RELIABLE AND ENERGY-EFFICIENT ROUTING FRAMEWORK FOR UNDERWATER SENSOR NETWORK USING SINK MOBILITY AND COOPERATIVE DIVERSITY

Ph.D Thesis

by

Shujaat Ali

152-FBAS/PHDCS/F16

Supervisor

Dr. Muhammad Nadeem
Assistant Professor

Co-Supervisor

Prof. Dr. Sheeraz Ahmad
National Iqra University, Peshawar

Department of Computer Science
Faculty of Computing and Information Technology
International Islamic University, Islamabad, Pakistan

2024

PhD

A dissertation submitted to the
Department of Computer Science
International Islamic University, Islamabad
as a partial fulfillment of the requirements
for the award of the degree of
Doctor of Philosophy in Computer Science.

INTERNATIONAL ISLAMIC UNIVERSITY ISLAMABAD
FACULTY OF COMPUTING AND INFORMATION TECHNOLOGY
DEPARTMENT OF COMPUTER SCIENCE

Date: 29 Aug, 2024

Final Approval

It is certified that we have read this thesis, entitled "Reliable and Energy-Efficient Routing Framework for Underwater Sensor Network using Sink Mobility and Cooperative Diversity" submitted by Mr. Shujaat Ali, Registration No. 152-FBAS/PHDCS/F16. It is our judgment that this thesis is of sufficient standard to warrant its acceptance by the International Islamic University Islamabad for the award of the degree of PhD in Computer Science.

Committee

External Examiner:
Dr. Muazzam A Khan Khattak,
Professor,
Department of Computer Science,
QAU University, Islamabad

External Examiner:
Dr. Adnan Sohail,
Professor,
IQRA University, Islamabad

29/08/2024

Internal Examiner:
Dr. Syed Musharraf Ali,
Assistant Professor,
Department of Computer Science,
FCIT, IIUI

Supervisor:
Dr. Muhammad Nadeem,
Assistant Professor,
Department of Computer Science,
FCIT, IIUI

Co-Supervisor:
Dr. Sheraz Ahmed,
Professor,
Department of Computer Science,
INU, Peshawar

29/8/24

Declaration

I, Shujaat Ali, affirm that the doctoral dissertation entitled "Reliable and Energy Efficient Routing Framework for Underwater Sensor Network Using Sink Mobility and Cooperative Diversity" submitted for the Doctor of Philosophy degree at International Islamic University is a product of my original research. To the extent of my understanding, unless explicitly acknowledged within the text, this dissertation does not include any previously published or authored material from another individual or any portions thereof. The work has not been previously submitted, either partially or in its entirety, for any other academic degree or professional qualification. Although certain sections of the introduction or literature review may reference existing research, all findings, analysis, and conclusions presented in this book are solely derived from my efforts. I have appropriately referenced all source material and resources by established academic practices. This doctoral dissertation results from my intellectual endeavor and does not include plagiarized material or violate copyright laws.

Shujaat Ali

Reg no: 152-FBAS/PHDCS/F16

Date:

Place: International Islamic University, Islamabad

Acknowledgements

I owe an outstanding debt of gratitude for the many things that made the successful completion of my Ph.D. dissertation possible. Most importantly, I thank the Almighty for giving me the strength, determination, and opportunities to stay afloat via this sojourn.

I want to take the opportunity to express deep thankfulness to my supervisor, Dr. Muhammad Nadeem, for his extraordinary guidance, recommendations, and constant support throughout the process. He was an excellent source of deep expertise, insightful knowledge, and continuous encouragement in developing and successfully completing this research. I have had the honor and privilege of working under his guidance.

I would also like to sincerely thank my co-supervisor, Dr. Sheeraz Ahmed, for his academic mentorship. He provided thought-provoking feedback and a willingness to enter into fruitful discussions that ultimately improved the quality of my work. His commitment to time and sharing of that experience has been pure gold.

I thank my family for all the love, patience, and support that constantly accompanied me in this doctoral journey. Your unshakable belief in me and those heartfelt prayers helped me through the tough times to where I am today.

Hopefully, the research presented in this dissertation can add meaningfully to the existing body of knowledge on its topic. I sincerely thank everyone who has provided invaluable assistance and mentorship to complete this work.

Shujaat Ali

Abstract

Underwater sensor networks (UWSNs) are necessary for environmental monitoring and exploration. Still, they are faced with unique challenges that differ from terrestrial communication, such as (a) high latency, (b) limited bandwidth, and (c) energy constraints. This research aims to develop an advanced framework to address these challenges to achieve better performance and increase the Acoustic Sensor life span. IoT-driven Location Aware Framework (ILAF) was developed for efficiency by minimizing broadcast packet responses and weaning out equitable energy consumption. Mobile sinks traverse specific regions to refresh data both vertically and horizontally. Sensors are randomly distributed and classified based on depth, transmission range, and location. In dormant mode, relevant sensors sleep until thresholds are reached; otherwise, only those sensors awake and respond to broadcast messages, transitioning to an active state. The node placement and routing are done optimally without using GPS, and the location of a sensor node is determined by x and y coordinates. The neighboring node is detected by transmission range. Numerical simulations show that ILAF achieves 99% PDR, saving as much as 20% energy over existing protocols. Fewer dead nodes and higher throughput are obtained, rendering ILAF suitable for real-time underwater applications. The Mobility-Adaptive with Energy-Aware Relay Node Selection (MAEARS) framework optimizes network structure based on node energy levels and mobility in real time to overcome dynamic topology and bandwidth constraints in 3D underwater environments. It achieves a PDR of 96.81% with low energy consumption and prolonged network lifespan. The Reliable and Energy Efficient Framework with Sink Mobility (REEFSM) takes advantage of advanced energy management strategies, which save up to 43% of energy compared to other protocols while increasing reliability by 35%. Minimum data packet drops and data accuracy that is sustainable and reliable for underwater acoustic sensor networks. 2D and 3D frameworks for localization, routing, and handling mobility issues. Energy consumption across the network is balanced, data transmission reliability is improved, and operations extend the operational lifecycle. Future work will incorporate lightweight IoT protocols, energy harvesting schemes, and machine learning models to enhance network performance in large-scale underwater deployments.

Contents

List of Figures

List of Tables

Abbreviations

ASN	Acoustic Sensor Node
AUV	Autonomous Underwater Vehicle
BCN	Beacon
BER	Bit Error Rate
BPS	Bits per Second (data rate unit)
BW	Bandwidth
CSMA	Carrier Sense Multiple Access
EA	Energy Adaptive
FD	Frame Duration
GPS	Global Positioning System
IoT	Internet of Things
MAC	Medium Access Control
MS	Mobile Station
PDR	Packet Delivery Ratio
PHY	Physical Layer
PRR	Packet Reception Ratio
QoS	Quality of Service
RA	Routing Algorithm
RBC	Receive Broadcast
RSL	Relay Sensor Node
RSSI	Received Signal Strength Indication
S-ALOHA	Slotted ALOHA
S-MAC	Sensor MAC
SNR	Signal-to-Noise Ratio
UASN	Underwater Acoustic Sensor Network
UCP	Underwater Communication Protocol
ULR	Underwater Localization Regions

UWSNs	**U**nderwater **W**ireless **S**ensor **N**etworks
WSN	**W**ireless **S**ensor **N**etwork

Chapter 1

Introduction

This chapter explores the realm of underwater wireless acoustic sensor networks, starting with a historical background to set the context. It then explores the infrastructure of these networks, providing a detailed analysis of their design and operational dynamics. A key focus is acoustic communication, examining its principles and challenges in underwater settings. This chapter also highlights the research significance, addresses the challenges and requirements of the field, defines the aims and objectives of the study, outlines the research contributions, and provides an overview of the dissertation's structure.

1.1 Background

Underwater Sensor Networks (UWSNs) are crucial for exploring and monitoring the extensive aquatic habitats of the Earth. The underwater domain covers over 70% of the Earth's surface and has always presented difficulties for thorough investigation and monitoring because of its intrinsic complexities. Utilizing technical breakthroughs, particularly in networks that rely on sensors, has become a crucial method for uncovering the enigmas of the undersea realm. This study explores the complexities of Underwater Wireless Sensor Networks (UWSNs), specifically emphasizing their design, communication protocols, and the primary objective of improving exploration and surveillance capabilities in underwater environments [2].

Ten percent of the extensive underwater areas have been surveyed or monitored thus far despite the immense importance of these ecosystems. The growing significance of undersea exploration arises from its various applications encompassing surveillance and resource exploration such as oil, and environmental monitoring. Deploying underwater sensor networks enables the investigation of these resources. Underwater networks differ from land-based systems because they utilize acoustic waves instead of electromagnetic waves for transmission, providing unique benefits. The decision is made based on the exceptional efficacy of acoustic signals in underwater settings, as evidenced by experimental investigations that compare the propagation characteristics of acoustic and electromagnetic waves [3].

1.2 Infrastructure of Sensor Networks

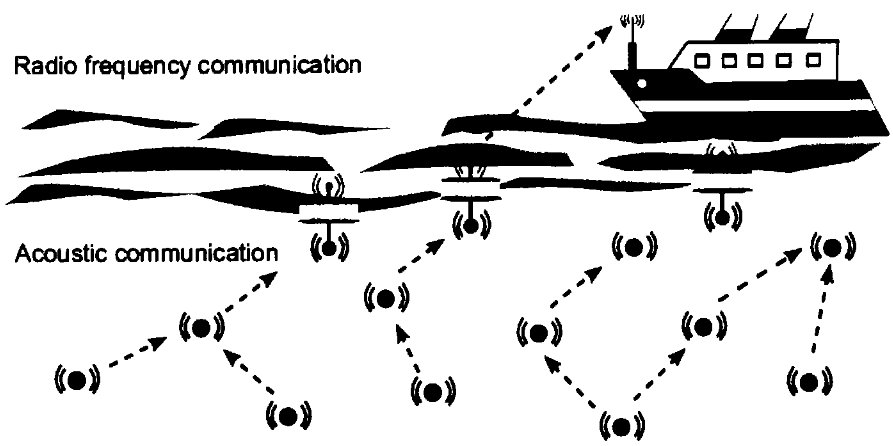

FIGURE 1.1: Sensor Nodes in Shallow Water [1]

The placement of sensors in underwater environments is regulated by various configurations and communication structures described in the current body of research. Researchers [4] have suggested several topologies, designs, and techniques for sensor placement. The configurations are classified into mobile, fixed, and hybrid combinations, considering two-dimensional or three-dimensional coverage in the aquatic environment. Figure 1.1 depicts fundamental instances of sensors installed in shallow waters, highlighting the complexities of underwater sensor networks.

The acoustic scenario contains a diversified arrangement of moving vehicles, anchors receiving data from sensors, and inter-sensor communication through an Information-Carrying Routing Protocol [5]. This network utilizes floating and stationary sensors fitted with acoustic modems to transmit sensed data to the sink by acoustic waves. Sink devices establish communication with base stations, enabling the transmission of received information to either terrestrial equipment or satellites. Subsequent surveillance and examination are conducted at data centers located at various sites.

1.3 Acoustic Communication

Underwater communication employs acoustic, optical, and electromagnetic waves to transmit sensed data between nodes within and outside the sensor network. Water's reflecting and absorptive qualities impede the transmission of electromagnetic waves, while water absorption limits the range of optical communication to short distances. Acoustic waves are favored because they experience minimal energy loss in water. Nonetheless, the spread of these waves is affected by other factors, including reflection, refraction, underwater temperature, and ambient noise.

The speed at which sound waves travel in water is considerably greater than in air, almost four times faster. However, this speed depends on the water's depth and averages around 1500 m/s. Mid-range frequencies demonstrate efficacy in both natural and artificial acoustic channels. Luo [6] proposed the use of acoustic spectrum utilization to enhance communication in underwater conditions. The propagation of acoustic signals is influenced by environmental factors such as spreading, attenuation, and scattering. These factors contribute to the complex nature of signal propagation, which can be affected by disturbances and noise sources. These sources range from human activities and shipping to ambient noise caused by unidentifiable objects.

1.4 Routing Protocols

To create efficient protocols for underwater communication networks, it is essential to have a comprehensive grasp of the obligatory limitations and prerequisites associated with acoustic communication among nodes. A recent evaluation of protocols highlights the primary emphasis on energy consumption in protocol design due to the distinctive obstacles presented by underwater acoustic communication compared to terrestrial communication. Protocols should include environmental effects such as spreading, attenuation, and scattering while also enabling efficient energy usage, diverse network structures, one-way communication, and the ability to handle delays in signal propagation.

The use of localized protocols such as Level-Based Adaptive Geo-Routing (LBAGR) introduced by Du et al. [7] relies on information about sensors, sinks, and depth to improve communication efficiency. In underwater environments, it is crucial to have various strategies, intelligence, flexibility, and compatibility with software-defined networking (SDN) and the Internet of Things (IoT) to provide the necessary dynamic routing. Protocols specifically developed for underwater environments, commonly known as "Smart Oceans," can transmit data to main stations over globally accessible infrastructures. Although multi-hop systems enhance the efficiency of packet transmission and reception, the simultaneous occurrence of transmitting and receiving packets might result in collisions. Therefore, protocol design must consider this possibility and strike a balance between energy consumption and maintaining a high packet delivery ratio.

1.5 Significance of the Research

The importance of this study is the thorough investigation and examination of underwater felt data, primarily concentrating on temperature, pressure, motions, military operations, and many scientific and industrial uses. Recent developments in sensor technology facilitate immediate investigation and supervision, specifically in military contexts that entail observing adversaries' vessels, tracking vehicle activities, identifying mine positions, and monitoring other vital data. The study seeks to enhance the continuous development of UWSNs, highlighting their pivotal significance in promoting scientific knowledge, industrial utilization, and strategic military maneuvers. This research aims to improve underwater sensor networks' dependability, effectiveness, and general functioning by incorporating new protocols and communication mechanisms. This will positively impact the wider field of marine exploration and monitoring.

1.6 Challenges of Acoustic Sensors Network

Underwater Sensor Networks (UWSNs) encounter numerous obstacles and possess distinct prerequisites because of the exceptional attributes of the underwater environment. following are the known problems for improvements and are given below:

- **Limited Bandwidth:** Acoustic waves travel in water compared to Electromagnetic waves but offer limited capacity for transmitting data packets, and hence 1500 m/s rate and data transmission capacity in sensor nodes network [8].
- **Propagation Delay:** Sound waves propagation in water has a high propagation delay due to the slower speed of sound relative to electromagnetic waves in the air. The delay greatly affects communication latency among sensor nodes with sink nodes [9].
- **Three-dimensional Topology:** There are two dimension-based wireless Networks. Acoustic Sensor nodes are deployed and operate in a three-dimensional (3D) environment. random movement of sensor nodes in 3D complex network's design, routing, and deployment [4].
- **Sensors Power Constraints:** All sensor nodes have a built-in battery with limited power, and it is very difficult to recharge or replace the battery. The network lifetime can be extended by designing and implementing energy-efficient protocols and methods [10].
- **Harsh and Dynamic Conditions:** These environments are classified as severe, changing, and non-predictable. Thus, it poses problems such as saltwater erosion, marine organisms' attachment, and water flow. These design and maintenance challenges should be considered in algorithms and protocols [11].
- **Restricted Communication:** The underwater medium weakens the sound wave signals, reducing bandwidth and communication among the sensor nodes. This constraint hampers the network's capacity to create and sustain dependable communication connections [12].

- **Underwater Localization:** Precise positioning of sensor nodes placement is difficult underwater since no GPS signals are available and specialized techniques are required for localization, i.e., coordinates with respect to deployed marks [13].

1.7 Aim and Objectives

This research aims to enhance the effectiveness and dependability of Underwater Sensor Networks (UWSNs) by tackling significant obstacles related to decreased dependencies on relay nodes, broadcast messaging, re-initialization, and path recalculation in ever-changing underwater settings. Furthermore, the secondary objective is to provide a well-organized framework of regions and zones integrating location data for sensor and mobile sink nodes. This infrastructure aims to enhance data transmission efficiency in the UWSN by ensuring its reliability.

- **Optimize Network Longevity by Minimizing Dependencies:** Developed Neighbor Discovery and packet-sending algorithms and executed communication protocols that decrease reliance on forwarder nodes. Created strategies for flexible adjustment to evolving undersea circumstances, aiming to prolong the network's total lifespan.
- **Enhance Energy Efficiency by Managing Sensor Activation:** Developed approaches to reduce the frequency of sensor activation, thus maximizing energy efficiency and sophisticated power management techniques to ensure efficient utilization of scarce energy resources in the UWSN.
- **Enhanced Reliability Measurements:** Enhanced the accuracy of reliability measurements by improving the ratio of successfully delivered packets. Created and executed resilient error correction algorithms to enhance the overall dependability of data transmission.
- **Improve Routing Algorithms:** Improved routing algorithms to optimize the packet delivery ratio, particularly in difficult underwater conditions, and achieved cooperative diversity by employing sink mobility. A predetermined approach for sink mobility was deployed to optimize cooperative variety among

sensor nodes. The effects of sink mobility on network connectivity and packet transmission were analyzed, to find the optimal balance between mobility and reliability.

1.8 Research Contribution

The primary goal is to extend the network's lifespan by minimizing the reliance on forwarder nodes. By reducing the number of forwarder nodes, the network's overall energy consumption can be optimized, thus prolonging its operational lifetime. This is achieved through the development of efficient routing protocols that distribute data forwarding tasks among multiple nodes while utilizing mobile sinks to collect data directly from sensor nodes.

A secondary objective involves implementing sink mobility and cooperative diversity. Sink mobility refers to the dynamic movement of sinks across the network, allowing them to adaptively adjust their positions to optimize communication paths, reduce energy consumption, and improve data collection. Integrating sink mobility into the network design and routing algorithms enhances coverage, reduces latency, and increases reliability.

The framework presents an innovative method for partitioning the whole space into four distinct regions, each comprising three horizontal portions. A structured layout guarantees an equitable allocation of mobile sinks and comprehensive coverage. The implementation of area division improves the overall structure of the network and streamlines the process of deploying and managing sensor nodes and mobile sinks, leading to increased efficiency.

The implementation of mobile sinks is integrated into the framework, with each region equipped with a centrally positioned mobile sink. The dynamic nature of mobile sinks enables strategic placement to optimize communication pathways, circumvent regions with signal deterioration, and enhance the network's overall efficiency. It facilitates the establishment of direct communication links between sensor nodes and mobile sinks in proximity within their respective regions.

The development of a distributed localization system allows sensor nodes to establish their positions inside the network autonomously. This eliminates the need for dependence on external positioning systems. A routing framework that utilizes the positional information of nodes to optimize the selection of paths for transmitting data towards sink nodes.

The proposed methods aim to optimize the next-hop selection and transmission scheduling by utilizing estimated position data. The objective is to achieve a balanced distribution of energy consumption throughout the network.

The framework's performance has been extensively simulated and evaluated based on key criteria such as delivery ratio, energy consumption, and network lifetime. Conducting a comparative study using baseline techniques.

We present an innovative approach to sink mobility that considers the energy consumption, network structure, and data transmission needs of underwater wireless sensor networks (UWSNs). The proposed method seeks to minimize the number of transmissions and maximize the network's longevity while assuring dependable data delivery.

We have devised a cooperative diversity system that facilitates the collaboration of several nodes in data transmission to the sink. Our approach enhances the dependability and energy economy of data transmission by utilizing the spatial diversity of the network, surpassing the performance of typical single-hop transmission.

We have developed a distributed localization system that allows nodes to determine their positions using acoustic signals. The foundation of our technique relies on a least-squares estimation algorithm, which enables precise estimation of node positions even when there is noise and multipath propagation.

We assess the effectiveness of our proposed framework by doing thorough simulations and contrasting it with established routing protocols for underwater wireless sensor networks (UWSNs). The outcomes of our study indicate that our framework surpasses existing standards in terms of network longevity, energy effectiveness, and dependability.

