Enhancing Communcation in Multi-Domain Ad-Hoc Networks for Maritime Critical Infrastructure Protection

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***Abstract*— The protection of critical maritime infrastructure, such as subsea pipelines and remote research stations, requires the implementation of reliable communication Networks and maritime domain awareness (MDA), particularly in regions where conventional communication infrastructure is either non-existent or inadequate. These regions present unique challenges for communications technology, as they are often either completely isolated or extremely difficult to access. This research addresses a critical gap by developing an improved Ad-hoc On-Demand Distance Vector (AODV) protocol suitable for Multi-Domain Ad-Hoc Networks. Our approach integrates surface and underwater communication domains supported by unmanned surface vehicles (USVs), unmanned underwater vehicles (UUVs), and unmanned aerial vehicles (UAVs), to ensure robust and efficient communication in challenging maritime environments. In particular, we analyze the latency of message types reaching UUVs and the traffic generated over acoustic links in different scenarios at different distances. Our simulation, performed in a custom MATLAB framework, provides insight into the communication delays and traffic load, highlighting the challenges posed by the underwater environment. These tests help to evaluate the theoretical performance and Network stability of our extended AODV protocol. We discuss potential optimizations to overcome these challenges and ensure efficient and reliable data exchange in maritime Ad-Hoc Networks.** **Keywords—Ad-Hoc Networks, IPv6, MATLAB, Radio Communication, Acoustic Communication.**

I. Introduction

In regions where traditional communications infrastructure is inadequate, it is essential to establish integrated Networks that link both underwater and surface platforms. These Networks should use protocols that ensure seamless routing and comply with existing standards to protect critical maritime infrastructure [1]. Autonomous systems, including UAVs, USVs and UUVs, enhance the security of these infrastructures by providing comprehensive surveillance and rapid response capabilities [2]. Effective communication between these systems is critical, using radio links for surface communications and acoustic links for underwater communications. The vast distances at sea, the need for flexible topologies and the impracticality of using terrestrial infrastructure require the adoption of maritime IoT solutions [3]. Our focus is on Ad-Hoc communication Networks, which are particularly suited to the maritime environment due to their ability to form dynamic, self-configuring Networks without relying on pre-existing infrastructure [4]. While both terrestrial and underwater Ad-Hoc Networks are well understood, the integration of these Networks to function seamlessly in a maritime context presents unique challenges. Existing simulation tools need to be evaluated to determine their suitability for modelling these complex maritime Network dynamics, in particular the use of USVs as communication gateways and the integration of both radio and acoustic links. In this paper, we use a simulation framework to evaluate the communication latency and data transfer times between UAVs and UUVs via USV gateways. This analysis is carried out for two different scenarios involving different USVs and UUVs, with the UAV always acting as the initiating node. The objective of this study is to provide a detailed understanding of the latency and efficiency of the Ad-Hoc Network in maritime environments, thereby identifying potential areas for optimization and improvement.

II. Background

This chapter provides an overview of the main routing protocols, discusses the unique challenges faced in maritime Ad-Hoc Networks, evaluates the currently available simulation tools, and highlights the importance and limits of developing specialized simulation frameworks for these complex environments.

