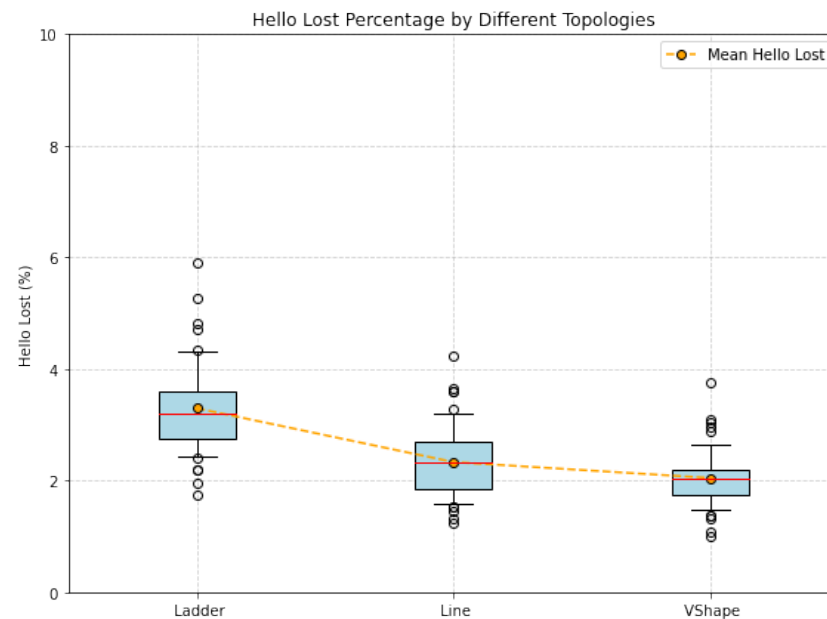


Figure 12. Effect of topologies on hello message loss percentage.

5.4. Scalability Performance

Besides reachability tests, scalability tests were also conducted to evaluate the behavior of the routing protocols under increasing traffic load. Two different test scenarios were considered in a line topology. In the first scenario, one end-to-end flow was created over five hops. This case represents a longer multi-hop communication path in the network. In the second scenario, eight nodes sent data to one central node at the same time. Compared to the first case, this creates a more challenging situation since multiple flows compete for the same acoustic channel. In both scenarios, packet delivery ratio (PDR) was used as the main KPI. Delay was not taken as the main metric because it is strongly affected by the send-or-drop behavior of the ALOHA MAC. The packet interval was gradually reduced from 60 s to 1 s in order to increase the traffic load and observe how the protocols behave under heavier channel usage.

The selected simulation scenarios are intended to represent compact coordination traffic in underwater drone swarms. In such scenarios, AUVs may periodically exchange small status messages for coordination, monitoring, or cooperative navigation. A typical compact message can include position information, velocity or heading information, a timestamp, and a small event or status field. In this work, the application payload is therefore set to 30 bytes. This corresponds to a packet with 12 bytes for position information, 12 bytes for velocity or heading information, 4 bytes for a timestamp, and 2 bytes for an event ID or status flag. The 30-byte payload is selected to represent compact periodic coordination traffic rather than high-volume sensor data or image/video payloads.

The results in Figures 13 and 14 show a clear trend for both scenarios. When the packet interval is high, meaning that the traffic load is low, all protocols achieve relatively high packet delivery ratios. In this case, the channel is less occupied, so the effect of routing overhead is more limited. However, when the packet interval is reduced, the network becomes more loaded, and the difference between the protocols becomes more visible. Under these conditions, the default AODV starts to lose more packets, while layer-2 AODV and layer-3 AODV with SCHC maintain better performance. This shows that routing overhead becomes much more critical when the channel is more heavily used.