In summary, our research focuses on tackling the specific difficulties of Underwater Wireless Sensor Networks (UWSNs) by developing a strong and efficient routing framework. This framework is designed to successfully manage the trade-offs between energy usage, network lifespan, and dependability. The versatility of our framework allows for its application in many fields such as environmental monitoring, underwater research, and catastrophe management.

1.9 Dissertation Structure

The dissertation is systematically structured into six comprehensive chapters as visually shown in Figure 1.2. Chapter 1 introduces the background, motivation, and objectives, and outlines the structure. Chapter 2 reviews existing approaches and identifies research gaps. Chapter 3 describes the existing approaches and methods. Chapter 4 presents the results and discussion of the Reliable and Energy Efficient Regional Routing Framework with Sink Mobility (REEFSM), focusing on energy consumption, packet delivery ratio (PDR), and throughput, and discusses limitations. Chapter 5 covers the results and discussion of the Location-Aware Framework for Enhanced Data Reliability and Network Lifetime (ILAF) and the Mobility-Adaptive Energy-Aware Routing Scheme (MAEARS), evaluating their effectiveness and comparing them with existing methodologies. Chapter 6 summarizes the key findings and contributions and suggests future research directions. The References section lists all academic sources and literature cited.

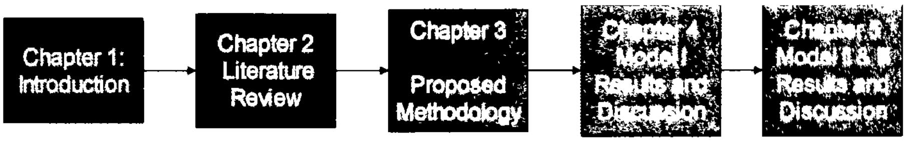

FIGURE 1.2: Dissertation Structure

Chapter 2

Literature Review

Chapter two of the dissertation thoroughly evaluates the prevailing methodologies within underwater wireless acoustic sensor networks (UWSNs). This chapter is dedicated to a meticulous analysis of the existing body of literature, enabling a critical review of current practices and theories. It aims to pinpoint and highlight the gaps and limitations in existing research, thus laying a solid groundwork for the arguments and propositions presented in this dissertation.

2.1 Overview of Underwater Acoustic Networks Challenges

Acoustic communication faces several challenges, including limited bandwidth, high propagation delay, energy constraints, and harsh environmental conditions.

2.2 Reliable and Energy-Efficient Routing Framework

The literature reviewed in this section provides a comprehensive overview of methodologies for ensuring reliable and energy-efficient frameworks in sensor networks. By addressing the limitations of previous approaches, the proposed framework positions itself within the broader context of ongoing research.

A. Hussain et al. [14] use advanced relay optimization techniques, extending the Neighboring-Based Energy-Efficient Routing (NBEER) protocol. Their evaluation shows that cooperation and relay optimization outperform previous methods regarding path loss, end-to-end delay, packet delivery ratio, and energy use. U. Satija et al. [15] also focus on relay optimization techniques, an extension of the NBEER protocol. They measure route loss, end-to-end delay, packet delivery ratio, and energy consumption and perform better than previous schemes. They evaluate factors like route loss, end-to-end delay, packet delivery ratio, and energy consumption, demonstrating superior performance over earlier schemes. M. Ali et al. [16] focus on the dynamic movement of the sensor nodes because of water currents, and to overcome this, authors consider spatial coordinates and vertical placement to select the best destination nodes concentrating toward the water surface. The source node decides both the relay node and the destination node and waits for an acknowledgment that data has been received well or else resent. Nguyen et al. [17] propose to use a multi-hop clustering technique for improving the data transmission rate with Relay-AUV to reduce latency and maximize channel bandwidth. This approach greatly enhances the data transfer rate, data throughput, program execution time, and packets delivered ratio. Kalinin et al. [18] minimize the path the signal has to cover. These solutions are based on a selection strategy derived from Boltzmann distribution principles and are refined by a bipartite matching problem approach to determine the optimal way to assign sensor nodes to relay groups. Rajeswari et al. [19] propose Cooperative Ray Optimization (CoROA) to combat geometric spreading and Doppler in UAN, decreasing packet loss and delay. CoROA boosts up the packet delivery fraction, throughput, and latencies through multiple relay node paths. Diamant et al. [20] the authors developed a topology optimization technique based on a minimum-weighted rigid graph for the sensors. Autonomous Underwater Vehicles (AUVs) employ the dynamic value-based path planning strategy in determining the most effective way of moving with regard to the information value within a specified time. Bagaa et al. [21] developed a strategy to position relay nodes, improving network durability by extending the operational lifespan of critical nodes. They use a weighted sum strategy to balance objectives, considering relay nodes' energy consumption. Ramasamy et al. [22] use the Ant Lion optimization algorithm (ALOA) to enhance underwater wireless sensor network durability. They collect data from sensor nodes within sub-clusters, reducing relay node transmission distances through multi-hop communication. Forwarder nodes collect data from a specific subset of nodes through one-hop connections. Nodes transmit data to forwarders at set intervals, reducing network-wide latency using a graph structure and mobile sink. The EEDG mechanism evaluates energy use, end-to-end delay, and throughput, as demonstrated by Shah et al. [23]. Sensor nodes in UWSNs face charging constraints. These networks typically use localization-based or non-localization-based deployment. Khan et al. [24] implemented the AF technique at relay nodes to aid efficient data forwarding, using FCR at the destination to select the desired signal. Relay nodes are chosen based on captured energy levels, but many cooperative UWSN routing solutions lack energy harvesting at relay nodes. Chaaf et al. [25] introduced sophisticated relay optimization techniques to extend the NBEER protocol, improving performance in route loss, end-to-end delay, packet delivery ratio, and energy consumption. Nguyen et al. [17] proposed a single-hop clustering that aims for direct communication between the cluster head and base station. Multi-hop clustering, using Relay-AUVs, minimizes latency and maximizes channel capacity, improving transmission rates, throughput, execution time, and packet delivery ratio. Jing et al. [26] developed a topology optimization strategy using a minimum-weighted rigid graph that helps sensor nodes transmit data efficiently to sinks, optimized by a dynamic value-based path planning methodology for AUVs. Subramani et al. [27] developed a framework for efficient relay node positioning to improve UWSN durability, balancing objectives with a weighted sum approach. Kumar et al. [28] proposed that the Ant Lion optimization algorithm (ALOA) enhances UWSN stability by collecting data within sub-clusters and reducing relay node transmission distances through multi-hop communication. Liu et al. [29] use the particle swarm optimization (PSO) technique to assign sub-cluster heads and minimize relay node transmission distances through multi-hop communication, balancing network energy and preventing energy holes.

Table 2.1 compares the proposed framework of system model I with existing methods.

TABLE 2.1: Proposed Framework I Enhancement Comparison

Protocol	**Strength**	**Weaknesses**	**Comparison with the Proposed Framework**
DBR [30]	Simple implementation and effective in dense networks.	Relies on depth information, leading to high packet loss in sparse networks. Low-depth nodes are overused as relay nodes, causing early energy depletion and network instability.	REEFSM reduces reliance on specific relay nodes by using mobile sinks, which facilitates direct communication and balances energy consumption.
EEDBR [1]	Balances depth and residual energy for better relay selection.	It considers both depth and residual energy but still faces unbalanced energy consumption. Nodes with high energy and low depth deplete quickly, creating network holes.	REEFSM employs dynamic mobile sinks, ensuring no single node is overburdened and maintaining balanced energy consumption.
DEADS [31]	Introduces mobile sinks to reduce reliance on fixed relay nodes.	Mobile sinks can converge at a single location, causing unbalanced energy consumption and reverting to DBR-like behavior.	REEFSM ensures mobile sinks follow predefined paths covering all regions evenly, preventing convergence and maintaining consistent energy consumption.
EERBCR [32]	Balanced energy consumption through regional division and mobile sink mobility. Enhances network lifetime and throughput.	Mobile sinks' fixed paths may still lead to unbalanced energy consumption if all sinks converge at a single region.	REEFSM further improves by dynamically adjusting mobile sink paths and reducing dependency on fixed relay nodes, enhancing energy distribution and reliability.
Co-DBR [33]	Enhances throughput and reliability through cooperative transmission.	Achieves better throughput but suffers from high end-to-end delay and increased energy consumption due to cooperative transmission.	REEFSM reduces the need for multi-hop and cooperative transmissions by introducing direct communication with mobile sinks, lowering delays and energy consumption.

Discussion:

- **DBR [30]:** The proposed REEFSM framework reduces reliance on specific relay nodes by using mobile sinks, which facilitates direct communication and balances energy consumption.
- **EEDBR [1]:** REEFSM employs dynamic mobile sinks, ensuring no single node is overburdened and maintaining balanced energy consumption across the network.
- **DEADS [31]:** REEFSM ensures that mobile sinks follow predefined paths covering all regions evenly, preventing convergence at a single location and maintaining consistent energy consumption.
- **EERBCR [32]:** The proposed REEFSM framework further improves on existing methods by dynamically adjusting mobile sink paths and reducing dependency on fixed relay nodes, thus enhancing energy distribution and network reliability.
- **Co-DBR [33]:** REEFSM reduces the need for multi-hop and cooperative transmissions by introducing direct communication with mobile sinks, which lowers delays and energy consumption.

2.3 Optimized Protocols for Energy Efficiency

This section reviews relevant, optimized protocols designed to enhance energy efficiency and resolve challenges of underwater communication, such as high latency, limited bandwidth, and energy constraints. Building on these insights, the proposed framework integrates autonomous positioning and location-aware routing to achieve superior energy efficiency and network resilience.

Farooq et al. [34] proposed a novel Underwater Sensor Acoustic routing protocol (IDBR) that considers depth information to reduce sensor energy. Packet transmission is prioritized based on the remaining battery life and adequate depths, reducing energy usage and extending network life. Dynamic network behaviour assessment and scalability for large installations are needed. Karim et al. [35] introduced GCORP, which combines spatial and cooperative opportunistic routing algorithms to handle obstacles such as high bit error rates, lengthy propagation times, and limited bandwidth in communication networks. It examines the location and remaining energy of the forwarding. Saeed et al. [36] proposed energy-efficient and robust security mechanisms to guard against underwater threats. It employs cooperative routing to refine network efficiency while keeping computational needs low. SEECR stands out for its effectiveness in reducing packet loss. However, it may lead to more energy usage. Hao et al. [37] implemented a novel geographic routing, combining location and energy awareness to enhance the transmission of data packets. The dispersal of the workload between numerous nodes and the use of geographic data improves the efficiency of the network. Ismail et al. [38] developed a scheme to choose nodes to send messages depending on their depth, remaining energy, and priority level. The selection of the sensor node calculated considers its residual energy and proximity to the available sink node, prioritizing those nodes with more power and nearest to the sink. Sharma et al. [39] proposed utilizing machine learning (ML) to forecast energy usage and longevity. They investigated three ML algorithms—decision trees, gradient boosting, and random forests—finding them useful but highlighting random forests for their accuracy. The drawback is real-time monitoring. Uyan et al. [40] provided another revolutionary ML-based solution that aims to maximize renewable energy utilization. This method requires substantial training data and comprises data cleaning, normalization, and feature selection to locate relevant data points. The ML model, trained with selected features, predicts each sensor node's ideal renewable energy distribution, allowing for real-time energy allocation. Zou et al. [41] use the particle swarm optimization (PSO) technique to assign sub-cluster heads (SH) within clusters. This reduces relay node transmission distances through multi-hop communication, balancing network energy and preventing energy holes. They employ both underwater acoustic (UA) and radio frequency (RF) modes to balance communication speed and distance. Ahmad et al. [42] address solitary relay node challenges by using sink mobility in the RACE-SM system, allowing direct communication with the sink if within range. Cooperative combining techniques enhance data transmission from source to sink nodes. Karim et al. [43] developed GCORP, a spatial and cooperative opportunistic routing, to improve data transfer reliability and effectiveness. A central node manages all network information, utilizing geographic and opportunistic routing by considering channel quality and node energy levels. Pradeep [44] suggests partitioning the network into distinct zones, with each zone having a leader node to direct data packets from source nodes to the sink efficiently. Gul et al. [45] partition the network into 12 regions in a grid format, with four mobile sinks and 100 randomly distributed sensing nodes.

The mobile sinks follow pre-established routes, and sensor nodes enter dormancy until the sink arrives, reducing overall network latency. Saeed et al. [46] introduce the "Secure Energy-Efficient and Cooperative Routing Protocol" (SEECR) for UWSNs, enhancing network efficiency and resilience against attacks through cooperative routing, though it may increase energy usage. Baranidharan et al. [47] focus on geo-opportunistic routing protocols to enhance residual energy range, ensuring successful packet delivery to at least one forwarder. These protocols reduce packet drops but may increase latency and complexity. Memon et al. [48] propose RMEER, a robust multipath energy-efficient routing protocol, to extend network lifetime and determine effective data transfer paths. This protocol uses multipath routing and multilink nodes to improve packet delivery and avoid non-working nodes. Tran-Dang et al. [49] use channel status information for cooperative packet forwarding, enhancing reliability in underwater sensor networks with a relay to improve packet delivery. Zhang et al. [50] use fuzzy logic to improve battery efficiency and reduce delay, selecting the best forwarder based on residual energy and coordinates, ensuring reliable packet delivery. Qadir et al. [51] address energy concerns and signal quality by using a noise-aware mechanism for network awareness, improving data transmission efficiency with a node selection technique based on noise parameters and depth. Mohemmed et al. [52] use multiple intermediate nodes for data forwarding, distributing traffic load efficiently and extending the battery life of forwarding nodes near the surface. Latif et al. [53] propose DIEER to reduce delay and energy consumption in high-density sensor node scenarios, aiming to minimize retransmissions and improve network lifetime. Shah et al. [23] developed CEER, focusing on dependable data transfer and energy efficiency using a clustering approach to manage energy usage and cooperative routing to improve network stability. Sajwan et al. [54] introduce GAER-UWSN, using genetic algorithms to find optimal routing. Ramesh et al. [55] propose a hybrid approach combining different methods to enhance UWSN performance, focusing on energy efficiency and communication efficacy using MAC protocols. Alkanhel et al. [56] present DEDG, optimizing energy efficiency and reducing data transmission delays with a cluster-based approach and multiple AUVs for efficient data collection in 3D-UWSNs.

Table 2.2 compares the proposed Model II framework enhancement over existing methods.

TABLE 2.2: Proposed Framework II Enhancement Comparison

Protocol	**Method**	**Weaknesses**
BES-OEERP (Bald Eagle Search-inspired Optimized Energy Efficient Routing Protocol) [57]	The Bald Eagle Search algorithm determines optimal packet transfer pathways, considering distance, battery life, and signal strength.	Computational complexity, scalability issues, not fully adapting to dynamic environments, and multipath fading and Doppler shifts.
IDBR (IoT-enabled Depth-Based Routing) [34]	It considers depth information and prioritizes packet transmission based on remaining battery life and adequate depths.	Scalability issues and focusing on in-depth information only.
Smart-IoUT (Smart Aquatic Monitoring Network) [58]	Integrates IoT architecture for real-time data collection on underwater temperature and dissolved oxygen.	Limited sensor capabilities, scalability challenges, and security concerns.
GCORP (Geographic and Cooperative Opportunistic Routing Protocol) [35]	Combines spatial and cooperative opportunistic routing algorithms to handle obstacles like high bit error rates and lengthy propagation times.	Increased complexity due to cooperative techniques.
EERSDRA (Energy-Efficient Region-based Source Distributed Routing Algorithm) [59]	Uses a region-based approach for source routing with sink mobility.	Reliance on precise localization, assumptions on predictable sink mobility, high initial energy consumption, scalability challenges, potential latency from multi-hop relays, and dependence on GPS.

Discussion:

- **BES-OEERP (Bald Eagle Search-inspired Optimized Energy Efficient Routing Protocol) [57]:** The ILAF framework introduces a location-aware method that optimizes node placement and routing based on geographic data, leading to balanced energy consumption and higher reliability in packet delivery.
- **IDBR (IoT-enabled Depth-Based Routing) [34]:** ILAF enhances packet delivery efficiency by using geographic coordinates for node placement and routing, which is particularly effective in highly dynamic underwater environments.
- **Smart-IoUT (Smart Aquatic Monitoring Network) [58]:** ILAF improves energy efficiency and reliability by optimizing node locations for efficient data collection.
- **GCORP (Geographic and Cooperative Opportunistic Routing Protocol) [35]:** ILAF simplifies the routing process by focusing on node coordinates and locations, reducing complexity while maintaining high reliability and efficiency.
- **EERSDRA (Energy-Efficient Region-based Source Distributed Routing Algorithm) [59]:** ILAF achieves a high packet delivery ratio and throughput by relying on location information (non-GPS) and an effective packet forwarding mechanism.

2.4 IoT-Based Framework for Optimizing Energy and Reliability

The literature reviewed in this section highlights the challenges of achieving energy equilibrium and maintaining reliable communication in dynamic underwater environments. This section positions the proposed framework within the broader context of ongoing research, demonstrating how cooperative diversity and sink mobility effectively address the limitations of previous approaches.

Kaveripaka Sathish et al. [60] improved power consumption, packet delivery, jitter, and delay. STAR-LORA disadvantages include the absence of direct application to real-world deployments and the possible influence of node mobility patterns or larger network scales on the selected protocols. In a similar study, Wang et al. [61] proposed optical MAC and acoustic links for channel congestion and node location, and high-data-rate directional optical lines enhance throughput by nearly 2x. Efficient optical handshaking under expected operating conditions is required. In another study, Nguyen et al. [62] presented 3D rotating cluster heads, used depth-based clustering, and chose energy-efficient routes based on cluster size and load-balancing parameters to balance network energy usage without assessing protocol overhead and complexity. Alablani et al. [63] stated that limited energy makes it hard for UWSN sensor nodes to recharge. They address the energy problem by considering finite power, multi-hop transmission, scope narrowing, inactivation mode, and energy balancing. Xiao et al. [64] proposed clustering and data fusion with enhanced back-propagation neural networks and genetic algorithms for optimal multi-hop transmission paths, but it increases computing complexity and requires parameter tuning to maximize benefits. Dogra et al. [65] developed a framework for data aggregation and multi-objective cluster head selection based on residual energy and sink distance. The selection of cluster heads adds complexity and overhead. SFO optimization is computationally expensive, but routing improvements may save energy. Alsamhi et al. [66] developed intelligent sleep scheduling and redundancy elimination by cluster heads and dynamic path prediction for AUV movement based on cluster head characteristics. Complex optimization methods and procedures may increase processing overhead, energy consumption, and delays. Subramani et al. [67] proposed the Cultural Emperor Penguin Optimizer-Based Clustering (CEPOC) approach selects ideal cluster heads, and a grasshopper optimization algorithm (MHR-GOA) multi-hop routing method finds optimal cluster-to-surface sink paths. The lack of real-world implementation and computational complexity are comparable with other approaches. Karim et al. [68] designed a 3D cube method that uses anchor nodes at the centroid as cluster heads. Unspecified network density, node dispersion, and channel conditions may influence scheme performance. Clustering, multi-hop communication, and void handling improve UWSN data transfer and network performance. Wang et al. [69] proposed Q-learning and magnetic induction to provide a practical routing framework. Q-learning has various drawbacks, such as convergence time, hyperparameter vulnerability, and failure to consider link quality or interference. Luo et al. [70] proposed a two-phase MALS-TSF to localize a 3D large-scale underwater wireless sensor network. However, this approach may increase mobile anchor node deployment and maintenance complexity, delays, and costs compared to other methods. Additionally, location precision is not addressed. Mani et al. [71] developed BBLA-KF, a revised 3D localization algorithm for large networks, which uses Kalman filtering and bounding boxes to localize accurately at a low cost. The method works for isotropic and anisotropic 3D network topologies and is more accurate than range-free approaches. Kaveripakam et al. [72] proposed a method to address power requirements, signal distance energy losses, acoustic medium transmission changes, and variable network conditions like sinkholes and curved routes. EBREC methods do not address practical implementation challenges and trade-offs. Wu et al. [73] developed Hierarchical Adaptive Energy-efficient Clustering Routing (HAECR) to balance energy usage and increase network lifetime. Node locations and energy levels may not be available in a natural real-time 3D environment. Rizvi et al. [74] proposed clustering methods using random, adaptive, and centrally controlled cluster head selection procedures and reduced energy consumption during re-clustering by setting up backup cluster heads and dedicated relay nodes. Multi-hop scenarios should be considered for future expansion. Wang et al. [75] proposed an adaptive-location-based routing protocol (ALRP) for 3-D underwater acoustic sensor networks by setting a plane boundary to limit forwarder nodes to those closer to the target, but the article does not provide a natural, real-world environment. Alghamadi et al. [76] developed an algorithm for duty cycling, opportunistic routing, and spatial routing to improve reliability and energy efficiency. The asynchronous duty cycle may result in higher latency, mobile sinks increase the additional overhead, and geographic routing introduces routing gaps. Wang et al. [77] calculated the forwarding area node degree using uniform node distribution without periodic broadcasting. The failure of the uniform node distribution assumption may affect the node degree estimate. Game theory is more complex than geographic routing. Luo et al. [78] introduced a modified Ant Colony Optimization (ACO) method with adaptive pheromone updates that improve path planning efficiency and reliability for communication, dynamic barriers, and energy constraints in a 3D environment. Wei et al. [79] combine routing and MAC protocols to improve reliability, latency, and energy efficiency. Improve network management but have scalability issues in large or dynamic situations and require accurate movement estimates in 3D underwater. Kim [80] proposed an autonomous vehicle navigation network using virtual agents and sensors in a 3D path planning system. This algorithm surpasses the 3D RRT-star in computing efficiency and path length, but real-world performance is uncertain. Yan et al. [81] select node depth to maximize global coverage and energy balance. Finally, all nodes descend to the computed place to build a 3D underwater network with balanced energy and non-uniform distribution. Xu et al. [82] analyzed the performance of UAV-assisted dual-hop FSO systems using amplify-and-forward relaying, intensity modulation, and direct detection. They examined the system's diversity order at high signal-to-noise ratios and investigated the impact of various parameters on system performance. Weiwei Jiang [83] addressed challenges in communication networks and topologies by detailing the application of GNNs in wireless networks, wired networks, and software-defined networking (SDN).