A. *Ad-Hoc Routing Protocols for Surface and Underwater Environments*

Ad-hoc routing protocols are essential for dynamic, self-organizing Networks, especially where fixed infrastructure is impractical, such as in maritime environments [4]. The AODV protocol is widely used for its efficiency in establishing routes only when needed, minimizing overhead and traffic. The main message types are Route Request (RREQ) and Route Reply (RREP) [5]. Dynamic Source Routing (DSR) and AODV are both reactive protocols, but there are also protocols that are inspired by nature. Besides Bee Ad-Hoc there is also the Ant based AODV [6]. Unlike DSR, which uses source routing with routes in the packet header, the Ant-based AODV uses probabilistic forwarding inspired by the behavior of ants. Ant-AODV, shows better results in scientific publications compared to AODV and DSR in terms of packet delivery ratio, throughput and average end-to-end delay [7]. These protocols are typically Internet Protocol (IP)-based and are used primarily for surface communications, such as between UAVs and USVs. In contrast, underwater communications often do not use IP-based protocols due to the unique challenges of the underwater environment, such as high latency, limited bandwidth, and the use of acoustic signals. Instead, specialized routing protocols such as Vector-Based Forwarding (VBF) are used, which are designed to meet the specific requirements of underwater acoustic communications [8]. While AODV and the Destination-Sequenced Distance Vector routing (DSDV) have been found to perform in underwater acoustic Networks as well, Optimized Link State Routing (OLSR) and DSR are less suitable due to their high energy consumption, low throughput, and poor packet delivery ratios. Therefore, AODV is generally more suitable for underwater acoustic Networks than other protocols [9]. Especially the Underwater Internet of Autonomous Vehicles (UWIA)-AODV is a protocol designed for efficient route discovery and maintenance in underwater environments, using IP-based routing to facilitate communication [10]. The Protocol Gossiping in Underwater Mobile Ad-Hoc Networks (GUWMANET) on the other hand, is an approach tailored to the specific challenges of underwater communications, focusing on reducing overhead and increasing efficiency [11]. In summary, the choice between these protocols depends on the specific project requirements. The IP-based routing is more suitable for projects that require high integration with existing Networks, scalability, and standardization, while non-IP-based approaches are preferable for scenarios that prioritize Network efficiency and adaptation to underwater conditions. Currently, it remains an open question what further modifications are necessary to effectively implement AODV over acoustic communication in underwater environments.

B. *Challenges in Maritime Ad-Hoc Networks*

Maritime Ad-Hoc Networks face unique challenges due to their separation into overwater and underwater domains. Overwater Networks use Radio Frequency (RF) signals and face issues such as signal propagation, vessel mobility, and environmental interference [6]. Underwater Networks mostly rely on acoustic communications and face limited bandwidth, high latency, variable propagation speeds, and higher power consumption [12]. Connecting these domains requires gateways that translate between RF and acoustic signals and ensure protocol compatibility. Strategic placement of these gateways is essential for efficient communication. An open question is what modifications are required for effective AODV implementation over acoustic communications.

C. *Evaluation of Simulation Tools for Maritime MANETs*

NS-3 and OMNeT++ are widely used Network simulators that support Ad-Hoc routing protocols such as the AODV protocol, making them suitable for simulating terrestrial Ad-Hoc Networks. However, simulating underwater communications using acoustic links presents additional challenges, such as significantly different transmission delays and packet loss due to the physical properties of water, such as multiple propagation path and behavior [13]. Both NS-3 and OMNeT++ do not natively support underwater acoustic communications and therefore require extensions or modifications such as the addition of absorption loss or propagation loss [9]. To address these challenges, we developed a suitable simulation framework from using MATLAB, which is presented in Figure 1. This framework is specifically designed to model the unique dynamics of maritime Ad-Hoc Networks, including the integration of USVs as gateways and the use of both radio and acoustic communication links.

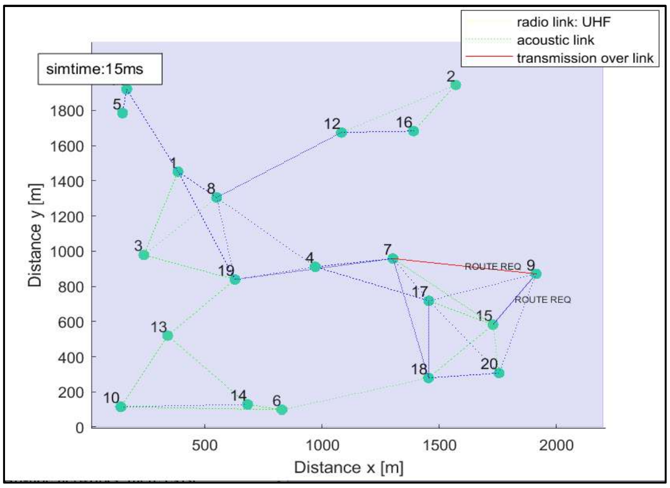

Figure 1: 2D simulation of an Ad-Hoc Network in MATLAB. Red connectors represent the transmission over link, green connectors the radio link and blue connectors represent the acoustic link.