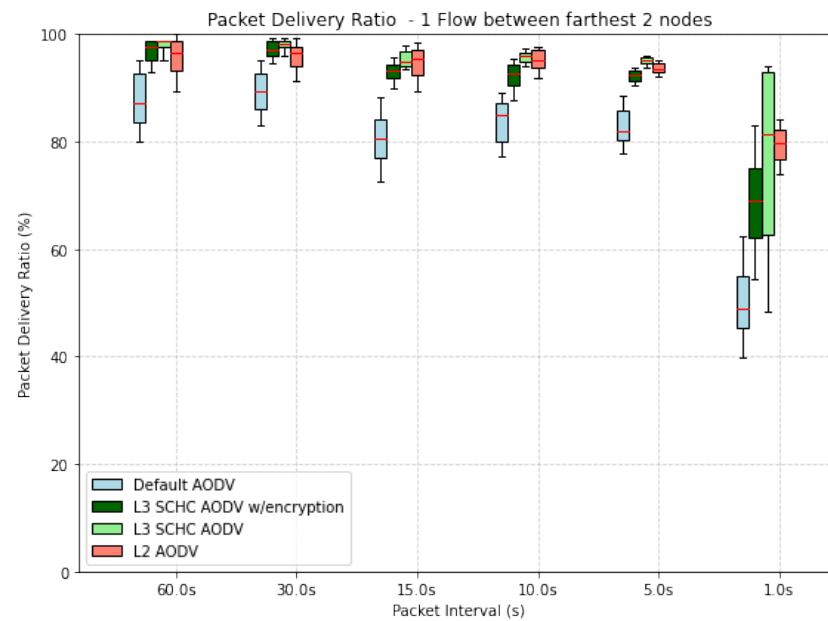


Figure 13. 1 End-to-end flow case.

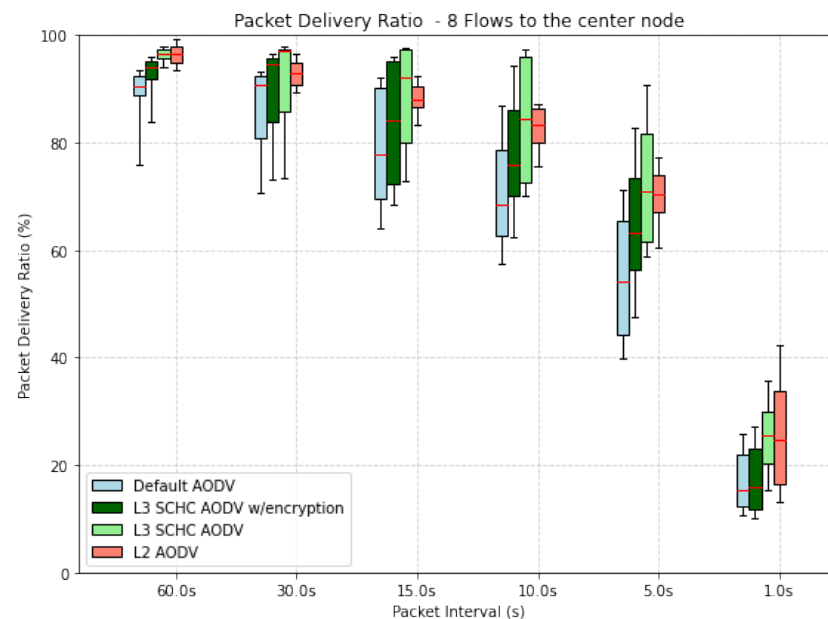


Figure 14. Eight flows to a central node case.

This behavior can be explained by the limitations of underwater acoustic communication. Since the available data rate is very low, the packet size has a direct effect on channel occupancy. Larger packets stay longer on the channel, which increases the probability of collisions, interference, and unsuccessful receptions. This becomes even more important when several nodes are active at the same time. The proposed routing schemes reduce packet size both for control packets and for data transmission. As previously shown in Table 7, the default AODV data packet size is 61 bytes, while it is reduced to 40 bytes in layer-2 AODV and 37 bytes in AODV with SCHC. Similar reductions are also achieved for hello, RREQ, RREP, and RERR packets. Because of this, the proposed protocols occupy the channel for a shorter time and create less overhead during communication. This is the main reason why they perform better in scalability tests.

In addition to PDR, the average number of neighbor link-break detections per node is evaluated as a routing-stability metric. Since the evaluated topologies are static, these

events do not correspond to physical mobility-related link breaks. Instead, they indicate cases where a node considers a neighbor unreachable due to missed hello messages, which can occur because of collisions, channel congestion, or excessive control/data traffic. Therefore, this metric reflects the stability of neighbor maintenance under increasing acoustic-channel load.