Table 2.3 shows the enhancement of Proposed Framework III over existing schemes.

TABLE 2.3: Enhancement of Framework III over existing Schemes

Existing Schemes	**Key Features**	**Limitation**
Energy-Efficient Clustering and Routing Protocol (EECRP) [84]	EECRP focuses on energy-efficient clustering and multi-hop routing, using cluster heads to aggregate and relay data to the sink.	EECRP needs to adequately address node mobility, which can lead to inefficiencies in dynamic underwater environments.
Modified Ant Colony Optimization (ACO) for AUVs [85]	This method uses a modified ACO algorithm to optimize Autonomous Underwater Vehicles (AUVs) path planning, focusing on energy conservation and obstacle avoidance.	While it improves path planning, it has limited scalability in highly dynamic environments and does not address relay node selection.
Q-learning and Magnetic Induction Routing (MIR) [86]	MIR uses reinforcement learning to balance energy conservation and delay in hierarchical underwater sensor networks.	MIR faces challenges with convergence time and hyperparameter sensitivity, which can affect its performance.
Energy-Efficient UWSN MAC/routing protocol (EE-UWSN) [63]	EE-UWSN addresses energy constraints by considering finite power, multi-hop transmission, inactivation modes, and energy balancing.	It lacks real-time adaptability to node mobility and environmental changes.
Hierarchical Adaptive Energy-efficient Clustering Routing (HAECR) [73]	HAECR introduces 3D-depth sensor node hierarchies to minimize energy consumption and enhance data transfer.	HAECR assumes static node locations and energy levels, which may not be realistic in dynamic underwater environments.

Discussion:

- **Energy-Efficient Clustering and Routing Protocol (EECRP) [84]:** MAEARS incorporates a mobility-adaptive approach, dynamically adjusting to node movements to maintain energy efficiency and network reliability. This ensures robust performance even in highly dynamic underwater environments.
- **Modified Ant Colony Optimization (ACO) for AUVs [85]:** MAEARS not only optimizes energy consumption but also includes a robust relay node selection mechanism that ensures efficient data relay in dynamic underwater environments, enhancing overall network performance.
- **Q-learning and Magnetic Induction Routing (MIR) [86]:** MAEARS employs a deterministic approach for relay selection and energy management, providing more predictable and reliable performance and avoiding the issues associated with reinforcement learning methods.
- **Energy-Efficient UWSN MAC/routing protocol (EE-UWSN) [63]:** MAEARS integrates real-time adaptability, allowing the network to adjust dynamically to topology and node energy level changes, ensuring continuous and efficient operation.
- **Hierarchical Adaptive Energy-efficient Clustering Routing (HAECR) [73]:** MAEARS dynamically adapts to the nodes' current positions and energy levels, making it more suitable for realistic and fluctuating underwater environments. This ensures efficient routing and energy usage.

2.5 Problem Statement

This literature review establishes the foundation for examining crucial elements of underwater sensor networks (USNs). The focus of our investigation revolves around four main problem areas: the limitations imposed by acoustic wave-based communication, the energy dynamics between various types of nodes and their activities specific to different regions, the influence of communication protocols on the reliability of the network, and the difficulties in designing protocols for USNs. Thorough investigations have been conducted in these areas, resulting in the development of precise research inquiries that delve into the intricacies of packet delivery ratios, energy consumption patterns, network lifetime, delay optimization, reliability improvement, cooperative diversity, and the integration of IoT protocols. The following sections of this thesis will thoroughly examine these issue statements, providing in-depth analyses and innovative contributions to underwater sensor networks.

2.5.1 Problem Statement I: Partial Coverage by South-Facing Sink Nodes

South-facing sink nodes are mobile and positioned at the top of each zone; the issue arises from their limited coverage range, which encompasses only half or a select few sensor nodes within each zone. This section examines the utilization of acoustic waves in Underwater Sensor Networks (USNs), distinguished by limitations such as a bandwidth below 100KHz, a propagation speed of 1500 m/s, and significant delays in end-to-end transmission and propagation. The research suggests implementing a stratified methodology considering transmission range, depth, and node position factors. The system incorporates a network initialization phase to establish regions and update the topology table, which activates alterations in the network's structure. The study also seeks to reduce transmission per event, second, and session, improving packet delivery by utilizing two-dimensional and three-dimensional sink mobility. The sink's trajectory adheres to a predetermined route, mostly encompassing the southern area, to enable direct and relay-based communication while evenly distributing energy usage among sensors.

2.5.2 Problem Statement II: Energy Efficiency in Sensor Node Activation Cycles

Sensor nodes operate on a finite energy supply and must toggle between sleep and active states in response to 'hello' and 'bye' signals from a sink node. This issue concerns the energy consumed during wake-up, active listening, and re-entering sleep mode. This section investigates the behavior of two types of nodes in underwater sensor networks: sinks with unlimited energy and moving horizontally along predetermined trajectories and nodes with limited energy and randomly placed in twelve regions. Every sink encompasses three distinct regions; nodes exclusively connect with the sink when it reaches their respective domain. The study examines nodes' sleep and wake patterns, triggered by hello packets from a sink, and then return to sleep mode after receiving a departure signal. The objective of this strategy is to optimize energy consumption in sensor nodes.

2.5.3 Problem Statement III: Limited Transmission Range of Sink Nodes

Excessive energy consumption is due to multiple transmissions of the same data packet, and potential data loss is possible if the relay node is also out of the sink's range. A sensor node with data, and if outside a sink node's range. This situation requires relaying data through the nearest sensor nodes, leading to two main issues: packet drop and energy consumption. This section investigates the energy consequences and effectiveness of protocols due to the energy needed to send and retransmit packets. Protocols must enhance reliability and energy usage. The investigation intends to employ cooperative diversity using mobile sinks to extend network lifespan, with mobile sinks offering a dependable direct link for sensor nodes to transmit their data, minimizing the requirement for multiple relay nodes and retransmissions, reducing delays, and enhancing network lifespan.

2.5.4 Problem Statement IV: Location Aware and Sensor Coordinates

Indexing Deficiency in Node-Region Association. The lack of a spatial indexing system leads to sub-optimal node-region association, as it requires a full scan of all regions for each node's coordinates. This inefficiency escalates with the network's scale, necessitating a refined approach that quickly associates nodes to their respective regions and neighboring nodes. This research focuses on protocols specifically intended for location-aware methods without installing GPS modules in each sensor node. All sensor nodes coordinated are determined at the time of deployment with respect to the deployed x-axis and y-axis as we know the GPS location of these identified locations.These protocols enable data transfer to main stations across a global infrastructure. It evaluates the escalation in packet transmission and reception in multi-hop schemes and the consequent problems, such as packet collision and excessive energy use, which could diminish packet delivery ratios.

2.6 Research Questions

Research questions are summarized in Table 2.4, illustrating the logical relationships between key problems and corresponding research questions in this thesis, providing a roadmap of the research structure.

TABLE 2.4: Relationship Between Problems and Research Questions

Problem	**Research Questions (RQs)**
Problem I: Partial Coverage by South-Facing Sink Nodes	RQ3: Will relocating the sink decrease the overall delay and enhance direct communication reliability? RQ4: Can cooperative diversity be achieved by using a mobile sink to cover both regions, improving performance?
Problem II: Energy Efficiency in Sensor Node Activation Cycles	RQ1: How can reducing reliance on forwarder nodes impact the overall energy consumption of the network?
Problem III: Limited Transmission Range of Sink Nodes	RQ2: What are the consequences of stopping the acceptance of hello packets on performance and dependability? RQ3: Will relocating the sink decrease the overall delay and enhance direct communication reliability?
Problem IV: Indexing Deficiency in Node-Region Association	RQ4: Can cooperative diversity be achieved by using a mobile sink to cover both regions, improving performance?

Chapter 2 of the thesis presents a thorough examination of existing research on underwater wireless acoustic sensor networks (UWSNs). The article explores different facets of UWSNs, including the properties and difficulties of transmitting acoustic waves in underwater environments, as well as the significance of energy management and operational tactics customized for certain regional circumstances. The chapter provides a thorough analysis of several communication protocols and evaluates their dependability, with a specific emphasis on their influence on the efficiency and energy consumption of UWSNs. The study also examines the concept of multi-hop communication, the use of cooperative and opportunistic routing, and the impact of relay nodes on improving network performance. The chapter emphasizes the necessity of effective routing protocols, considering the distinct underwater environment and its limitations, such as restricted bandwidth, significant delay, and energy limits of sensor nodes.

2.7 Thesis Organization

The organization of the thesis is visually summarized in Figure 2.1. The figure provides a roadmap of the chapters, illustrating how each section of the thesis builds upon the previous ones.

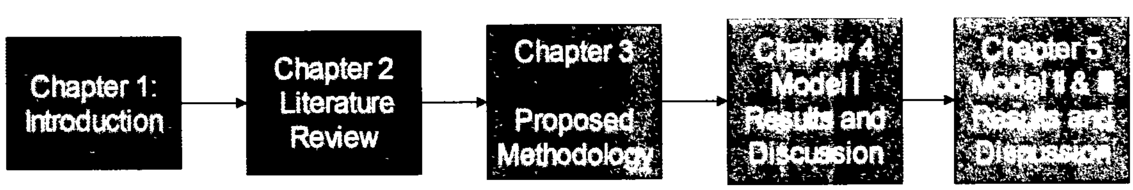

FIGURE 2.1: Organization of the Thesis

Chapter 3

Research Methodology

This chapter presents the research methodology for developing and evaluating innovative system models dedicated solely to acoustic sensor networks. The approach outlined in this document is not only well thought out but also scientifically rigorous, ensuring that the research work meets its goals effectively and efficiently and provides accurate results. These techniques are instrumental in solving the problems unique to UANs and guarantee the complete effectiveness of the proposed framework. To increase the system's throughput, the routing protocols are optimized so that the most significant number of packets are delivered, and there is the slightest possibility of packets getting lost or the system must re-transmit them. The overhead is maintained at a low level since there are few serializations of control messages due to the efficient neighbor discovery and routing mechanisms, which also tackle the delay problem. The work employs the experimental design research method as the most effective means of evaluating the newly proposed routing algorithms in UWSNs. This technique, consisting of three essential phases, is a robust and reliable approach that ensures the validity and credibility of the research results. The proposed techniques consist of three essential phases:

1. **Development of the 2D and 3D Conceptual System Models:** This stage involves developing a theoretical model for the Proposed system. This model involves a detailed review of the literature and a search for potential areas that do not use current UWSN technologies. It is the basis for other future developmental stages. Monitoring emergencies in that packet transmission is carried out as a priority, depending on the importance of the data. Mobile

sinks make the coverage of some areas flexible while guaranteeing that pieces of information can be sent directly to the sink nodes without loss or much delay. In defining the framework, some provisions allow nodes in an emergency to switch from the sleep mode to the active mode, minimizing the latency experienced when waking up the nodes. The framework also accommodates the giving of priority to specific packets, especially critical ones waiting to be transmitted.

2. **Simulation and Implementation:** Many simulation methods are employed to help develop realistic underwater wireless sensor network (UWSN) models. These technologies allow the building and fine-tuning of the proposed routing structure on the simulator, which provides conditions that are as close to a realistic underwater environment as possible. The theoretical aspect of the framework is that under the best environmental conditions, including clean water, moderate temperature, and low noise levels, the framework can attain the best network performance by using ideal routing paths and low energy levels.

3. **Evaluation and Testing:** The final process, Evaluation, and Testing, is a series of well-designed tests that put the framework to the ultimate test. The proposed framework's efficiency and reliability are assessed by statistically analyzing simulation data and comparing it to existing UWSN methods.

Interpreting results regarding its challenges and objectives forms part of qualitative analysis. It requires a critical assessment of how the findings derived from quantitatively based research address inquiries and advance the discipline. The measures used to validate or verify information in the research involve many ways of ensuring the credibility of the findings. Comparative Analysis: This involves comparing the proposed framework's outcome with other existing and proven Underwater Wireless Sensor Networks (UWSNs) protocols. The comparison with benchmarking shows how the proposed framework has improved the existing solutions. Key performance indicators, including energy consumption, data transfer rate, and the network's sturdiness, are used to compare performance. Sensitivity Analysis involves analyzing the framework's robustness to different network conditions and environments. This analysis enables us to explore the framework's limitations and opportunities in various situations. The Study Limitations recognize that research carried out through simulation analysis has general limitations. They take an opportunity to list the constraints and assumptions made during the study. It is crucial to provide such a context to understand the research findings.

3.1 Proposed System Model I

Sensor nodes are initially positioned unevenly and randomly throughout the two-dimensional underwater space to gather data about the underwater environment and transfer it to a sink node on the sea surface. The main advantage of the proposed framework is that it employs relatively lightweight protocols that are not difficult to implement and that can be computed on the limited resources of sensor nodes. The total area is divided into four regions, and each region is further divided into three sections as depicted in Figure 3.1. The following presumptions are considered here:

1. The typical sensor nodes have the same initial energy and communication range and move with the current.
2. Sink nodes, which travel horizontally and have infinite energy, are placed in the middle of each region.
3. The north and south of each region are covered by four sink nodes horizontally deployed in the middle of each region.
4. A section's sink node is the point of communication for all sensor nodes. Assume that both the nodes' and the sinks' locations are known.

3.2 Acoustic Communication Model

The attenuation and absorption loss are calculated using the simplified Thorp model by counting underwater conditions. Signal loss V is given by the following equations:

$$V = A \cdot f^2 \cdot D \tag{3.1}$$

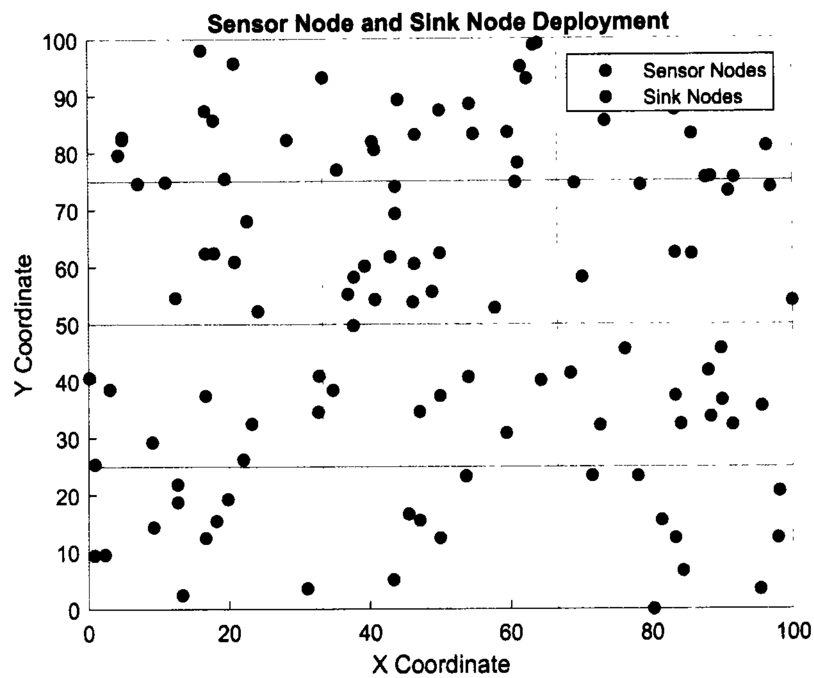

FIGURE 3.1: Proposed Network Model I

Where V is the signal loss (absorption) in dB, A stands for the coefficient of absorption while a signal is propagating underwater and is measured in decibels per kilometer, f is the acoustic wave frequency in kilohertz, and D stands for propagation distance in kilometers.

When the frequency range exceeds 0.4, the model's Eq. 3.2 is applied:

$$V = \frac{0.11 f^2}{(1+f^2)} + \frac{44 f^2}{(4100+f)} + 2.75 \times 10^{-4} f^2 + 0.003, \quad f > 0.4 \tag{3.2}$$

If the frequency range is smaller or below 0.4, the following formula as given in Eq. 3.3 is employed:

$$V = 0.002 + 0.11 \left(\frac{f}{1+f} \right) + 0.011, \quad f < 0.4 \tag{3.3}$$

3.3 Packet Transmission Energy Model

Sensor nodes send packets and consume energy which is indicated by E_{Tx}. Equation 4.5 is defined in detail to understand and design protocols that are energy efficient and use the least amount of energy.

$$E_{Tx} = P_{Tx} \cdot \left(\frac{1}{V} \cdot BW\right) \tag{3.4}$$

Where E_{Tx} is the energy consumed in Joules for packet transmission, P_{Tx} is the energy the transmitting node requires in watts, V represents the signal attenuation factor, and BW denotes the bandwidth.

3.4 Packet Reception Energy Model

Equation 4.5 represents the energy the receiving sensor node uses to receive packets in Joules.

$$E_{Rx} = P_{Rx} \cdot \left(\frac{1}{V} \cdot BW\right) \tag{3.5}$$

Where E_{Rx} is the energy consumed in Joules for packet reception, P_{Rx} measures the wattage required to process packets, and V and BW represent the signal attenuation factor and bandwidth, respectively.

3.5 Block Diagram of REEFSM

This article proposes reliable and energy-efficient regional routing algorithms for underwater sensor networks. Figure 3.2 shows the block diagram for the proposed REEFSM model.