This specialized framework enables more accurate analysis of Network performance, helps optimize gateway selection, and improves overall communication efficiency in challenging maritime environments.

D. *Limitations of Existing Simulations for Maritime Applications*

Realistically simulating underwater Ad-Hoc Networks with MATLAB or any other tool is challenging. First, the low speed of sound in water results in high latencies that are difficult to model accurately. Second, the speed of sound varies with temperature, salinity, and pressure, requiring complex adjustments. Third, reflections from the surface and seafloor cause multipath propagation, which is difficult to simulate realistically [14]. Acoustic noise from natural and human activities degrades signal quality and is often inadequately accounted [15]. Finally, specialized MAC protocols are required, increasing complexity and reducing simulation efficiency [16]. These factors must be considered in order to implement a simulation as realistically as possible.

E. Practical setup of a Multi-Domain Ad-Hoc Network

In order to set up a Multi-Domain Ad-Hoc Network, it is necessary to carry this out conceptually in a simulation, as well as initial physical tests. For our work we have decided to develop and test the logic of the Network Layer which is based on AODV in the simulation. This will then be tested in practice. Therefore, we use a USV, which will act as a translator from radio to acoustic communication in the future. A seamless Ad-Hoc protocol will enable interoperability between the domains.

III. SIMULATION FRAMEWORK FOR MARITIME DOMAIN

The framework enables the simulation of interactions between different types of unmanned vehicles - UAVs, USVs, and UUVs - in realistic maritime scenarios and tests the Network dynamics under different conditions. Our simulation framework is based on the Open System Interconnection (OSI) model, which provides a standardized framework for Network protocols and their interactions. Specifically, our simulation focuses on accurately modeling the Physical Layer, Data Link Layer and Network Layer, to address the unique challenges of maritime communication environments. Each Layer is designed to meet the specific requirements of the maritime domain, ensuring robust and efficient communication across different environments.

A. Main Simulation

The main simulation iterates through each node in the Network, establishing core functionality based on the Network topology. The key properties of each node include connecting to neighboring nodes via radio or acoustic links, moving according to predefined motion functions, and generating pakets once. Each node is processed individually to establish connections with its neighbors. Connections are determined based on the communication medium - radio for surface links and acoustic for underwater links. Nodes are moved according to specific motion functions, simulating realistic motion patterns for UAVs, USVs, and UUVs. We have deliberately chosen a 3D simulation to differentiate our work from traditional Network simulators such as NS-3 and OMNeTT++, which operate primarily in a 2D space. This choice allows a more realistic representation of the maritime environment, capturing the complexities of three-dimensional movement and communication between airborne, surface, and underwater nodes and is shown in Figure 2. This dynamic aspect allows the simulation to account for the constantly changing Network topology in maritime environments. Each node generates packets once to initiate the communication process. This initial packet generation initiates the routing and data transmission procedures within the Network.

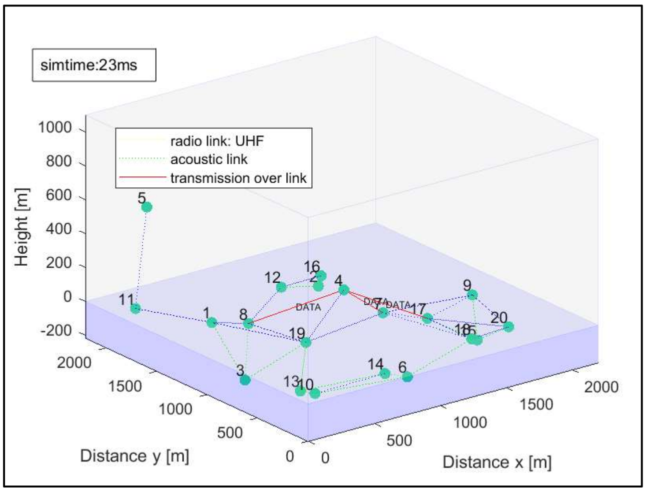

Figure 2: Extension of the Simulation in 3D to simulate a realistic operational scenario.