Figures 15 and 16 show that default AODV experiences a higher number of neighbor link-break detections compared with the proposed schemes. This is expected because larger control and data packets occupy the acoustic channel for a longer time, increasing the probability of hello message losses and neighbor timeouts. The L3 AODV w/ SCHC achieves the fewest link-break detections in both traffic scenarios, indicating more stable neighbor maintenance under load, followed closely by L2 AODV. This suggests that minimizing packet airtime improves stability in constrained underwater acoustic channels.

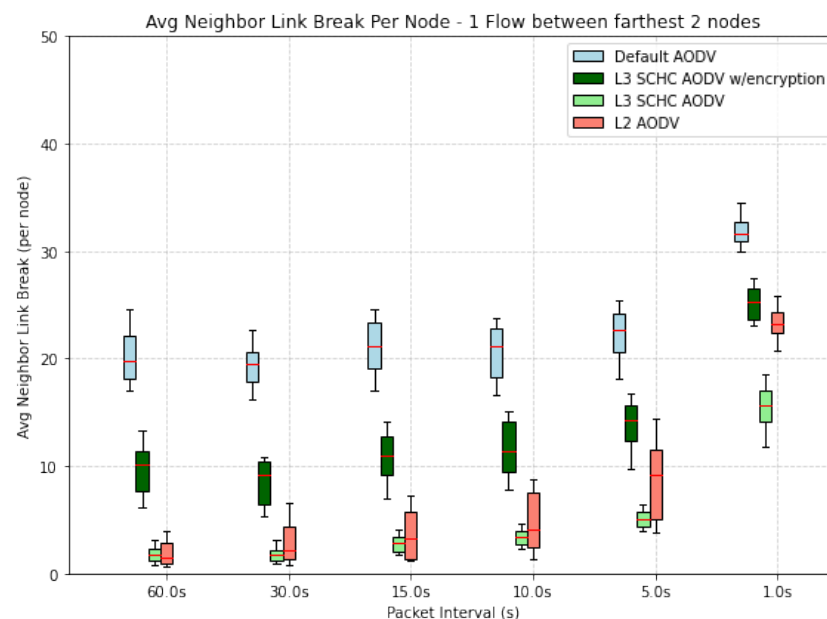


Figure 15. Average neighbor link-break detections per node for 1 end-to-end flow between the farthest two nodes.

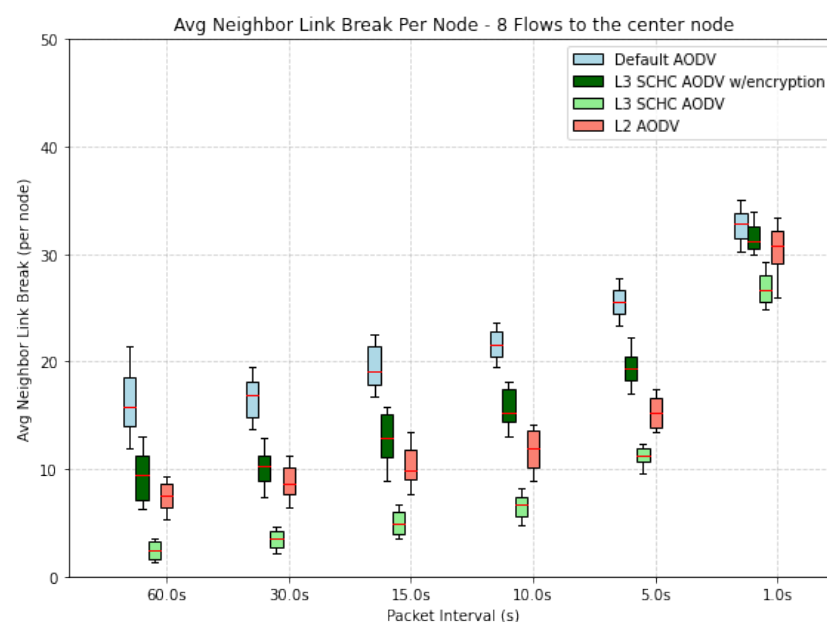


Figure 16. Average neighbor link-break detections per node for 8 flows toward the center node.