3.6 Framework Overview

The proposed framework's efficiency and reliability are assessed by statistically analyzing simulation data and comparing it to existing UWSN solutions. A comprehensive quantitative analysis is expressed by a mathematical model that captures

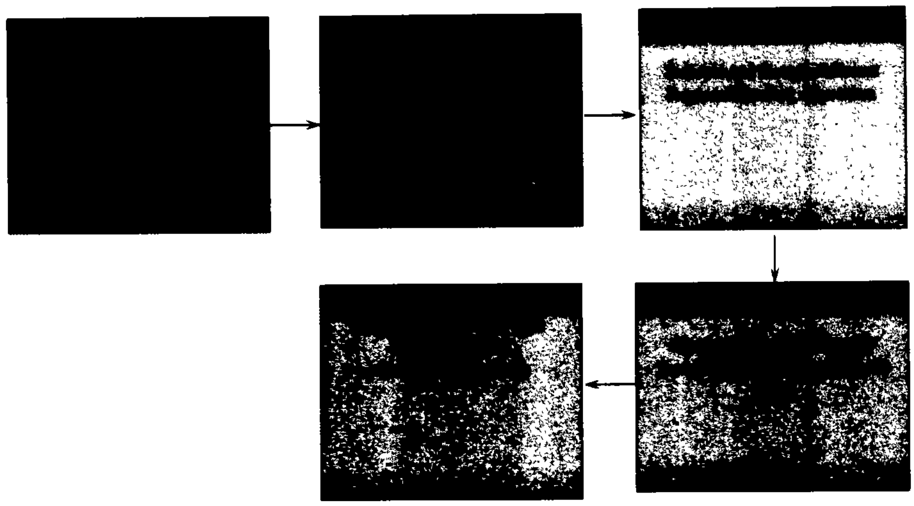

FIGURE 3.2: Block Diagram of REEFSM

energy consumption against node density, communication range, and other parameters. This model is applied to forecast the network performance and efficiency under various circumstances for routing protocols and nodal management schemes. The framework is structured into several phases:

3.6.1 Initialization Phase

The Initialization Phase represents the initial step of simulation. The process entails the preparation of the network environment and all requisite parameters before the commencement of the real simulation. In a concise elucidation:

- **Parameter Definition:** During this phase, the user establishes various parameters and constants to govern the simulation's behavior. The parameters encompass several factors, such as the number of sensor nodes, the dimensions of the simulation area, the initial energy levels, communication ranges, and additional settings particular to the simulation.
- **Deployment of Nodes:** Sensor nodes are placed randomly inside the simulation region. Each node is assigned random coordinates (x, y) and an initial energy level. The nodes will serve as the entities inside the network responsible for collecting and transmitting data.
- **Region Information:** To optimize routing and facilitate effective communication, calculate and store region information for individual sensor nodes

depending on their respective positions. The provision of regional information facilitates the decision-making process of nodes in determining which neighboring nodes to establish communication.

- **Initialization of Sink Nodes:** If a network contains sink nodes, which are specialized nodes responsible for collecting data from other nodes, it is necessary to initialize them with predetermined placements. Sink nodes are of paramount importance in data gathering and routing. Direct transmission involves sending data packets directly to the sink, while indirect transmission involves sending data packets through other nodes called intermediaries

- **Statistical Tracking:** The fundamental values for statistics tracking, including the number of packets sent and dropped, are established. Additionally, a round counter is initialized to monitor the progression of the simulation across numerous rounds.

3.6.2 Neighbor Discovery Phase

Identifying nearby nodes in simulation is a critical component known as the Neighbors Discovery Phase. During this phase, the nodes within the network determine the presence of neighboring nodes by considering their respective positions and areas. This phase establishes the fundamental framework for effective communication and routing inside the network. Nodes are supposed to wake up only when they receive a "hello" signal from a nearby sink and when they have certain very important data to forward. Once their job is done, nodes go back to power-saving mode to save power.

The operational process is round-based, and the Neighbors Discovery Phase occurs throughout each round, symbolizing a distinct time interval inside the simulation.

- **Sink Nodes Mobility:** Sink nodes' mobility involves their ability to move along predetermined paths during each round. Sink nodes commonly serve as the ultimate recipients of data gathered by sensor nodes. The framework employs a regional approach to organize the sinks, assigning each sink to a region. However, when sinks migrate, and intersections occur, the framework

Algorithm 1 Region Formation

```
procedure INITIALIZE SIMULATION AND NODES
    N ← 100                                        ▷ Total number of nodes
    xm, ym ← 100, 100                              ▷ Area dimensions in units
    Eo ← 10                                        ▷ Initial energy for each node in joules
    Initialize arrays for cumulative statistics
    cumulative_packets_sent, cumulative_packets_dropped, cumulative_network_energ
    cumulative_dead_nodes, cumulative_alive_nodes ← Arrays of zeros (size max + 1)
    Initialize node structure
    S ← Structure Array with fields 'xd', 'yd', 'Neighbors', 'Region', 'E', 'Id'
    node_coordinates ← 2D Array of size N × 2
    for i ← 1 to N do
        S[i].xd ← Random(0, xm)
        S[i].yd ← Random(0, ym)
        S[i].Neighbors ← Empty Array
        S[i].Region ← Empty Array
        S[i].E ← Eo                                ▷ Set initial energy
        S[i].Id ← i
        node_coordinates[i] ← [S[i].xd, S[i].yd]
    end for
    Calculate and store region information for each node
    zone_width ← xm/num_zones
    region_height ← ym/num_regions_per_zone
    for i ← 1 to N do
        zone ← ⌊S[i].xd/zone_width⌋ + 1
        region ← ⌊S[i].yd/region_height⌋ + 1
        S[i].Region ← [zone, region]
    end for
    Initialize sink nodes
    num_sinks ← Number of rows in sink_paths
    sinks ← Structure Array with fields 'xd', 'yd'
    sink_coordinates ← 2D Array of size num_sinks × 2
    for s ← 1 to num_sinks do
        sinks[s].xd ← sink_paths[s][1]
        sinks[s].yd ← sink_paths[s][2]
        sink_coordinates[s] ← [sinks[s].xd, sinks[s].yd]
    end for
end procedure
```

manages sinks' mobility and the nodes' communication events to reduce energy consumption and prevent collisions.

- **Packet Broadcasting:** In the context of packet broadcasting, sink nodes transmit "hello" packets. These packets function as signals that notify sensor nodes in the proximity of their existence and accessibility. Broadcasting hello packets serves as a mechanism for sink nodes to communicate their presence effectively to the network.
- **Total Energy Calculation:** The total energy calculation in the network is performed at the commencement of each round. This computation aggregates the residual energy of all sensor nodes inside the network.
- **Neighbor Identification:** The process through which each sensor node identifies and establishes connections with its neighboring nodes. Determining node position, region information, and the reception of hello packets are the factors considered in this process. When two nodes are in proximity and mutually exchange hello packets, they establish a neighbor relationship. Neighbors refer to nodes that can engage in direct communication.
- **Region-based Communication:** Region-based communication is a strategy employed by nodes to enhance the efficiency of communication processes. Nodes within a given region may tend to establish communication primarily with other nodes within the same region due to their proximity and the increased likelihood of maintaining a stable connection.

3.6.3 Packet Send, Forward, and Drop

The present phase involves modelling the data transmission process within the network, determining optimal timing, and developing methods for packet transmission, forwarding, or discarding.

- **Rounds-Based Operation:** The operation based on rounds is analogous to the phase of Neighbors Discovery. This particular phase functions by dividing the simulation into discrete time steps, with each round representing one of these steps.

Algorithm 2 Neighbor Discovery

```
procedure DISCOVER NEIGHBORS
    for each node i in N do
        Initialize neighbor list[i] as an empty list
        if S[i].E > 0 then
            Broadcast HELLO message with S[i].Id and S[i].(xd, yd)
        end if
    end for
    for each node i in N do
        while receiving messages do
            if message is HELLO then
                Extract sender ID and sender location from the message
                Calculate distance between S[i] and sender
                if distance ≤ transmission range and sender ID not in neighbor list[i] then
                    Append sender ID to neighbor list[i]
                    Send ACK message to sender ID with S[i].Id and S[i].(xd, yd)
                end if
            end if
            if message is ACK then
                Extract sender ID from the message
                if sender ID not in neighbor list[i] then
                    Append sender ID to neighbor list[i]
                end if
            end if
        end while
    end for
end procedure
```

- **Sink Nodes Mobility:** The mobility of sink nodes introduces the possibility of updating their placements in each cycle.

- **Data Transmission Decision:** Each sensor node decides on data transmission. It determines whether it possesses data that needs to be sent to a sink node or whether it should pass data received from other nodes. The selection is made by considering parameters such as the node's energy level and its proximity to the destination.

- **Data Forwarding:** If a sensor node elects to transmit data, it will directly send it to the sink node, provided it is within the communication range. Energy is consumed throughout the data transmission process, resulting in the need to update the node's energy level. In the context of data forwarding, when a sensor node decides to transmit data, it proceeds to relay this data to a neighboring node that is closer to the intended destination, such as a sink node. Packet forwarding continues until it reaches its intended destination or exceeds the transmission range limit. In addition to energy consumption, the act of forwarding data also necessitates the updating of energy levels in the intermediary nodes.

- **Packet Dropping:** Packet Dropping occurs when a sensor node possesses data that it intends to transmit but cannot establish a connection with a sink node or a neighboring node capable of passing the data within its designated transmission range. In such cases, the packet is designated as dropped. This phenomenon may occur when a node experiences energy depletion or is positioned beyond its communication range.
- **Dead Nodes:** During the simulation, the system records nodes that have reached or fallen below zero energy levels, called dead nodes. The nodes are deemed inactive and no longer engage in data transmission.

3.7 Evaluation Criteria

The following criteria are used to evaluate the proposed framework:

3.7.1 Duration of Network Operation

Equation 3.6 describes the unique challenges and characteristics of the underwater environment; the calculation of network lifetime is typically more complex in underwater sensor networks. Batteries frequently power underwater sensors, and replacing or recharging them isn't easy. Therefore, it is essential to maximize the network's lifespan.

$$E_{NLT} = \min\left(\frac{E_{SNI} - E_{SNCT}}{\frac{1}{N}\sum E_{SNCS}}\right) \tag{3.6}$$

Where E_{SNI} represents the initial energy of sensor node i. The variable E_{SNCT} represents the energy spent by node i at a given time t. Calculating network lifetime

Algorithm 3 Packet Management for Network Communication

```
procedure MANAGE PACKETS
    for each round r from 0 to r_max do
        for each node i in N do
            Initialize min_dist_sink to i
            for each sink s in sinks do
                Calculate Euclidean distance dis_to_sinks[s] from node i to sink s
            end for
            Find minimum distance min_dist and corresponding sink min_sink from dis_to_sinks
            Initialize has_data_to_send to False
            if S[i].E > 0 and min_dist within TX_range then
                Set has_data_to_send to True
            else
                for each neighbor node j of node i do
                    if S[j].E > 0 then
                        Calculate distance dist between node i and j
                        if dist < min_dist then
                            Update energy of S[j] (subtract E_RX)
                            Calculate temporary distance temp_dist to sink via j
                            if temp_dist < min_dist then
                                Update min_dist and min_dist_sink to temp_dist and j
                            end if
                        end if
                    end if
                end for
                if min_dist within TX_range then
                    Set has_data_to_send to True
                end if
            end if
            if has_data_to_send then
                Output "Node i sending data to Sink min_sink in Round r"
                Update energy of S[i] (subtract E_TX)
                Increment packets_sent counter
            else
                Output "Node i cannot send/forward data in Round r"
                Increment packets_dropped counter
            end if
        end for
        Update cumulative statistics for the round
    end for
    Output cumulative statistics
end procedure
```

involves determining the minimum energy level across all nodes and dividing it by the average energy consumption rate.

3.7.2 The Number of Active Nodes

The process of acquiring adequate energy to operate a sensor node. Equation 3.7 represents the residual energy of a node on the ith round, denoted as E_R^i.

$$K_x^i = E_R^i > 0 \tag{3.7}$$

3.7.3 Throughput

To get the average throughput, equation 5.3 adds up all of the bits or packets that each sensor node in the network successfully sent, then divides the total by the length of the simulation.

$$\text{Throughput} = \frac{\text{Packets}_{NS}}{T_{st}} \tag{3.8}$$

Where Packets_{NS} is the bits or packets successfully received from all N sensor nodes. T_{st} is the total rounds or simulation time.

3.7.4 Packet Delivery Ratio

The ratio of successfully delivered packets to the total number of packets communicated in an underwater sensor network (UWSN) is known as the packet delivery ratio (PDR). Equation 5.2 is to determine the PDR for N sensor nodes:

$$\text{PDR} = \frac{\text{Packets}_{nds}}{\text{Packets}_T} \tag{3.9}$$

Where Packets_{nds} is the total number of packets delivered successfully, Packets_T is total packets transferred.

3.7.5 Delay

Equation 3.10 represents the time difference between the timestamps at the source and destination nodes and the time needed for a packet to reach its destination. To calculate the average delay, add the total time required for all packets and divide it by the total number of packets transmitted.

$$\text{Delay} = \frac{\text{Packets}_{st}}{\text{Packets}_{rt}} \tag{3.10}$$

3.7.6 Packet Drop Ratio

Equation 3.11 represents the packet drop ratio (PDR) and is the proportion of dropped packets to all packets transmitted. It displays the proportion of packets not successfully received or delivered at their intended sensor nodes.

$$\text{PDR} = \frac{\text{Packets}_{lost}}{\text{Packets}_{send}} \tag{3.11}$$

Variable(s)	Value(s)
Number of Sensor Nodes SN_n	100
Sensor Node Energy E_{SN}	10 Joules
Number of Mobile Sink Nodes MSN_n	4
Simulated Network Area	100-meter x 100-meter
Size of Packet P_s	1 kilobit
Bandwidth BW_{Hz}	30 KHz
Data Rate R_{bps}	250 kbps
Sensor Nodes Communication Range SNR	12.5 meters
Sensor Nodes Amplifier Energy SNE_{amp}	0.0013 pJ/bit/m^4
Sensor Nodes Electronics Energy SNE_{elec}	50 nJ/bit

TABLE 3.1: Simulated Variables

The values in Table 5.1 were obtained through simulations conducted to assess the effectiveness of the proposed model.

The methodology described in this chapter establishes a solid basis for investigating and creating a dependable and energy-efficient routing framework for underwater sensor networks (UWSNs). This research has successfully addressed the intricate issues specific to UWSNs by employing a rigorous experimental strategy that combines theoretical modeling with practical simulation and implementation.

The data-gathering methods, principally utilizing advanced computer simulations, have facilitated a thorough investigation of the proposed framework across several realistic underwater circumstances. The simulations have played a crucial role in obtaining vital data necessary for comprehending the performance and feasibility of the proposed routing protocol.

Using analytical tools, including quantitative and qualitative approaches, has guaranteed a thorough framework assessment. The framework's efficiency and dependability have been quantitatively analyzed, providing measurable insights. Additionally, qualitative study has contributed to a greater understanding of the framework's practical implications in UWSNs.

Validation techniques, such as comparison and sensitivity analysis, have played a crucial role in confirming the proposed framework's strength and superiority compared to existing protocols. The thorough validation process highlights the dependability and relevance of the research findings.

This study has consistently upheld ethical norms in computational research, demonstrating transparency and integrity in its methods to ensure the credibility and reproducibility of the results.

Although recognizing the inherent constraints of a simulation-based methodology, this study establishes a foundation for further investigations and real-world applications in UWSNs. The identified constraints guide future studies, directing efforts to enhance and adjust the suggested framework for practical use.

This research thoroughly explains the research methods used and makes a substantial contribution to Underwater Wireless Sensor Networks (UWSNs). It is a vital link between theoretical study and practical application, establishing a solid basis for future progress in this rapidly developing field. The research methodology and findings can potentially improve the efficiency and lifespan of underwater wireless sensor networks (UWSNs), representing a substantial advancement in underwater communication and exploration technology. Figure 3.3 shows the simplified flow diagram.

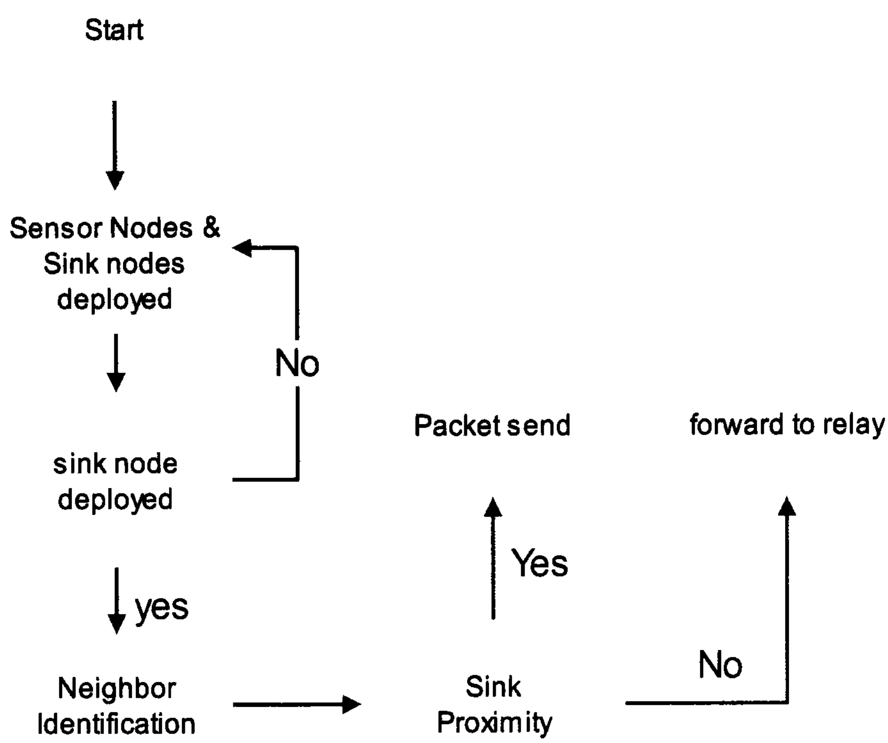

FIGURE 3.3: Packet Flow Diagram

3.8 Proposed Framework II

This section of the study examines the complexities of a model for an Underwater Acoustic Sensor Network (UASN) system and how it functions. This methodology aims to comprehensively analyze and enhance the efficiency of a location-aware routing framework in UASNs, which face challenges that typical terrestrial network strategies cannot address due to the distinct characteristics of underwater settings. The main emphasis lies in effective and dependable data transmission in these demanding circumstances, focusing on energy efficiency, precise position recognition, and adaptable routing algorithms. This methodology establishes a foundation for a thorough comprehension of the dynamics of underwater sensor networks and the creation of inventive solutions to improve their effectiveness and dependability. In the proposed framework, reliability is measured as a set of attributes such as successful delivery of data packets, time that the network is up, and node survival rates. This framework is enhanced to achieve these reliability metrics regarding data transfer within harsh underwater environments

3.9 System Model II

An Underwater Acoustic Sensor Network (UASN) is a network of sensor nodes strategically positioned underwater to observe and gather data about the marine environment. Sensor nodes are commonly outfitted with acoustic communication modules, enabling them to establish communication among themselves and with the sink node, which serves as a bridge between the UASN and the terrestrial network.

As shown in Figure 3.4, the suggested framework is deployed in a simulated 100m x 100m network, separated into 12 distinct areas called regions and a dynamic topology model. The coordinates of all sensor nodes are recorded relative to the x and y axes, along with their corresponding region. The coordinates of the four sink nodes are recorded and updated as they move in parallel.

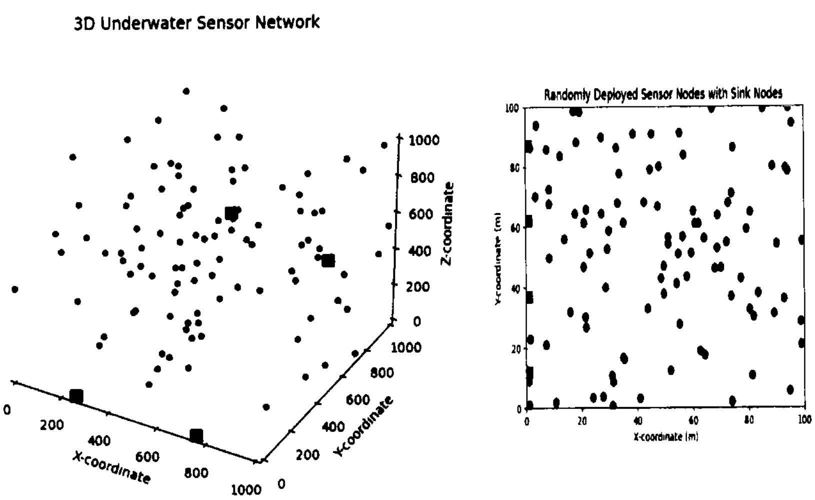

FIGURE 3.4: 2D Location-Aware and 3D Dynamic Models: red square representing sink nodes, and blue circle representing sensor nodes

3.10 Location Detection and Update Mechanism

The sensor nodes transmit their area ID to their neighboring nodes in the hello message. Sink nodes regularly transmit their coordinates and region identification to all sensor nodes. Sensor nodes utilize this information to update their routing tables.