B. Simulation of the Nodes

Each node in the simulation can generate packets and access the Network Layer where the AODV protocol operates. Nodes also handle packet reception, sorting them into different queues based on type and priority. Nodes create packets to initiate communication. They access the Network Layer to use the AODV protocol for route discovery and maintenance. Nodes receive packets over radio or acoustic links, which are then processed and placed into appropriate queues. Received packets are sorted into different queues. This queuing mechanism helps to efficiently manage traffic, prioritize critical messages, and ensure timely delivery of data. Different queues handle control messages, data packets, and error messages.

C. Link Layer

The Link Layer in our simulation framework plays a crucial role in managing the communication channels between nodes. It ensures that the channels are appropriately blocked for the duration of transmissions, taking into account various factors such as antenna duration and propagation delays. The primary function of the Network Layer is to block the communication channel during data transmission to prevent collisions and ensure data integrity. In the simulation, the calculation of transmission time in the radio domain is derived from Network engineering principles. There are several Media Access Control (MAC) protocols that can be used to manage access to the communication medium. In our framework, we have chosen the basics for implementing the ALOHA protocol. ALOHA is a simple and effective protocol for managing the transmission of data in a Network where nodes communicate over a shared medium. It helps to identify collisions and ensures efficient use of the communication channel. The duration for which the channel is blocked is calculated based on the time required for the antenna to transmit or receive a signal and the additional delay introduced when transmitting between USVs and UUVs or between UUVs, which are described in the Physical Layer.

D. Physical Layer

The Physical Layer is responsible for realistically modeling the propagation of electromagnetic waves for radio communications and acoustic signals for underwater communications. This layer ensures that the transmission characteristics reflect the actual physical environment, providing a more accurate simulation of maritime communications. For radio communications between UAVs and USVs, the Physical Layer models the propagation of electromagnetic waves, including factors such as the degradation of signal strength as it travels through the air, which is affected by distance and environmental conditions, and the effects of obstacles and the earth's surface on radio waves, causing them to be reflected or diffracted, which affects the range and strength of the signal. It also takes into account the presence of background noise and potential interference from other sources that can degrade signal quality. For underwater communications between USVs and UUVs or between UUVs, the Physical Layer models the propagation of acoustic signals, including factors such as the speed of sound in water, which varies with temperature, salinity, and. This propagation delay accounts for the time it takes for the acoustic signals to travel through the water. Given the slower speed of sound in water compared to radio waves in air, this delay can be significant and must be accurately modeled to ensure realistic simulation results. In the simulation, the calculation of transmission time in the radio domain is derived from the principles of Network engineering. The transfer time is discovered by converting the packet length into bits and dividing by the effective transfer rate. This is shown in equation 1:

$$duration = \frac{\text{packetlen} \times 8 \times 1000}{(\text{r\_bitrate}) \times (\text{R\_coding})} \quad (1)$$

The formula takes into account the packet size, bit rate, and encoding rate to determine the duration of the packet transfer. The (r_bitrate) represents the bitrate, the rate of data transfer, measured in kilobits per second (Kbps). The (R_coding) is the coding rate, which takes into account the redundancy that is added by the forward error correction to improve reliability. Acoustic propagation delay is calculated by first determining the speed of sound, which depends on several factors including average depth, temperature, salinity, and other constants. Subsequently, the average depth and temperature of the water are calculated, along with the distance between the two nodes. The delay is calculated using the following equation 2:

$$delay = \frac{\text{distance}}{\text{sos}} \quad (2)$$

The symbol "sos" represents the speed of sound. This method ensures that the simulation accurately reflects the real-world delays experienced in both radio and acoustic communications.