Overall, the scalability results confirm the same point observed in the reachability tests. In underwater acoustic swarm networks, reducing routing overhead improves communication performance, especially when the traffic load increases. For the same information payload, smaller packets reduce channel occupancy and lower the probability of collisions. As a result, layer-2 AODV, AODV w/ SCHC, and its encrypted version achieve higher packet delivery ratios than default AODV in the evaluated scalability scenarios.

6. Conclusions and Future Work

In this paper, we investigated low-overhead routing design for underwater acoustic swarm networks. The main goal was to reduce routing overhead in a highly constrained communication environment where low data rates, long propagation delays, and unstable channel conditions make efficient multi-hop communication difficult. For this purpose, three complementary design strategies were considered: architectural simplification through a layer-2 AODV design, protocol-level compression through SCHC-based AODV, and acoustic-aware parameter tuning. The layer-2 AODV approach removes layer-3 features to reduce packet size and avoid ARP-related exchanges, while the SCHC-based approach keeps layer-3 operation and reduces header overhead through static context compression. Both approaches were implemented in ns-3 and compared with the default AODV under different reachability and scalability test scenarios.

The results show that reducing packet size has a clear positive effect on routing performance in underwater acoustic networks. In the reachability tests, the proposed protocols achieved lower hello loss percentage and better first route creation time compared to the default AODV. In the scalability tests, they also achieved higher packet delivery ratios under increasing traffic load. Overall, the results confirm that routing overhead has a strong effect on network performance in underwater acoustic swarm scenarios and that lightweight routing approaches are better suited for such constrained environments. This work also showed that topology and protocol parameter tuning play an important role in underwater acoustic routing. Even when the same number of nodes is used, network density can affect collision probability and hello message loss. In addition, default AODV parameters are not directly suitable for underwater acoustic conditions and need to be adapted according to the long propagation time and low transmission rate of the channel. Therefore, improving routing performance in underwater networks is not only a matter of protocol design but also of properly tuning the protocol to the characteristics of the acoustic medium.

As future work, more realistic swarm scenarios with node mobility should be investigated to evaluate the behavior of the proposed protocols under dynamic topology changes, link breakages, and frequent route rediscovery. Such mobility-aware evaluations would provide a better understanding of how the proposed layer-2 AODV and AODV w/ SCHC schemes perform in actual cooperative AUV deployments. In addition, future work can consider other underwater MAC strategies, larger network sizes, different node densities, and additional security-related overhead. More realistic acoustic-channel conditions, including time-varying propagation, multipath effects, Doppler shifts, and environmental noise, should also be included in future evaluations. Finally, experimental validation beyond simulation, such as pool tests or sea trials, would be valuable to assess the practical applicability of the proposed routing approaches in real underwater acoustic systems.

Author Contributions: Conceptualization, O.O., J.H. (Jetmir Haxhibeqiri), J.-F.D., J.H. (Jeroen Hoebeke) and E.D.P.; Methodology, O.O., J.H. (Jetmir Haxhibeqiri) and E.D.P.; Software, O.O.; Investigation, O.O., J.H. (Jetmir Haxhibeqiri), J.-F.D. and E.D.P.; Writing—original draft, O.O. and J.H. (Jetmir Haxhibeqiri); Writing—review & editing, O.O., J.H. (Jetmir Haxhibeqiri), J.-F.D., J.H. (Jeroen Hoebeke) and E.D.P.; Supervision, J.H. (Jetmir Haxhibeqiri), Jeroen Hoebeke and E.D.P.; Project administration,

J.-F.D., J.H. (Jeroen Hoebeke) and E.D.P.; Funding acquisition, J.-F.D., J.H. (Jeroen Hoebeke) and E.D.P. All authors have read and agreed to the published version of the manuscript.

Funding: The research that led to these results has received funding from the Belgian Defense through contract number 24DEFRA003.

Data Availability Statement: The simulation data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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