The location-based next-hop selection process incorporates an additional variable called Region ID. To achieve more direct and efficient packet forwarding, the system selects surrounding nodes in the same geographic area as the target node.

3.11 Neighbors Discovery and Routing Phase

The process of identifying neighboring nodes and determining the optimal route is similar to the previous iteration but now incorporates an extra verification step to examine the area ID of the next node before forwarding the packet. When the destination node is located in a region different from the next hop, the sensor node will utilize the modified location-aware next-hop selection algorithm to choose a new next hop. The location-aware framework for UWSNs incorporates region-based neighbor discovery and routing to optimize performance, considering the mobility of sink nodes, issues in underwater communication, energy limitations, and the need for region-based neighbor discovery.

3.12 Model for the Transmission of Sound Waves Across a Medium

Elevated bit error rates, extended propagation delays, and restricted bandwidth characterize underwater acoustic propagation. The absorption, attenuation, and scattering in saltwater can be attributed to its intricate physical properties. Thorp model, which considers the underwater conditions. The absorption loss is quantified in decibels per kilometer (dB/km), whereas the frequency f is measured in kilohertz (kHz).

3.13 Model for Energy Usage During Transmission and Reception

The energy consumption of sensor nodes is a crucial limitation in the design of Underwater Acoustic Sensor Networks (UASN). Batteries commonly power sensor

Algorithm 4 Region-Based Neighbor Discovery (RBND)

```
procedure ASSOCIATE NEIGHBORS
    // Step 1: Initialize an empty list for each sensor node to store neighboring node IDs
    for i ← 1 to N do
        neighbors[i] ← []
    end for
    // Step 2: Associate each sensor node with its region
    for i ← 1 to N do
        sensorNodeInfo[i]['region'] ← assignRegion(sensorNodeInfo[i]['x'], sensorNodeInfo[i]['y'])
    end for
    // Step 3: Make all sensor nodes in the same region neighbors by default
    for i ← 1 to N do
        for j ← 1 to N do
            if sensorNodeInfo[i]['region'] == sensorNodeInfo[j]['region'] then
                neighbors[i].append(sensorNodeInfo[j]['node_id'])
                neighbors[j].append(sensorNodeInfo[i]['node_id'])
            end if
        end for
    end for
    // Step 4: Find additional neighbors based on transmission range
    for i ← 1 to N do
        for j ← 1 to N do
            if i ≠ j and sensorNodeInfo[i]['region'] ≠ sensorNodeInfo[j]['region'] then
                distance ← sqrt((sensorNodeInfo[i]['x'] - sensorNodeInfo[j]['x'])^2 + (sensorNodeInfo[i]['y'] − sensorNodeInfo[j]['y'])^2)   if distance ≤ TX_range then
                neighbors[i].append(sensorNodeInfo[j]['node_id'])
            end if

        end for
    end for
    // Step 5: Update the sensor node information with the list of neighbors
    for i ← 1 to N do
        sensorNodeInfo[i]['neighbors'] ← neighbors[i]
    end for
end procedure
```

nodes and require extended durations of operation without the need for recharging. Hence, it is crucial to devise protocols that minimize the energy consumption of sensor nodes.

Various factors, including the distance between nodes, the transmission power, and the data rate, influence the energy consumption of sensor nodes for transmission and reception.

This research emphasizes the original method by incorporating a location detection and update mechanism and a phase for region-based neighbor finding and routing. By including geographical knowledge in the routing process, we have successfully tackled a significant obstacle on UASNs - guaranteeing effective and dependable packet delivery in the face of ever-changing underwater conditions.

This methodology demonstrates the capacity for progress in underwater sensor networks. This study provides vital insights into the efficient operation of UASNs and paves the way for future research and development in this vital subject. This research explores the theoretical and practical aspects of underwater communication, leading to the development of more robust, efficient, and environmentally friendly technology for underwater exploration and monitoring.

Chapter 4

Reliable and Energy-Efficient Framework

The Reliable and Energy Efficient Regional Routing Framework with sink mobility for Underwater Sensor Networks (REEFSM) has been evaluated and is recognized as the most reliable protocol. It demonstrates exceptional reliability by maintaining a network without inactive nodes and effectively managing packet losses. This characteristic renders it especially well-suited for applications that demand excellent data reliability and energy conservation.

The DEADS protocol is the second most energy-efficient. However, it encounters difficulties sustaining node connectivity and ensuring reliable packet delivery over time, resulting in lower reliability than REEFSM.

EERBCR is positioned between REEFSM and DEADS, offering a harmonious equilibrium between energy efficiency and dependability.

4.1 Results, Analysis, and Discussions

This section discusses the proposed Model, the Reliable and Energy Efficient Regional Routing Framework with sink mobility for Underwater Sensor Networks (REEFSM). The proposed methodology is implemented in Python. The effectiveness of the

REEFSM-UWSN approach is evaluated using many performance measures, including network lifetime, energy consumption, throughput, packet loss rate, packet delivery ratio, the ratio of dead nodes, packet received ratio, and the ratio of alive nodes. The results obtained are examined using established methodologies.

The proposed protocol is compared with Gul et al. al. [87] EERBCR: Energy-efficient regional-based cooperative routing protocol for underwater sensor networks with sink mobility and Authors [88] DEADS: Depth and Energy Aware Dominating Set Based Algorithm for Cooperative Routing along with Sink Mobility in Underwater WSNs.

4.1.1 Analysis of Experimental Results of REEFSM

Based on the simulation results, this section provides a detailed performance analysis of the Reliable and Energy-Efficient Regional Routing Framework with Sink Mobility (REEFSM). The study covers multiple dimensions, including packets sent, packets dropped, network energy, dead nodes, alive nodes, packets received, packet received ratio, and packet drop ratio, as shown in Table 4.1.

TABLE 4.1: Simulation Results and Performance Evaluation

Rounds	Packets Sent	Packets Dropped	Network Energy	Dead Nodes	Packets Received	Packet Received Ratio	Packet Drop Ratio
100	7961	539	941	0	7262	0.912197	0.067705
200	13967	933	899	0	13034	0.9332	0.088995
300	20150	1324	856	0	18820	0.933995	0.087891
400	26581	1739	809	0	24842	0.934577	0.080584
500	32755	2133	764	0	30634	0.935247	0.082705
600	38950	2526	720	0	36420	0.935045	0.087599
700	45381	2939	672	0	42442	0.935237	0.090831
800	51567	3333	629	0	48234	0.935366	0.090271
900	57750	3727	583	0	54020	0.935411	0.090234
1000	64235	4145	536	0	60090	0.935471	0.091663

The number of packets sent and received provides traffic capacity and data delivery efficiency. Over 1000 rounds, the number of packets sent increased steadily, reaching a maximum of 64235 packets. Correspondingly, the packets received also showed a consistent increase, with the highest value being 60090 packets at 1000 rounds. These indicate the robustness of the Proposed Framework for ensuring reliable data transmission.

The packets dropped represent the number of packets that failed to reach the sink nodes. Throughout the simulation, the number of packets dropped increased gradually, which is expected as network traffic grows. However, the Packet Drop Ratio remained relatively low, peaking at 0.0917, demonstrating the framework's efficiency in minimizing packet loss.

The initial value of the network energy was 944 joules at round 100, and it declined round-wise up to 536 joules at round 1000. This suggests the energy consumption for transmitting and receiving data. However, the network always ensured that both energy consumption and energy production were equal, which is crucial in enhancing the network's life cycle. The number of alive nodes remained constant at 100, and there was no dead node. This consistency shows how REEFSM is useful in keeping nodes alive, which is crucial in determining the network's stability and longevity.

The Packet Drop Ratio was maintained at a low level, which was good news for network traffic handling and packet dropout. According to the performance analysis, there was an indication of the efficiency and reliability of the system. It is also evident that the framework kept a low packet drop ratio and, at the same time, ensured appropriate energy distribution. Also, the network stability was supported by the number of alive nodes remaining constant for the entire duration of the simulation rounds. These results prove the usefulness of REEFSM in increasing the performance of UAN.

4.1.2 Comparison of Proposed REEFSM with Existing EERBCR Protocol

The proposed research work, referred to as REEFSM, has been compared with the existing EERBCR (Energy-Efficient Regional Cooperative Routing) protocol to validate the performance of the proposed work.

4.1.2.1 Total Network Energy

REEFSM consistently shows higher total network energy than other protocols throughout the simulation rounds, indicating its efficiency in energy consumption. By the end of 1000 rounds, REEFSM maintains 536 joules of energy, whereas other protocols, like DBR and EEDBR, deplete their energy completely.

EERBCR Shows a steady and linear decline in energy levels, indicating consistent energy consumption. DEADS Exhibits a sharper decline, suggesting higher energy consumption over time. DBR Experiences the steepest decline, reaching zero energy by round 1000, indicating it is the least energy-efficient protocol. EEDBR Similar to DBR, it depletes energy quickly, reaching zero by round 900. REEFSM Maintains higher energy levels over time, ending with 536 joules at round 1000, indicating superior energy efficiency as shown in Figure 4.1.

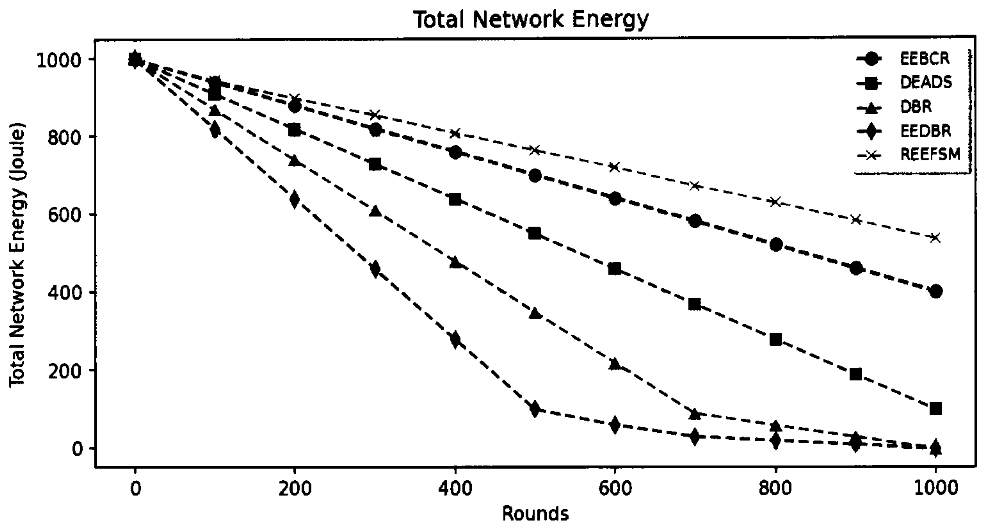

FIGURE 4.1: Total (Remaining) Network Energy

4.1.2.2 Number of Packets Sent to Sink Node

The number of packets REEFSM receives exceeds EERBCR, DEADS, DBR, and EEDBR. However, this indicates a more conservative and efficient data transmission strategy and prioritizes energy savings and network longevity mechanisms over other protocols. EERBCR Shows a reliable increase in packet send count, reaching 60000 by round 1000. DEADS Demonstrates robust throughput, with packet send numbers reaching 63000 by round 1000. DBR Sends fewer packets than others, peaking at 50000 by round 1000. EEDBR Has the lowest throughput, with packet send numbers peaking at 30000 by round 1000. REEFSM Exhibits the highest throughput, with packet send numbers reaching 64235 by round 1000 as shown in Figure 4.2.

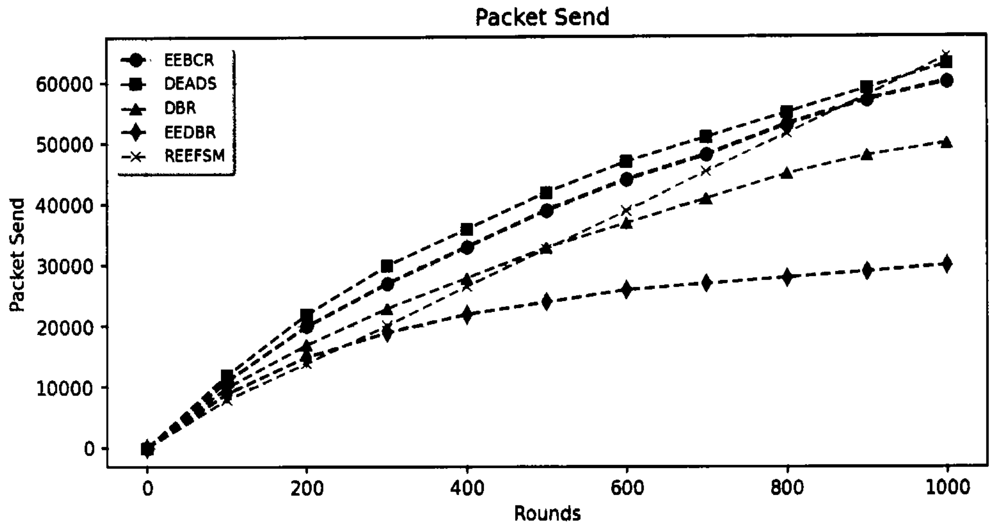

FIGURE 4.2: Number of Packets Sent to Sink Node

4.1.2.3 Number of Packet Drop

The Innovative Framework exhibits significantly lower packets dropped than other protocols, as shown in Figure 4.3. This demonstrates its superior reliability and effectiveness in maintaining robust communication channels and reducing data loss. EERBCR shows a steady increase in packet drops, reaching 40000 by round 1000. DEADS Has a slightly higher packet drop rate than EERBCR, reaching 41000 by round 1000. DBR Exhibits the highest packet drop rate, with 42000 drops by round 1000. EEDBR Shows a moderate packet drop rate, with 30000 drops by round 1000. REEFSM Demonstrates the lowest packet drop rate, with 5888 drops by round 1000. Regarding packet drop, REEFSM is the most reliable protocol with the lowest packet drop rate. EEDBR shows moderate reliability, while EERBCR and DEADS exhibit higher packet drop rates. DBR is the least trustworthy, with the highest packet drop rate.

Each protocol has strengths and weaknesses, and the best choice depends on the application's specific requirements regarding energy efficiency, throughput, and reliability. REEFSM stands out as the top performer across all metrics.

Concluding this chapter on the Reliable and Energy Efficient Regional Routing Framework with sink mobility for Underwater Sensor Networks (REEFSM), The evaluation showed that it is highly effective in addressing energy efficiency challenges

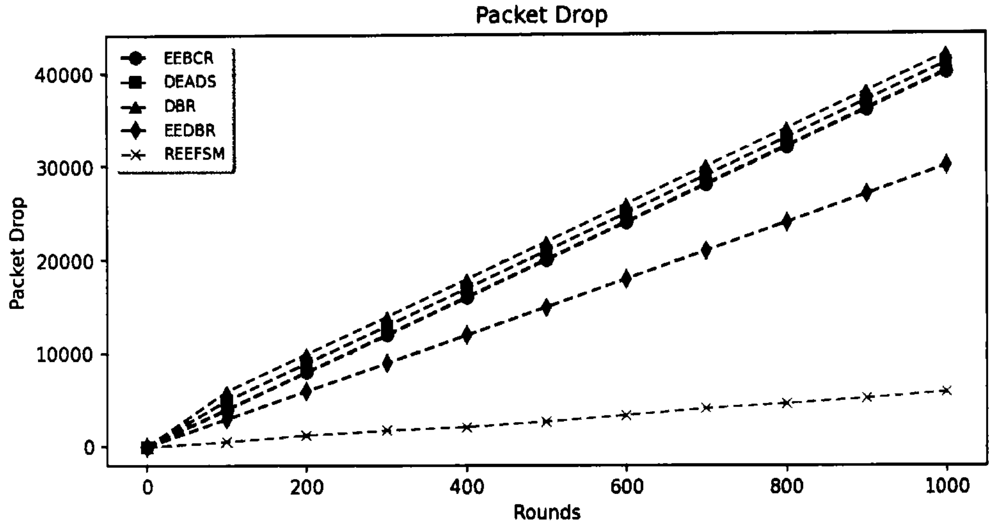

FIGURE 4.3: Number of Packet Drop

and data reliability. Significant reductions in energy consumption and improvements in reliability have been seen compared to existing protocols like EERBCR and DEADS. The framework ensured zero dead nodes, minimized packet drops, and maintained high data accuracy throughout the simulations.

REEFSM is the most energy-efficient protocol; although DEADS also showed commendable energy efficiency, it faced challenges maintaining node connectivity and packet delivery reliability over time. EERBCR, on the other hand, provided a balanced approach between energy efficiency and reliability.

Future research should focus on integrating advanced optimization techniques, such as autonomous path planning, energy harvesting, and machine learning, to further enhance network longevity and performance.

4.2 2D Network Setup and Communication Phases

This section describes the Acoustic Sensor's network deployment and communication phases in a simplified structure, as shown in Figure4.4 to illustrate the functionality of the proposed framework.

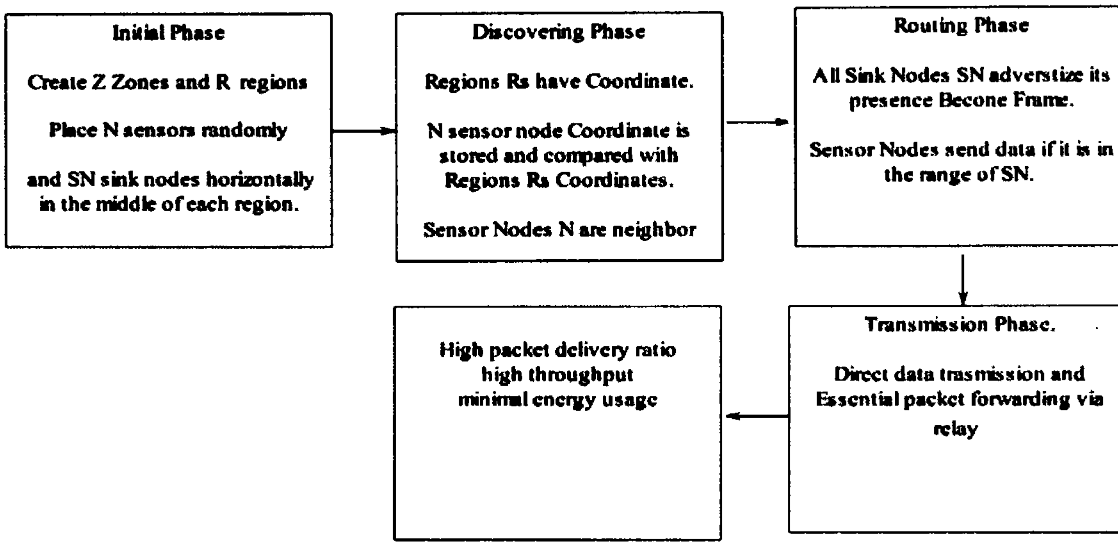

FIGURE 4.4: The phases of Acoustic Sensor Deployment involve the sensor's location, neighbor identification based on coordinates, and forwarding packets to their destination.

4.2.1 Location Detection and Update Mechanism

In the neighbor's discovery phase, a sensor node is used to identify all its neighbor's sensor nodes by their coordinates and their region's coordinates. If its region coordinate is similar, it is neighbors, and this information is stored in neighbors tables with sensor nodes ID, coordinate, and residual energy. All sensor nodes have a table called 'Sensor node input' containing the neighbors' details. The coordinates show precisely where each sensor is located, and the current amount of energy in each is listed. In contrast, the method sorts each node into a specific region by checking its coordinates against the known edges of the regions in a collection called region coordinates. Each area has its own set of coordinate boundaries that make it unique.