IV. Analysis of RREQ, RREP and Data Message Types

The structure and functionality of the RREQ, RREP, and Data messages in the AODV protocol are based on Requests for Comments (RFC) 3561 [17]. These messages are essential for route discovery and maintenance in Ad-Hoc Networks. Our simulation framework and the protocols analyzed are based on IPv6, which offers several advantages over IPv4, including a larger address space, improved routing efficiency, and enhanced security features. IPv6 uses 128-bit addresses compared to the 32-bit addresses used in IPv4, allowing for a significantly larger number of unique addresses. In the context of the AODV protocol, IPv6 enables more efficient routing and scalability, which is particularly important in dynamic and large-scale Ad-Hoc Networks. The structure of messages in AODV, such as RREQ, RREP, and Data messages, must conform to the IPv6 address format. The bit definitions for these message types are detailed in the following chapter.

A. *Structure and Functionality of RREQ, RREP and Data*

The RREQ, RREP, and Data messages in the AODV protocol are structured to facilitate route discovery and maintenance in IPv6-based Ad-Hoc Networks. The RREQ message initiates the process by sending specific message, which contains essential addressing and sequence information. Upon receiving the RREQ, the destination or an intermediate node responds with a RREP (shown in Table 1) message containing the necessary details to establish a reverse route to the source. Once the route is established, data messages are sent along the path containing the source and destination addresses and the payload. These messages provide dynamic, efficient, and reliable communication across the Network. In addition, Hello messages can be used in AODV to verify the connectivity of neighboring nodes and to maintain up-to-date routing tables. These messages are periodically sent by each node to its immediate neighbors to confirm their presence and to ensure that the links between them are active. Hello messages help detect link failures early, allowing the Network to dynamically adapt and maintain reliable communication paths.

Table 1: Structure of a RREP Message in IPv6

Parameter	Bits reserved for RREP
Type	8
Flag	8
Hop Count	8
Destination IPv6 Adress	128
Destination Seq Number	32
Source IPv6 Adress	128
Lifetime	32

B. *Route Error Messages (RERR)*

Route Error (RERR) messages are essential for maintaining the integrity of the routing tables in AODV. When a link failure or an unreachable destination is detected, a RERR message is generated and propagated through the Network to inform other nodes of the invalid route. This mechanism ensures that nodes promptly remove the invalid routes from their tables, preventing the use of outdated or incorrect routing information. The RERR message contains information about the unreachable destinations, including their addresses and sequence numbers, which helps nodes accurately update their routing tables. The handling of RERR messages differs between overwater and underwater AODV implementations due to the different characteristics of their communication environments. In overwater AODV, RERR messages are transmitted using radio waves, which have high bandwidth and low latency, allowing for rapid dissemination of error information. In contrast, underwater AODV relies on acoustic signals for RERR message transmission, which introduces higher latency and potential delays in error propagation due to the slower speed of sound in water and the susceptibility of acoustic signals to environmental factors. This can result in a slower Network response to link failures and a higher probability of temporary routing inefficiencies until the error information is fully propagated and alternative routes are established.

C. *Challenge in Reaching UUVs*

The greatest difficulty in integrating UUVs into an Ad-Hoc Network, even if the gateway function is provided by USVs, is that the underwater propagation speed of acoustic signals is about 1,500 meters per second, much slower than the airborne speed of radio waves, which is about 300,000 kilometers per second. This significant difference in propagation speed results in longer delays for message delivery and acknowledgement, further complicating the timely and efficient exchange of data. UUVs are also frequently in motion, which means their positions change frequently. This mobility requires constant updates of their locations within the Network, which is challenging due to the high latency and limited bandwidth of underwater communications. Maintaining up-to-date information about the position of UUVs is particularly difficult because the transmission of Hello messages, which are used to verify the connectivity of neighboring nodes, is less frequent and less reliable underwater. The high latency and potential delays in transmitting these messages mean that by the time a Hello message is received, the UUV may have moved to a new location. This results in increased difficulty in maintaining accurate and up-to-date routing tables, leading to potential route failures and increased Network overhead to rediscover routes.