4.2.2 Discovery of Coordinates-Based Neighbors

A novel technique in wireless sensor networks determines whether nodes are close enough to interact directly. This strategy is handy when several sensors are dispersed across a large area and divided into areas. A simplified algorithm with component breakdown: The number (N) of sensor nodes in the network. The number of regions (R) divides the network into zones. The maximum distance (Tx. Range:

Transmission Range) two sensor nodes can send and receive signals. This list (Sensor.Node.Info) is a comprehensive catalog of sensor nodes. The following list displays each node's geographical position and the amount of energy it currently possesses. These points (regional coordinates) define each region's beginning and end.

Algorithm 5 Discovery of Coordinates-Based Neighbors

```
Input:
    N: Total number of sensor nodes
    R: Total number of regions
    TX_range: Maximum transmission range of a node
    sensorNodeInfo: List containing all sensor nodes with their coordinates and energy
    region_coordinates: List containing coordinates defining each region
Output:
    Each node's neighbors list is updated with the IDs of neighboring nodes within the same region and transmission range
for each node in sensorNodeInfo do
    Determine the region of the node based on its coordinates
    Initialize an empty list to store neighbors for the node
end for
for i from 0 to N − 1 do
    Set node_i to sensorNodeInfo[i]
    for j from 0 to N − 1 do
        if i is equal to j then
            Skip to the next iteration
        end if
        Set node_j to sensorNodeInfo[j]
        if node_i and node_j are in the same region and the distance between node_i and node_j is less than or equal to TX_range then
            Append the ID of node_j to the neighbors list of node_i
        end if
    end for
end for
```

This technique helps to manage large networks efficiently. Separating the network into regions can better manage the data and ensure network stability. Establish a system where every sensor node knows other sensors to facilitate direct connection. However, only sensors close to the signal and within their range should be considered.

4.2.3 2D Mathematical Model of RISNDBC

Each Sensor Node S_i has a neighbors list N_i and updated to add all Sensor Node S_j that meets the criteria of excluding the node itself ($i \neq j$), nodes must be in the same region ($r(S_i) = r(S_j)$), the distance $d(S_i, S_j)$ between nodes have not exceeded the transmission T_xMax. Equation 5.1 shows the Neighbor list.

Each pair of Sensor Nodes ($S_i, S_j \in S \times S$, where $i \neq j$) performs the following steps.

Step 1. Neighbors and adjacency thresholds.

$$r(S_i) = r(S_j) \text{ and } d(S_i, S_j) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \leq T_x$$

Step 2. Update neighbor list N_i

$$\{j | r(S_i) = r(S_j)\,,\; d(S_i, S_j) \leq T_x\text{max} \forall j \neq i, j \in \{1, 2, \ldots, N\}\} \tag{4.1}$$

4.2.4 Acoustic Wave Transmission Model

Elevated bit error rates, extended propagation delays, and restricted bandwidth characterize underwater acoustic propagation. Saltwater's intricate physical properties contribute to its absorption, attenuation, and scattering.

Thorp's model considers underwater conditions. Equation 4.2.4 defines signal (f) as the frequency and (V) as a function that characterizes the reduction and absorption of an acoustic wave during its transmission over a distance of (d).

$$V = A * f^2 * d$$

V represents the attenuation of a signal, which refers to the reduction in signal strength (absorption) measured in decibels (dB) when the movement travels through water. A is the absorption coefficient, which quantifies the absorption rate per kilometer in decibels. The frequency of the acoustic wave, denoted as F, is measured in kilohertz. D represents the propagation distance, kilometers between the source and destination nodes. When dealing with frequencies exceeding 0.4, we utilize the methodology stated in Equation 4.2.4 to determine velocity (V), where V combines various factors, including the frequency (f) measured in kilohertz (kHz):

$$V = \frac{(0.11f^2)}{(1+f^2)} + \frac{44f^2}{(4100+f)} + 2.75 * 10^{-4} * f^2 + 0.003$$

For frequencies at or below 0.4, however, we use the formula in Equation 4.2.4.

$$V = 0.002 + 0.11\left(\frac{f}{1+f}\right) + 0.011$$

Here, we calculate the absorption loss in decibels per km (dB/km), given the frequency f in kilohertz (kHz).

4.2.5 Acoustic Sensor Node Energy Model

Efficient management of energy consumption is crucial in underwater acoustic sensor networks (UASNs) for monitoring and optimizing the usage of sensor nodes. Given the nature of these nodes, which are typically powered by batteries and required to operate for extended periods without recharging, monitoring their energy consumption closely becomes crucial. Several factors affect the energy consumption of the sensing node during data transmission ($E(Tx)$) and reception ($E(Rx)$). Consider the distance from the node, the transmission power, and the data transfer speed. These are primary factors for designing and optimizing routing protocols.

$$E\left(Tx\right) = P\left(Tx\right) * \left(\frac{1}{V}\right) * BW$$

Equation 4.2.5 shows the energy required for packet sending across harsh underwater environments. This equation describes packet transmission energy in Joules as $E(Tx)$. The power required for packet transmission by the node is $P(Tx)$. Packet transmission energy is measured in watts. $E(Tx)$ represents the data transport energy, while $P(Tx)$ represents the transmission power of the acoustic sensor node.

Internet connectivity uses energy, as seen in Equation 4.2.5. The energy consumption of a sensor node during packet transmission and reception in each time frame is measured in Joules. $P(Rx)$ can measure the node's power consumption during data receiving, revealing how much power is consumed. The calculated value of the received signal, represented as $E(Rx)$, is determined by multiplying the period by the probability of receiving the call, denoted as $P(Rx)$. Mention in Equation 4.2.5. $E(Rx)$ measures the energy usage of a sensor node during data receipt, while $P(Rx)$ measures data handling and receiving power. UASNs need energy efficiency to operate.

$$E\left(Rx\right) = P\left(Rx\right) * \left(\frac{1}{V}\right) * BW$$

4.3 3D Network Architecture

Functional responsibilities and interconnections of various nodes, together with a structured approach, are used to evaluate the performance of mobility-adaptive routing and energy-aware relay node selection in dynamic underwater situations. Sensor Node (n_i), Relay Nodes (r_j), Sink Nodes (k_k), Adjacency Matrices (A_{ij}), and Routing Matrices (R_{ij}) are depicted in Equations 4.3 to 4.3.

$$S = \{n_i | i = 1, 2, 3, \ldots, n\}$$

$$R = \{r_j | j = 1, 2, 3, \ldots, m\}$$

$$K = \{k_k | k = 1, 2, 3, \ldots, l\}$$

$$A_{ij} = \begin{cases} 1, & \text{if node i can communicate with node j} \\ 0, & \text{otherwise} \end{cases}$$

$$R_{ij} = \begin{cases} 1, & \text{if node i routes data through node j} \\ 0, & \text{otherwise} \end{cases}$$

4.4 Node Mobility Model

The mathematical framework utilized to simulate underwater network sensor node mobility is based on a modified random walk model. This model realistically represents underwater sensor node movements, which are affected by several environmental conditions, by careful tuning. The model simulates underwater dynamics with water currents, pressure changes, and temperature variations. Position update is depicted in Equation 4.4, where $X_i(t)$, $V_i(t)$, and Δt is node i position, velocity vector at time t, and time stamp.

$$X_i(t + \Delta t) = X_i(t) + V_i(t) \cdot \Delta t$$

Velocity determination is described in Equation 4.4, where v_{avg} represents the average velocity, and $\text{dir}(t)$ denotes the direction of node i at time t.

$$V_i(t) = v_{avg} \cdot \text{dir}(t)$$

Directional changes are depicted in Equations 4.4 and 4.4, where $\theta_i(t)$ and $\varphi_i(t)$ are Azimuth and polar angle concerning time, and $\Delta\theta_i$ and $\Delta\varphi_i$ are changes in angle caused by environmental factors.

$$\theta_i(t + \Delta t) = \theta_\imath(t) + \Delta\theta_\imath$$

$$\varphi_\imath(t + \Delta t) = \varphi_\imath(t) + \Delta\varphi_\imath$$

Equation 4.4 describes Depth Control via Buoyancy, where $\Delta Z_\imath(t)$ is a change in depth.

$$Z_\imath(t + \Delta t) = Z_\imath(t) + \Delta Z_\imath(t)$$

4.5 Energy Consumption Model

This model quantitatively describes nodes' energy usage based on their numerous operations, such as data transmission, reception, and idle states.

Transmission Energy E_{tx} is shown in Equation 4.5, where P_{tx}, d, α, and s is transmission power, distance, path loss, and packet size.

$$E_{tx}(d, s) = P_{tx} \cdot d^\alpha \cdot s$$

Reception Energy E_{rx} is given in Equation 4.5, where P_{rx} and s is the power consumed during the reception of the packet.

$$E_{rx}(s) = P_{rx} \cdot s$$

Idle Energy E_{idle} is depicted in Equation 4.5, where $P_{\imath dle}$ is the amount of power consumed during an idle state, and Δt is the duration of the idle state.

$$E_{idle} = P_{idle} \cdot \Delta t$$

Energy Optimization and Adaptive Power Control are described in Equations 4.5 and 4.5, where n, d_i, s_i, k, and β are nodes in the routing path, including distance and packet size, environmental conditions, and node sensitivity toward power change, are also considered.

$$\min \sum_{i=1}^{n} (E_{tx}(d_i, s_i) + E_{rx}(s_i))$$

$$P_{tx} = k \cdot d^{\beta}$$

4.6 Data Transmission and Relay Node Selection

Selection of relay nodes and data transmission mathematical modeling is developed to ensure adequate network operation. Algorithms 6 to 9 describe the schemes more systematically.

Algorithm 6 Probability of Packet Transmission

1: **Input:**
2: $d(i, j)$: Distance between nodes i and j
3: γ: Decay constant
4: E_i: Residual energy of node i
5: **Output:**
6: $P_{tx}(i, j)$: Probability of packet transmission from node i to node j
7: Calculate $P_{tx}(i, j) = \frac{e^{-\gamma d(i,j)}}{E_i}$

Algorithm 7 Packet Success Rate

Input:
  $SNR(i, j)$: Signal-to-noise ratio between nodes i and j
  η: Environmental noise factor
  ζ: Signal quality factor
Output:
  $S(i, j)$: Packet success rate between nodes i and j
Calculate $S(i, j) = \frac{1}{1+e^{-(\eta SNR(i,j)-\zeta)}}$

Algorithm 8 Relay Node Selection

Input:
  R: Set of relay nodes
  λ: Weight for energy efficiency
  $E_{tx}(i, r)$: Transmission energy between nodes i and relay node r
  $S(i, r)$: Packet success rate between nodes i and relay node r
Output:
  $R_{selected}$: Selected relay node
Calculate $R_{selected} = \text{avg}\max_{r\in R}(\lambda E_{tx}(i, r) + (1 - \lambda)(1 - S(i, r)))$

Algorithm 9 Path Optimization

Input:
  ρ: Set of all possible paths
Output:
  $P_{optimal}$: Optimal path
Calculate $P_{optimal} = \text{avg}\max_{P\in\rho}(\sum_{(i,j)\in P} S(i, j))$

4.7 Efficient Routing and Energy-Aware Relay Selection Algorithm

Algorithm 10 Describe the mechanism of relay node selection.

4.8 Metrics for Evaluation

Several critical characteristics and metrics were selected for evaluation to analyze the mobility-adaptive routing protocol as given below:

Algorithm 10 Mobility-Adaptive Relay Node Selection

Input:
  Network graph $G(V, E)$
  Source node s
  Destination node d
Output:
  Optimal relay node for data transmission
Initialize parameters:
  $HR(e)$: Historical Reliability of edge e
  $E(n_i)$: Residual energy of node n_i
  $D(n_i, d)$: Distance between node n_i and destination node d
  $R(n_i)$: Relay suitability of node n_i
for each edge e in E **do**
  $HR(e) \leftarrow \text{calculateHistoricalReliability}(e)$
end for
for each node n_i in V **do**
  $R(n_i) \leftarrow \alpha \cdot HR(e) + \beta \cdot E(n_i) + \gamma \cdot (1/D(n_i, d))$
end for
$n_{optimal} \leftarrow \arg\max_{n_i} R(n_i)$ **return** $n_{optimal}$

4.8.1 Sensor Node Density

The number of nodes per unit volume within the simulated area. This parameter helps comprehend the impact of network density on communication effectiveness and energy efficiency.

4.8.2 Communication Range

The maximum distance between two nodes can effectively communicate. This range impacts the hops required for message delivery and influences the network's topology dynamics.

4.8.3 Node Mobility

Encompasses the maximum speed of node movement and the variability of their movement patterns, which affect the network topology and the routing protocol's ability to adapt.

Algorithm 11 Energy-Aware Relay Selection

```
Input:
    Set of candidate relay nodes R
    Source node s
    Destination node d
Output:
    Selected relay node r
Initialize best_score to infinity
Initialize selected_relay to NULL
for each node r in R do
    if r is active and not the source or destination then
        Compute proximity_score = distance(s, r) + distance(r, d)
        Compute energy_score = residual_energy(r)
        score(r) = α · proximity_score + β · (1/energy_score) // alpha, beta are weights
        if score(r) < best_score then
            best_score = score(r)
            selected_relay = r
        end if
    end if
end for
if selected_relay is NULL then
    Handle error or select an alternative relay based on secondary criteria
end ifreturn selected_relay
```

4.8.4 Battery Capacity

Initial energy for sensor nodes is Critical because this parameter impacts network longevity. Relay selection algorithm energy-saving features depend on energy management and conservation.

4.8.5 Data Generation Rate

The rate at which nodes generate data affects network traffic and protocol efficiency, especially under strain. Higher data output rates may cause congestion; thus, the protocol must manage data efficiently.

4.8.6 Packet Delivery Ratio (PDR)

The ratio of data packets delivered to their destinations due to routing and relay decisions; high PDR indicates network reliability.

4.8.7 Throughput

Data sent and received per unit of time is network throughput, which assesses network traffic efficiency.

4.8.8 Energy Efficiency

Sensor nodes transmit packets at the cost of energy. Managed transmission techniques minimize energy and, hence, increase network lifespan.

4.8.9 End-to-End Delay

End-to-end latency is the average data packet transmission time between nodes.

4.8.10 Network Lifetime

Network life continues until the first sensor node dies. This statistic shows real-world network efficiency and sustainability.

4.8.11 Node Survival Rate

The survival rate tracks the percentage of active nodes. Energy management of route and relay selection methods is assessed. With energy optimization, more nodes last longer.

4.9 Conceptual Model of the Sensor Network System

To develop a conceptual model that illustrates the structural and narrative connections between the components of the sensor network system.

4.9.1 Conceptual Model Description

Sensor Nodes:

- **Role:** These are the principal data collection points in the network. They are equipped with suitable ambient change sensors and acoustic modems for communication purposes.
- **Interaction:** Sensor nodes are responsible for acquiring data, while sink nodes receive data from the sensor nodes. Data transfer and energy expenditure are the two main elements of sensor node communication, which must be managed to maintain the network's life.

Sink Nodes:

- **Role:** These are some of the network's data collection points. Non-moving nodes, or sink nodes, are designated to retrieve data from the sensor nodes and forward it to the base station or relay nodes.
- **Interaction:** Sink nodes' main role is to interact with sensor nodes to ensure that all the data is transmitted as required while ensuring proper network coverage. The location and movement of the sink node are some of the essential aspects that affect the network's performance.

Network Topology:

- **Role:** The network's topology defines the structure of the sensor nodes and communication patterns between sink nodes and other nodes.

- **Interaction:** The topology affects the routing paths, energy consumption, and reliability of data transmission. The network topology must be flexible to changes in the environment and sink nodes' mobility.

Energy Management:

- **Role:** Energy is a very important resource in the sensor nodes since they are powerless. Thus, plans for effective energy management should be considered to extend the network's lifetime.
- **Interaction:** The conceptual model must highlight how energy is used during data transmission and reception, and the measures taken for energy conservation, such as sleep cycles and routing protocols.

Data Routing and Transmission:

- **Role:** The routing protocol defines the procedure for forwarding data from the sensor nodes to the sink nodes. The objectives include avoiding delay, energy consumption, and packet drop.
- **Interaction:** The routing decision depends on the location of sensor nodes, the mobility of sink nodes, and the energy level of the nodes at that particular time. The conceptual model should depict these factors in relation to how the routing protocols work to ensure proper and accurate routing under these factors.

Mobility of Sink Nodes:

- **Role:** The mobility of the sink nodes is a key aspect of the proposed network model. Mobile sink nodes effectively reduce the congestion faced by the relay nodes and enhance the extent of coverage.
- **Interaction:** The sink node's mobility influences routing paths, energy utilization, and overall network stability among the other nodes in the network. The conceptual model should illustrate how sink node mobility is managed to enhance these factors.

4.9.2 Illustrating the Conceptual Model

The conceptual model can be illustrated using a flow or block diagram that connects these components. Interactions are often depicted with arrows and additional texts to describe the type of interaction. For example:

- **Sensor Nodes → Sink Nodes:** Data transmission that considers the energy consumed.
- **Sink Nodes → Central Base Station:** Forwarding the collected data.
- **Network Topology ↔ Energy Management:** The effect of topology on energy distribution and routing efficiency.
- **Mobility of Sink Nodes ↔ Routing Protocols:** The change of routing paths according to the movement of the sink node.

4.9.3 Purpose of the Conceptual Model

The conceptual model in this research seeks to provide a broad picture of how various components of the underwater sensor network will be designed to meet the intended objectives of reliability, energy efficiency, and efficient data transmission. The conceptual model, which provides both a visual and textual description, assists in comprehending how the whole system works and which interactions are significant for the network's performance.

Chapter 5

Location Aware Framework for Underwater Network

The Location-Aware Framework for Enhanced Data Reliability and Network Lifetime in Acoustic Sensor Networks (ILAF) has left a lasting impression with its remarkable efficacy in the analysis parameters, covering Packet Delivery Ratio (PDR), throughput, node longevity, and packet losses. Its convincing and impressive performance makes a solid case for its adoption in underwater sensor networks.

The framework establishes the concept of regions based on the dynamics of sink mobility and the geography of the underwater terrain. Every geographical zone can be tied to a single sink, and the number of nodes present in a specific geographical zone depends on factors such as the coverage area that must be addressed and the energy available in the nodes.

Another strategy is to define the region's flexibility, where sinks can move in or out depending on the current network conditions. This dynamic region management allows the framework to keep the target nodes covered optimally while conserving the nodes' energy resources.

The proposed framework employs a distributed localization system in which the sensor nodes can determine their positions individually with reference to given anchor nodes or reference points. This system has to work efficiently in water where signals such as GPS are out of reach.

The protocol operates across several layers of the network stack, each handling specific tasks: all seven-layer descriptions are outside the scope of our research, but they will be in future work.

To promote openness and provide a rationale for the simulation technique, including the selection of parameters and their respective values, the thesis presents a comprehensive Initialization Phase. This phase is critical as it entails setting up the network environment and configuring all essential parameters before commencing the accurate simulation. Here is a detailed analysis of how this is accomplished:

The Parameter Definition stage establishes parameters and constants determining the simulation's behaviour, including the number of sensor nodes, the spatial measurements of the simulation region, the initial energy levels of the nodes, communication distances, and extra configurations tailored to the simulation.

Thus, the statistical Tracking stage is not just another step in the simulation process. It is an important part that guarantees the reliability of the simulation outcomes. Adhering to specific procedures for preserving statistical data during the simulation ensures the authenticity of the data collected, which in turn lends credibility to the research findings. This stage is critical in ensuring that the results obtained through simulation are accurate and that we, as the authors, are confident in our findings, which are presented to you, dear reader. To make the variables realistic, the environmental variables are also chosen to mimic the real conditions for the underwater sensor network. This ensures that the simulation results are as close to real life as possible and relevant in the same sense. It is flexible enough to support both dynamic and static deployment instances, with more attention paid to dynamic deployment strategies involving mobile sinks. Static deployment of sensor nodes fixes the nodes at certain locations, and the framework then determines the routing paths according to the static nature of the topology. In the dynamic deployment scenario, mobile sinks roam across the network, thus achieving better coverage of the target area and avoiding the requirement of multiple-hop information collection from the sink. The framework also controls the energy of the nodes and changes the routing paths to respond to any form of movement exhibited by the sinks.

In the proposed framework, there are considerable gains in energy efficiency, as unnecessary transmission is greatly combatted through the establishment of efficient routing paths. The packet delivery ratio is also enhanced, pointing out that the framework has higher reliability in packet transmission than the referenced works.

Node failures use Cooperative Diversity. Nodes volunteer to work together to ensure that the data will be transmitted regardless of whether one or more nodes are destroyed.

Relay node selection includes energy levels, node distance from the sink node, and reliability. This process is controlled at each node independently to determine its suitability as a relay based on the information received from the neighboring nodes and sink

The framework helps track the state of nodes while predicting failure based on energy level and communication traffic. It is designed so that when a node is deemed to have failed, the framework ensures that no data is sent through it to prevent disruption.

The thesis is well-developed for the simulation, as it defines all the parameters and reasonably justifies them. This methodology enhances the credibility of the simulation results and ensures that the findings are relevant and useful in the real world.

5.1 The Phases of Two Dimensions IlAF

During the neighbor discovery phase, every sensor node acquires its neighbors by their coordinates and region and stores this information in the neighbor table, which consists of an ID, the coordinates of the sensor node, and its residual energy. The coordinates precisely locate each sensor and determine its region by comparing them to predefined regional boundaries. It is a novel technique to identify coordinates-based neighbors, beneficial for large, dispersed networks divided into regions. The process involves determining each node's region, locating potential neighbors within the same region and the transmission range, and creating a list of neighbors for each node to facilitate direct communication, as shown in Figure 5.1. This method enhances network management and stability by ensuring each sensor node can connect with nearby nodes within its signal range.

Each Sensor Node S_i has neighbors list N_i and updated to add all Sensor Node S_j that meets the criteria of excluding the node itself ($i \neq j$), nodes must be in the same region ($r(S_i) = r(S_j)$), the distance $d(S_i, S_j)$ between nodes has not exceeded the transmission T_{xMax}. Equation 5.1 shows the Neighbor list.

$$N_i = \{j \mid r(S_i) = r(S_j), d(S_i, S_j) \leq T_{xMax}, \forall j \neq i, j \in \{1, 2, \ldots, N\}\} \tag{5.1}$$

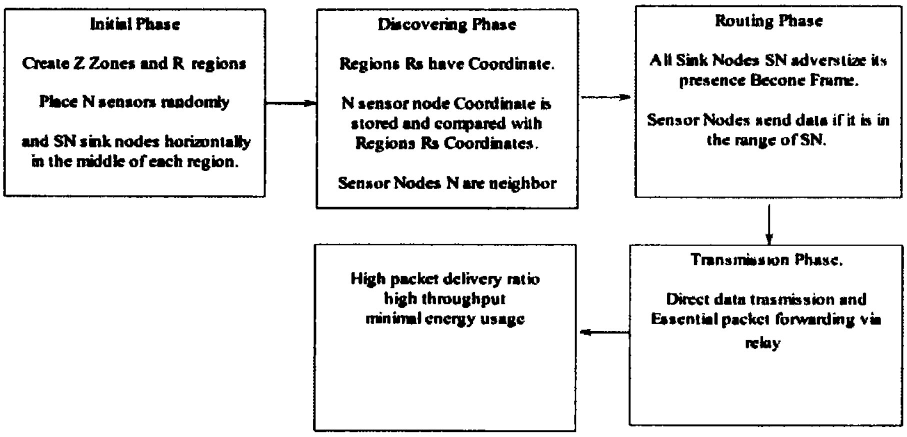

FIGURE 5.1: Phases of the Proposed 2D Location-aware Model

5.1.1 Results, Analysis, and Discussion

The simulation in Python was carried out to evaluate the performance of Proposed Protocols for underwater sensor networks, namely ILAF, and compared with the Energy Efficient Region-based Source Distributed Routing Algorithm for Sink Mobility in Underwater Sensor Networks (EERSDRA) [89]. Simulation parameters are given in Table 5.1.

Variable(s)	Value(s)
Energy per Node	10 Joules
Packet Size	1000 bits
Data Rate	250 bps
Number of Mobile Sinks	4
Network Area	10,000 square meters
Frequency Range	30,000 Hz
Number of Sensor Nodes	100
Round Duration	0.001 second

TABLE 5.1: Simulated Variables

5.1.2 Efficiency Relevant Metrics

The Packet Delivery Ratio (PDR) represents the proportion of successfully delivered packets, as depicted in Equation 5.2. PDR quantifies the network's efficiency in transmitting packets from source nodes to sinks in the simulation parameters. The metric is a percentage, where larger values indicate superior packet delivery performance.

$$PDR = \frac{Total\ Number\ of\ Packets\ send}{Number\ of\ Packets\ Received} \times 100 \tag{5.2}$$

Throughput in the provided simulation measures the rate at which data is successfully sent in the network, as shown in Equation 5.3. It considers the aggregate data gathered and the overall duration. Throughput is commonly quantified as the data transfer rate in bits per second (bps), serving as an indicator.

$$Throughput = \frac{Total\ Data\ Received}{Total\ Time} \tag{5.3}$$

5.1.3 Packet Delivery Ratio (PDR)

Figure 5.2 shows the packet delivery ratio (PDR), which measures reliability and efficiency. ILAF's PDR is over 99.8% across all rounds, dropping from 99.91% to 99.814% from 100 to 1000. At round 1000, EERSDRA lowers from 99.775% to 99.759%. Both protocols transmit packets well, although ILAF has a slightly higher PDR across rounds. ILAF's high PDR suggests it can successfully send packets underwater, where multi-path fading, high latency, and variable noise levels might impede communication. Despite its lower PDR, EERSDRA has a good ratio, indicating a reliable gearbox. The modest PDR fluctuation could be significant in long-term deployments. More rounds may kill more nodes, lowering both protocols' PDRs. Node failure can split the network, prolonging paths and increasing packet loss.

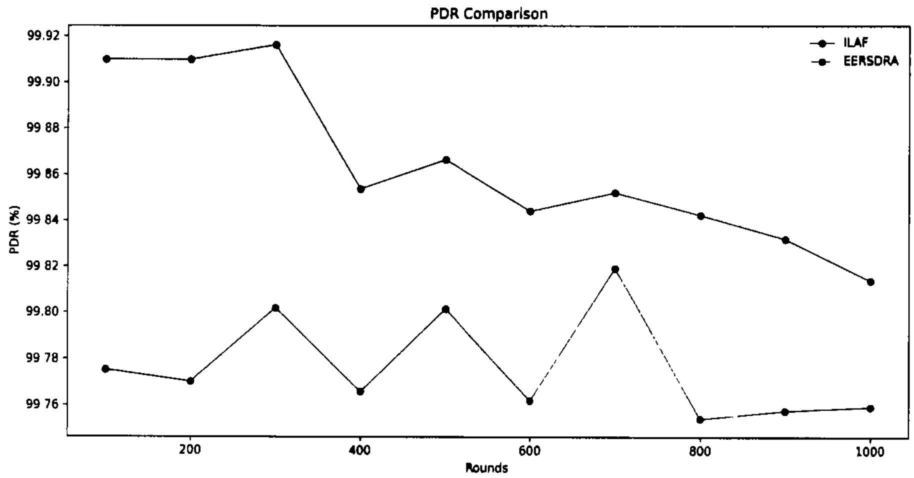

FIGURE 5.2: Packet Delivery Ratio (PDR)

5.1.4 Throughput

Throughput is crucial to protocol performance. ILAF beats EERSDRA in all rounds. As network demand rises, ILAF throughput drops from 6 kbps at 100 rounds to 5.712 at 1000 rounds. In contrast, EERSDRA starts at 5.88 kbps and reduces to 5.49 by the 1000th round, indicating a higher throughput loss. ILAF's higher throughput shows that it manages data needs better than EERSDRA. Better packet scheduling and other factors may explain this. ILAF's high throughput is advantageous in places with limited bandwidth due to route loss, noise, and Doppler. Lower throughput may suggest prioritizing energy efficiency or error resistance over data transfer speed. In conclusion, ILAF exceeds EERSDRA in throughput. Finally, ILAF is more reliable than EERSDRA, as shown in Figure 5.3.

5.1.5 Packet Drop

ILAF beats EERSDRA in packet dropouts. ILAF has nine packet drops at 100 rounds, while EERSDRA has 22. This indicates a higher packet delivery rate. ILAF had 177 packet dropouts after 1000 rounds, and EERSDRA had 220. ILAF drops fewer packets than EERSDRA despite these challenges. ILAF's packet handling efficiency reduces retransmissions, saving energy. EERSDRA's higher packet drop rate may be due to less effective routing in the highly variable undersea environment or a trade-off between energy efficiency and computing complexity. Finally, ILAF has

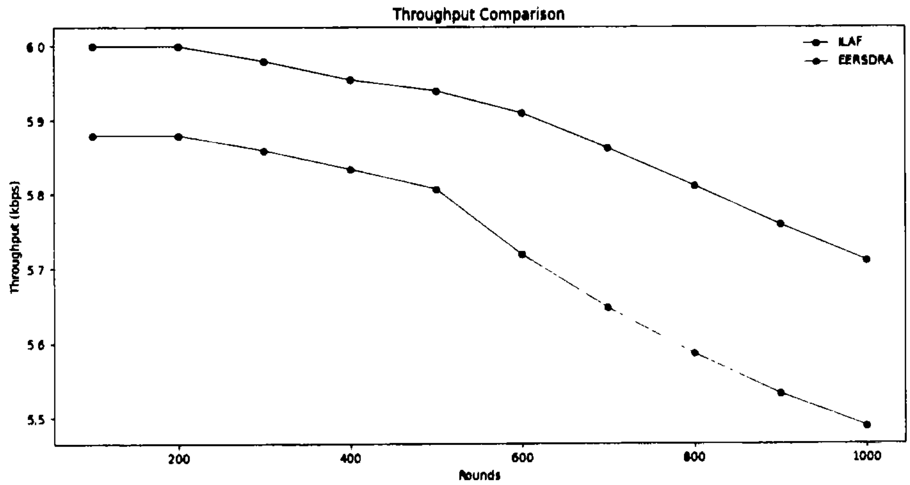

FIGURE 5.3: Throughput

a superior packet drop profile, and the best protocol should balance dependability, energy usage, and latency, as shown in Figure 5.4.

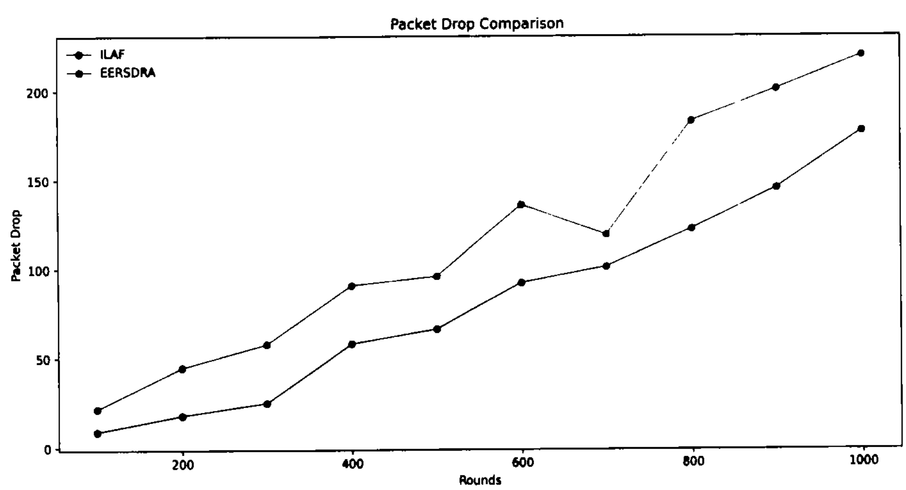

FIGURE 5.4: Packet Drop

This section has presented a thorough examination of the Location-Aware Framework for Enhanced Data Reliability and Network Lifetime in Acoustic Sensor Networks (ILAF) and a critical assessment of other relevant protocols, such as EERSDRA. The findings from this study emphasize the efficacy of ILAF across many essential performance indicators and provide benefits linked to EERSDRA.

The energy consumption of the ILAF and EERSDRA protocols in underwater acoustic sensor networks was analyzed. Energy consumed by EERSDRA was much higher than that of ILAF. The fact that there are more living nodes and the transmission of large packets is possible in ILAF makes it efficient. Although EERSDRA obtained more energy than the other algorithms, it had more dead nodes and lower packet transmission rates. The recommendations of this study focus on the importance of energy-efficient protocol design at UW-ASN. ILAF controls energy consumption to ensure that the networks and their resources are optimally used and efficiently transfer data. The analysis demonstrates that EERSDRA efficiency exhibits energy resource management questions, especially regarding long-term network usage.

5.2 Three-Dimensional Model

The flowchart outlines all phases of mobility adaptive with Energy-aware relay node selection of 3D framework (MAEARS) as shown in Figure 5.5, initialization of a 3D Acoustic network, sensing environmental data, and determining the best way to transmit that data. It starts with setting up the network and gathering data from the surroundings. The Proposed algorithm then checks if a sink node is nearby to send the packet directly. If not, it looks for a relay node. If a relay node is found, it evaluates and calculates its effectiveness and stability, selects the optimal relay node, and transmits the data. If neither a sink nor a relay node is available, the packet is dropped, and the process concludes. The presented models and simulations require a few important assumptions. Consistent Environmental Conditions: When the network is on, environmental factors such as water temperature, clarity, and noise level are assumed to be within some standard levels. Uniform Node Distribution: The models assume that the sensor nodes are uniformly distributed over the deployment area, which is convenient both for analyzing the system and for developing the routing protocols. Stable Node Behavior: This means that nodes will act as expected on issues related to sleep wake-up schedules, data transfers, and energy consumption.

The amount of data, packet size, and energy consumption. Smaller packets increase efficiency and decrease error rates and retransmission requirements, but there are some issues because you need more packets to send the same quantity of data. Large packets are less redundant and, hence, better in terms of overhead but tend to be more affected by noise and error than small packets. It adapts the packet size to facilitate communication based on the network's current situation and the channel's quality. For instance, when operating in a noisy environment, the framework might pack data into smaller packets to process minimal re-transmissions, thus consuming small bandwidth; in less reliable channel conditions, big packets are used to increase the framework's efficiency.

The Framework mainly concentrates on Acoustic communication, as this is more effective than electromagnetic waves and sound navigation and ranging, which get highly attenuated in water. Another good reason for using acoustic waves is that they lose their energy at less distance than other waves and can travel longer distances in water.

The extensible bodies of knowledge are made available on the web to act as a key constituent in the proposed framework aimed at improving the network steadiness as well as availability through the following ways: It must be mentioned that the distribution of energy consumption is fair across the network so that no node is exhausted early and network stability is preserved. The paths for routing the data are kept redundant for each transmission so that the network is still functional in case of failure of one or several nodes. While connected, the size and position of regions are dynamically changed depending on the current load level of networks and the sink's movement to guarantee that the coverage and availability are always existent.

Relay nodes are chosen based on each node's energy level and the distance between the sensor nodes and the sinks. These relay nodes help ensure that data can be transferred easily, without many hops, and with a low rate of energy consumption.

The scanning phase in the proposed framework includes the occasional waking of nodes to identify nearby sinks or any other node that may need relaying data. The time taken in this process is important so that the network does not use a lot of energy while responding to the changes in the environment. The framework further enhances the time taken to complete the scanning process by dynamically adjusting the frequency and length of the scanning intervals depending on the network's current status. For instance, it can be a few seconds in a highly dynamic network or an environment where all constituents are steady. However, in a high-traffic situation or when a sink is active in the network, the intervals may be reduced to enable real-time data capture. It also provides for adaptive scanning, in which nodes can change their scanning rate based on their energy level and the distance from the nearest sink. This means that the scanning is efficient in terms of energy consumption and malleable to the network's aspects.

Expected to respond to changes in the sink node positions, especially those brought about by unpredictable activities such as wild flow. This adaptability is achieved through several key mechanisms: The framework periodically checks the positions of the network sink nodes and dynamically optimizes the routing trails to guarantee that data can still be efficiently delivered to them despite their mobility. Relay nodes are selected to be nearer to the sink nodes than the other two. The framework can reallocate relay nodes whenever a sink node changes its location to ensure good data transmission. It also has procedures for estimating the movement of sink nodes based on their history and the prevailing trends in the existing environment. This makes it possible for the network to predict where the sinks will likely be positioned at certain times, hence changing the routing and communication modes in anticipation of the new positions.

In more dynamic conditions with variations in water forces, temperature gradients, and obstacles. These scenarios are intended to check the framework's performance in conditions that cannot be well controlled and are more similar to real-life conditions.

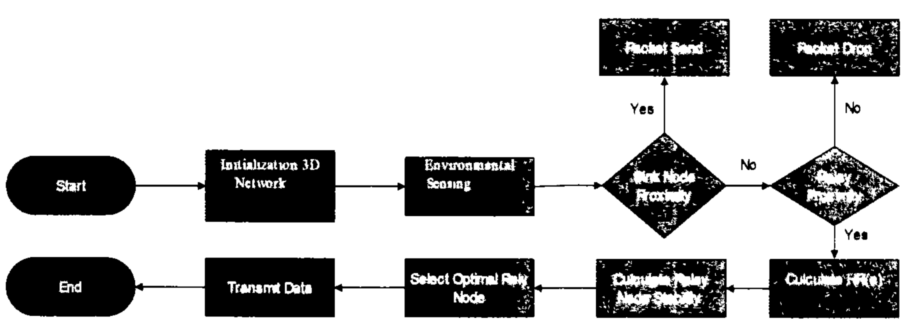

FIGURE 5.5: Simplified Flow Chart of MAEARS

5.2.1 Analysis of MAEARS Result

Table 5.2 shows the performance analysis of MAEARS, which optimizes energy efficiency, PDR, throughput, and node performance in 3D underwater environments. It outperforms EECRP because of its consistent energy consumption management, sustained PDR above 90%, higher throughput, and superior data traffic management. Scalability and relay node selection improve the dependability and flexibility of 3D underwater sensor networks. MAEARS is reliable, extendable, and energy-efficient for large submerged applications, exceeding EECRP [90].

Round	Total Energy Remaining	Packets Sent Directly	Packets Relayed	Packets Dropped	Alive Nodes	Dead Nodes	PDR (%)	Throughput (kbps)
100	934 79922	325	3762	423	100	0	90 62	90 82
200	867 77241	720	7605	762	100	0	91 61	92 5
300	800 38375	1039	11500	1041	100	0	92 33	92 88
400	731 4036	1288	15518	1216	100	0	93 25	93 37
500	661 83041	1623	19537	1343	100	0	94 03	94 04
600	590 53841	1977	23651	1384	100	0	94 88	94 92
700	520 37218	2308	27707	1392	100	0	95 57	95 29
800	449 42528	2688	31790	1397	100	0	96 11	95 77
900	380 9209	3061	35730	1405	100	0	96 5	95 78
1000	317 17424	3419	39392	1411	100	0	96 81	95 14

TABLE 5.2: Simulation Results of MAEARS

5.2.2 Performance of Mobility-Adaptive Routing

The protocol exhibits impressive mobility-adaptive routing performance, delivering a consistently high packet delivery ratio (90.62% to 96.81%) and increasing throughput (90.82 to 95.14 kbps) as the network topology changes due to node mobility. This adaptability ensures reliable data transmission in dynamic underwater conditions.

5.2.3 Effectiveness of Relay Node Selection

The relay node selection mechanism of MAEARS is highly effective, successfully relaying a substantial and increasing number of packets (3762 to 39392) while keeping packet drops relatively low (423 to 1411). This enhances network reliability and coverage and minimizes packet loss in environments with signal attenuation challenges.