D. *Impact of Multiple UUVs at Different Depths: Conceptual Structure*

In this chapter, we describe the setup of our simulation, which investigates the impact of multiple UUVs operating at different depths. The core scenario involves UAVs, referred to as Node 4, that needs to send a message, for example a position change message, to the UUVs. The central interface in this communication is provided by the gateways, which are represetend as USVs. These gateways perform a critical translation function from the radio communication used by the UAV to the acoustic communication used by the UUVs. In our scenario, which is presented in Figure 3, the gateways are USV 19 and USV 20. The UUVs to receive the data are UUV 3 and UUV 15. Characteristic of the AODV protocol is that other nearby UUVs may also receive the message, but they will not process the message unless it is specifically addressed to them. The distance from USV 19 to UUV 3 is 470 meters, while the distance from USV 20 to UUV 15 is 432 meters. These distances are calculated with the euclidiean distance of the three dimensions. The simulation setup thus examines how effectively messages can be relayed from airborne to underwater vehicles via surface gateways, considering varying distances and the involvement of multiple UUVs.

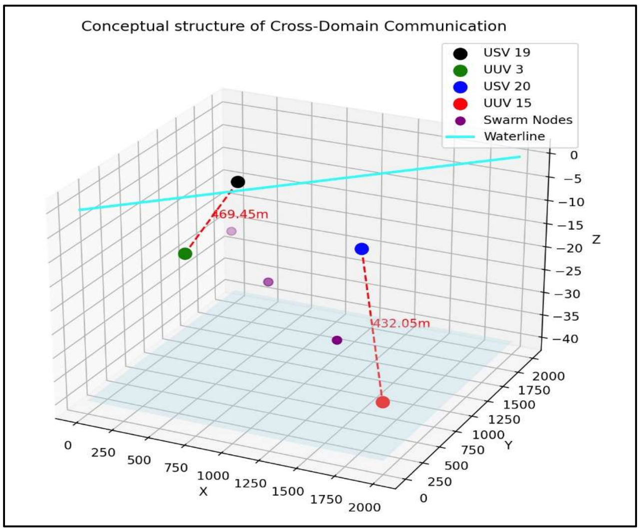

Figure 3: Concept of the data routing from USV 19 to UUV 3 and from USV 20 to UUV 15. The sending node is a UAV in both scenarios.

E. *Traffic Analysis*

In this chapter, we analyze the traffic generated in our simulation, focusing specifically the RREQ messages. We measure the time it takes for these RREQ messages to travel from the UAVs to the respective UUVs via the USVs acting as gateways. The message RREQ is sent by UAV 4 and the time taken for this RREQ to be received in full by UUV 3 and UUV 15 via gateways USV 19 and USV 20 is measured and is presented in Figure 4. Our measurements show that UUV 3 received the RREQ from UAV 4 through USV 19 in 313 ms. In contrast, UUV 15 received the RREQ from UAV 4 via USV 20 in 207 ms. The difference in transmission times can be attributed to the different distances between the USVs and the UUVs. Specifically, the distance from USV 19 to UUV 3 is 37.4 m shorter than the distance from USV 20 to UUV 15. This shorter distance results in a slightly longer transmission time for the RREQ to reach UUV 3. Similarly, we observed the transmission of data packets. After AODV established the route through each node, data packets were sent from UAV 4. UUV 3 received the data via USV 19 after 971 ms, while UUV 15 received the data via USV 20 after 613 ms. Again, the difference in transmission times is explained by the different distances between the USVs and the UUVs. The overall longer transmission times for data packets compared to RREQ messages is due to the significantly larger byte size of the position data packets, which was approximately 1000 bytes. This larger data size increases the transmission time, highlighting the importance of optimizing data packet size and transmission protocols. Furthermore, the bytes were analyzed, which are generated by the acoustic communication of both simulations. It should be noted, however, that in addition to UUV 3 and UUV15, there are other UUVs in the Network that also receive the RREQs, but do not process them because they are not destination nodes. This leads to the explanation of the bytes, which were also evaluated in Figure 4. The first simulation of USV 19 to UUV 3 resulted in a total of 7766 bytes and the simulation of USV 20 to UUV 15 resulted in 6662 bytes. The difference can be explained by the difference in simulation time.

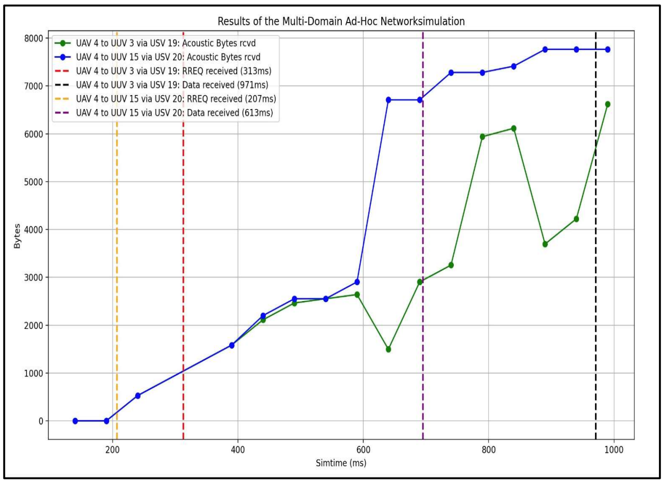

Figure 4: Results of the simulation. The simulation time and the bytes generated during data transfer are shown. The time at which the message types RREQ and Data reach the UUVs is illustrated.

V. Conclusion and Outlook

In this paper, we have fundamentally explained the importance of establishing a seamless Ad-hoc Network that operates both above and below water. Existing routing protocols and potential simulation tools were reviewed to understand their applicability in the maritime domain. Based on the performance analysis, AODV was selected and simulated.

A. *Summary and Findings*

Existing routing protocols and potential simulation tools were reviewed to understand their applicability in the maritime domain. Based on the performance analysis, AODV was selected and simulated using MATLAB. The application of AODV based on IPv6 shows that the structured message types (RREQ, RREP, and RERR) introduce a specific overhead. Each message type requires a certain bit size for the necessary information, which contributes to the overall message overhead. Our simulation showed that AODV can effectively handle both overwater and underwater communications, with USV gateways facilitating the transition between radio-based and acoustic-based links. By simulating the propagation delay of acoustic channels, we showed that it can take nearly 1000 ms for data to be successfully transmitted to a UUV, highlighting the latency involved. While it is debatable whether IP-based Ad-Hoc data routing is suitable for underwater use, our simulation shows that the overhead for RREQ messages results in relatively short delays of 200 ms to 300 ms. The major advantage of using IP-based routing both above and underwater is the high interoperability of the Networks. Gateways do not require extensive modifications to switch from non-IP-based to IP-based routing. In the future, it will be critical to implement logic to select the appropriate USV to reach the required UUV. Our simulation clearly shows that data transmission over the acoustic link can take from 300 ms to nearly 1000 ms. This highlights the need for the Network to understand the mission plans of the UUVs in order to reconfigure the Network in advance. Ultimately, our research suggests that in the evolution of AODV, especially for future Multi-Domain routing approaches, Network reconfiguration with embedded intelligence will be a critical foundation.

B. *Future Work*

In future work, it would be feasible to analyze how to enable targeted routing, ensuring that routing is done only through those USVs that have a realistic chance of reaching the UUV at a given time. This approach will involve developing algorithms that dynamically select the optimal USVs for routing. In addition, it is necessary to monitor ongoing research and explore ways to improve the performance of AODV in underwater environments. By focusing on the unique challenges of underwater communications, we aim to optimize AODV to take full advantage of standardized IPv6 routing both above and below the water surface. This includes addressing issues such as latency, bandwidth limitations, and signal attenuation to ensure robust and efficient communication in the maritime domain.

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