5.2.4 Comparative Analysis with Existing Methods EECRP

MAEARS protocol is evaluated against several existing methods (EECRP, FCMMFO, FBCPSO, EGRC, LEACH-ERE LEACH) based on energy consumption, packet delivery ratio (PDR), throughput, and packets sent to the sink as depicted in Table 5.3. Compared to other methods, MAEARS demonstrates superior energy efficiency, with 317.174236 units of energy remaining after 1000 rounds. Its PDR starts at 90.62% and increases to 96.81%, indicating robust data delivery. Throughput peaks at 95.78

kbps at 900 rounds and slightly declines to 95.14 kbps at 1000 rounds, showcasing efficient data handling. Additionally, MAEARS consistently sends more packets to the sink, reflecting better overall network performance.

Metric	MAEARS	EECRP	FCMMFO	FBCPSO	EGRC	LEACH-ERE	LEACH
PDR (%)	96.81	96	95 5	94	93	92	91
Throughput (kbps)	95.14	92	90	88	85	80	75
Packets Sent	High cumulative packets	Moderate	Moderate	Moderate	Lower	Lower	Lowest

TABLE 5.3: Performance Comparison

The proposed framework is also compared with Chaotic Search-and-Rescue-Optimization-Based Multi-Hop Data Transmission Protocol for Underwater Wireless Sensor Networks.

The experimental setting presented in the thesis aims to emulate the actions of UWSNs under various circumstances, with the purpose of gauging the prospect framework's efficiency in enhancing energy consumption, reliability, and network performance. The simulation environment also includes an actual capability model of underwater acoustic communication, where certain parameters, including signal attenuation, noise, and propagation delay, are vital. These sink mobility patterns and densities of network nodes and environmental conditions effectively cover a broad spectrum of possible application areas. The simulation settings, such as the number of nodes, packet length, power level of the desirable data transmission, and sleep/wake time, were decided considering the recommendations from the literature survey and the scope of the present work. These parameters were chosen so that the results obtained after running the mentioned simulations are as close as possible to the real-world UWSNs.

MAEARS enhances the packet delivery ratio by optimizing the relay selection process, ensuring data is reliably transmitted from sensor nodes to the sink node. Its ability to adapt to changing conditions, such as node mobility and varying network topologies, ensures consistent and reliable communication. It has been validated through extensive simulations, showing its potential for real-world environmental monitoring and military surveillance applications.

5.2.5 Packet Loss Ratio (PLR)

MAEARS remained the most dependable and consistent technique, maintaining a low PLR throughout all simulations, as shown in Figure 5.6. This low PLR indicates the MAEARS system's ability to maintain data integrity and network stability for underwater sensor networks. EECRP, FCMMFO, FBCPSO, EGRC, and LEACH-ERE have packet loss spikes throughout the simulation despite low PLRs. This shows that protracted network activity may compromise protocol dependability. The rising PLR of these protocols may be due to poor routing, energy management, or underwater adaptation. By keeping PLR low, MAEARS increases data transmission reliability and network robustness. That makes it perfect for long-term stability and precision underwater sensor network applications.

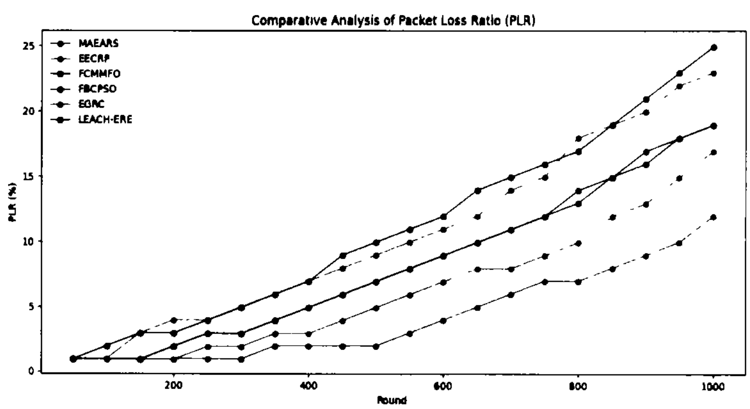

FIGURE 5.6: Packet Loss Ratio (PLR)

5.2.6 Packet Delivery Ratio (PDR)

MAEARS starts at 99% and delivers packets with a PDR of over 88% after 1000 cycles, as shown in Figure 5.7. Our underwater sensor network needs high PDR for stable communication and accurate data analysis. MAEARS's steady performance demonstrates it can traverse underwater currents and acoustic signal attenuation. EECRP, FCMMFO, FBCPSO, EGRC, and LEACH-ERE have high PDRs. PDRs for various treatments decrease over time. The drop implies that some protocols may weaken over long network durations. This decline may have been caused by poor routing, energy management, or underwater adaptation. MAEARS' high PDR indicates network communication dependability and consistency, as shown in Figure 5.7.

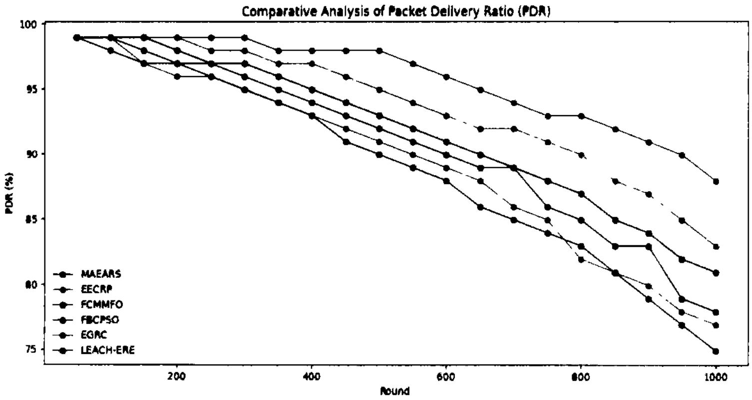

FIGURE 5.7: Packet delivery Ratio (PDR)

5.2.7 Energy Consumption

MAEARS consume energy better than other methods, as shown in Figure 5.8. This efficiency boosts data transmission, node survival, and network lifespan by increasing energy reserves. MAEARS's energy management keeps nodes powered for lengthy periods. Underwater battery charging is impossible; thus, this is vital. EECRP, FCMMFO, and FBCPSO became energy efficient but struggled to sustain it. Continuous usage of these strategies increases energy utilization, suggesting better energy management. Misuse of energy depletes node batteries, limiting network lifespan and data transmission reliability. Energy-wasting EGRC, LEACH-ERE, and LEACH therapies consume energy quickly. These factors make MAEARS the finest underwater sensor network and data transfer choice. Energy control makes network monitoring and data collection reliable and accurate. For stable network applications, underwater MAEARS is best.

The 3D MAEARS framework Key achievements include energy efficiency by selecting relay nodes based on residual energy levels and proximity to the source and destination nodes, improved packet delivery ratio (PDR) by optimizing relay selection to ensure reliable data transmission from sensor nodes to the sink node, latency reduction by strategically positioning relay nodes to minimize transmission time, adaptability to changing conditions such as node mobility and dynamic network

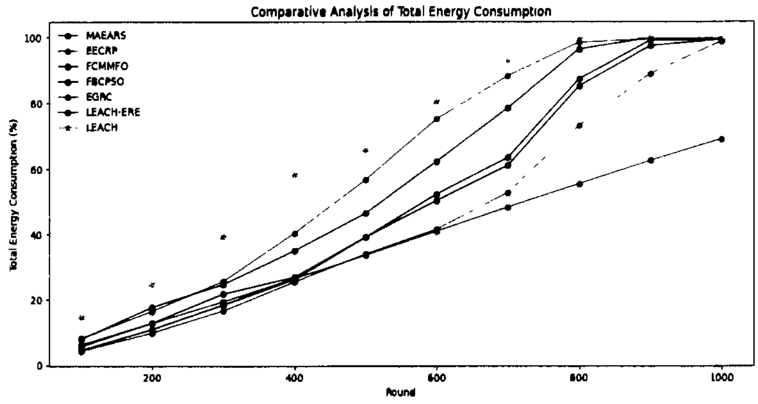

FIGURE 5.8: Total Network Energy

topologies. Future research will focus on conducting long-term trials and real-world deployments to validate MAEARS's durability and efficiency, studying environmental effects to develop adaptive algorithms, implementing hierarchical routing and scaling to manage more extensive networks, incorporating machine learning algorithms for predictive analytics, energy harvesting optimization, and intelligent modulation, developing robust security protocols, and collaborating with oceanic researchers and environmental monitoring organizations to demonstrate MAEARS's value in real-world applications.

5.3 Integrating MQTT and CoAP Protocols at Sink Nodes Level

The choice between MQTT and CoAP depends on network needs. MQTT is ideal for efficient publish-subscribe architectures in resource-limited scenarios, while CoAP suits resource-constrained environments with RESTful API support. Modifying these protocols for underwater settings requires considering limited data transfer, delays, and signal fluctuations. Install acoustic modems on sink nodes with enough computational capacity to handle these modifications, including temporal parameters, message sizes, and error management. Ensure protocol compatibility with the sink nodes' operating systems. Optimize the network structure for data transmission, considering sink node positioning and movement. Data aggregation and compression at sink nodes are used to reduce transfer volume and develop data caching and queuing techniques for intermittent links. Simulate the modified protocols before implementation to assess efficiency and optimize settings.

5.4 Benefits of Deploying MQTT and CoAP in UWSNs

MQTT and CoAP protocols can be modified to improve reliability, overcoming high error rates and fluctuating signals. Their versatility supports various network architectures, from simple point-to-point connections to complex multi-hop networks, suitable for diverse underwater operations. Optimizing these protocols for energy consumption is crucial for battery-powered underwater sensor nodes.

The proposal integrates MQTT and CoAP at UWSN sink nodes. MQTT's publish-subscribe model is beneficial for UWSNs with restricted power and bandwidth. Adapting MQTT to handle underwater delays and limited data transfer ensures reliable messaging. CoAP, designed for resource-constrained environments, fits well with UWSNs. Enhancing CoAP involves optimizing request/response interactions for underwater delays. Analyzing CoAP's role in resource management and scalability is essential.

Choosing between MQTT and CoAP depends on network size, node mobility, and energy limits. A hybrid protocol combining both can effectively address underwater communication challenges. Implementing these protocols involves technical challenges such as adaptation and performance impact, including energy efficiency and network longevity. Case studies or simulations can demonstrate their effectiveness in UWSNs.

Integrating MQTT and CoAP with the Location-Aware Framework for Enhanced Data Reliability and Network Lifetime (ILAF) aims to improve UWSN scalability and adaptability. These protocols' adaptability allows them to form various topologies, meeting UWSN scalability needs. Optimizing them for restricted bandwidth and delays enhances their capability to manage networks of different scales. Enhanced interoperability with surface and terrestrial networks supports seamless data integration, which is crucial for UWSNs. In summary, modifying MQTT and CoAP, along with the LAFU protocol, improves UWSN reliability, expandability, and energy efficiency, making them suitable for complex underwater environments.

5.5 Summary of Key Findings

In this section, the key results for each research question are summarized to highlight the major outcomes of the research. These summaries are presented for the outcome of the research.

5.5.1 Key Findings for Each Research Question

Research Question 1 (RQ1): *How can reducing reliance on forwarder nodes impact the overall energy consumption of the network?*

- The REEFSM framework effectively reduces reliance on forwarder nodes, leading to a significant decrease in energy consumption across the network.
- Optimized routing paths and the use of mobile sinks enhance energy efficiency, extending the operational life of the network.

Research Question 2 (RQ2): *What are the consequences of stopping the acceptance of hello packets on performance and dependability?*

- Limiting hello packet transmissions results in a more stable network with reduced energy wastage.
- The network maintains high packet delivery ratios and low latency, even with a reduced frequency of hello packets, demonstrating robust performance.

Research Question 3 (RQ3): *Will relocating the sink decrease the overall delay and enhance direct communication reliability?*

- Relocating mobile sinks significantly reduces end-to-end delays and enhances the reliability of direct communication between sensor nodes and sinks.
- The framework is adaptable to dynamic underwater environments, ensuring consistent communication quality.

Research Question 4 (RQ4): *Can cooperative diversity be achieved by using a mobile sink to cover both regions, improving performance?*

- The use of mobile sinks to achieve cooperative diversity leads to improved network performance, particularly regarding data throughput and energy efficiency.
- The framework remains robust and efficient even in challenging underwater conditions, demonstrating its effectiveness in enhancing overall network performance.

Research Question 5 (RQ5): *How can the deployment of mobile sinks improve the overall network lifetime in a UWSN?*

- The deployment of mobile sinks optimizes energy consumption across the network by reducing the burden on specific nodes, thereby extending the overall network lifetime.
- The strategic movement of sinks ensures balanced energy usage and prolonged network sustainability.

Research Question 6 (RQ6): *What are the effects of node mobility on the reliability of data transmission in UWSNs?*

- Node mobility, when managed effectively, enhances the reliability of data transmission by dynamically adjusting to changing network conditions.
- The framework's adaptive routing protocols ensure that data is reliably transmitted even as nodes move, minimizing the impact of mobility on communication quality.

Research Question 7 (RQ7): *How does the proposed framework improve the trade-off between energy consumption and data reliability?*

- The proposed framework successfully balances the trade-off between energy consumption and data reliability by optimizing routing paths and employing energy-efficient transmission techniques.

- Enhanced data reliability is achieved without compromising energy efficiency, demonstrating the effectiveness of the proposed approach in addressing this critical trade-off.

Research Question 8 (RQ8): *Can the proposed model efficiently handle high-density networks while maintaining performance?*

- The proposed model is highly effective in managing high-density networks, maintaining performance by efficiently routing data, and minimizing energy consumption.
- Network performance, including throughput and reliability, remains high even in dense network conditions, showcasing the framework's scalability.

5.5.2 Concluding Remarks

The key findings for each research question have been summarized and highlighted to enhance the clarity and accessibility of the results presented in this chapter. This approach helps readers quickly grasp the core insights without sifting through lengthy text sections.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

This thesis explored the various aspects of underwater sensor networks, such as node residual energy and mobility, transmission distance, and power increase and decrease to optimize energy utilization, 2D and 3D environments with the coordinate-based location without a GPS module installed, minimizing unnecessary hello and bye packet and maximum utilization of modified duty cycle. This motivation leads to developing novel models, algorithms, and techniques for reliable communication protocols such as REEFSM, MAERS, and ILAF. As with most networks, categorizing with a general appreciation of how they work and their true characteristics, especially regarding energy density, reliability, and the critical issue of communications over water, are concerned.

The assessment of the constituent aspects of the REEFSM protocol shows that it aids in energy conservation, reflected by its percentage, which shows the amount of energy used. Moreover, it meets high scalability and reliability since there are no dead nodes, and the packet drop rate is very small. This is a progression towards finding the procedures to support long-term functioning in underwater climates without eradicating substantial data. In addition, the ILAF protocol has been tested to achieve a higher PDR and the maximum number of nodes in real simulations; it has indicated its possible contribution to improving network stability and data transmission.

The analysis of these protocols helps to define the concern of the energy consumption and network stability relationship. The objectives of this thesis are twofold: to become familiar with these protocols and understand specific cases of their usage for solving real-life problems in sea security, monitoring the environment, and searching for resources in water bodies.

Several limitations were observed during this study, including the interference of the simulated conditions and the task of achieving a realistic simulation of underwater conditions. These challenges give signals that would be useful for future empirical work when exploring the reactions of resource constraint and simulation flexibility. They emphasize the demand for the design of better and more flexible communication systems that should be applicable in the ever-changing and unfriendly subaqueous conditions.

This thesis focuses on the technological developments at UWSN and shows how this field has been enhanced. These developments not only help energy conservation techniques with sensor node mobility but also assist in exploring and advancing 3D dynamic mobility protocols.

6.2 Future Work

The analysis of the underwater sensor network in this thesis reveals many opportunities for additional future research. Particular emphasis should be placed on defining the interaction patterns that are progressively complex and less prone to defects in contemporary systems. Furthermore, it is proposed to study and apply the possibility of creating new techniques, such as introducing the features and functionality of Internet of Things protocols in the developed framework for global connectivity and enhanced applications to find energy-reliable solutions and prepare the base for considering all constraints and features, which could be adaptable in acoustic sensor networks in many dimensions.

An avenue for further research should be adaptive Quality of Service (QoS) that forms the basis for future work. The researcher would allow networks to tweak certain parameters as may be dictated by the dynamic conditions of the water, such as currents, temperatures, and depth. Hence, the security and stability of the communication lines should be enhanced through flexibility in future underwater acoustic networks due to the environment's vulnerability.

Another area with a high level of potential is the design and creation of specific IT equipment for underwater sensor nodes. In future work, efficient and mechanically sturdy sensor nodes will be designed to withstand the stringently unfavorable underwater environment, specifically in pressure and chemical interaction.

The development of three-dimensional and realistic models of underwater sensor networks is also an essential research direction. Specifically, researchers have to learn more about how to effectively and sustainably scale such systems, as the demand for the mentioned networks is predicted to grow. To this end, one has to address the emerging design patterns of new network topologies and related communications processes together with energy awareness in large deployment scenarios.

Since underwater sensor networks are becoming more prominent, improving their safety is essential. Future work should be devoted to creating efficient security methods to protect networks and the data they transmit against attacks and unauthorized access.

Several critical domains are significant for the development of Second-Generation Underwater Wireless Sensor Networks and can transform the dynamics of the Earth's water bodies. Many new directions for exploration are possible, and they can be pursued more largely in the future, especially in the sphere of signaling and underwater research.

Bibliography

[1] A. Wahid, S. Lee, H. J. Jeong, and D. Kim. Eedbr: Energy-efficient depth-based routing protocol for underwater wireless sensor networks. In *Communications in Computer and Information Science*, volume 195 CCIS, pages 223–234, 2011.

[2] T. Bala, V. Bhatia, S. Kumawat, and V. Jaglan. A survey: Issues and challenges in wireless sensor network. *International Journal of Engineering and Technology(UAE)*, 7(2):53–55, 2018.

[3] J. Wang, J. Shen, W. Shi, G. Qiao, S. Wu, and X. Wang. A novel energy-efficient contention-based mac protocol used for oa-uwsn. *Sensors (Switzerland)*, 19(1), 2019.

[4] M. Al-Bzoor, T. Gharaibeh, and O. Ai-Ta'Ani. Avoiding routing voids with selective transmission power in underwater wireless sensor networks. In *Proceedings of the 2021 IEEE Jordan International Joint Conference on Electrical Engineering and Information Technology (JEEIT)*, pages 13–18, 2021.

[5] J. Luo, Y. Chen, M. Wu, and Y. Yang. A survey of routing protocols for underwater wireless sensor networks. *IEEE Commun. Surv. Tutor.*, 23(1):137–160, 2021.

[6] J. Luo, Y. Chen, M. Wu, and Y. Yang. A survey of routing protocols for underwater wireless sensor networks. *IEEE Communications Surveys and Tutorials*, 23(1):137–160, 2021.

[7] K. Sun, W. Cui, and C. Chen. Review of underwater sensing technologies and applications. *Sensors (Basel)*, 21(23), 2021.

[8] O. Gupta, N. Goyal, D. Anand, S. Kadry, Y. Nam, and A. Singh. Underwater networked wireless sensor data collection for computational intelligence

techniques: Issues, challenges, and approaches. *IEEE Access*, 8:122959–122974, 2020.

[9] A. Khan, M. Khan, S. Ahmed, M. A. A. Rahman, and M. Khan. Routing protocols for underwater wireless sensor networks: taxonomy, research challenges, routing strategies and future directions. *Sensors (Switzerland)*, 18(5), 2018.

[10] Y. Wang, Y. Liu, and Z. Guo. Three-dimensional ocean sensor networks: A survey. *Journal of Ocean University of China*, 11(4):436–450, 2012.

[11] A. M. Khedr, A. Aziz, and W. Osamy. Successors of pegasis protocol: A comprehensive survey. *Comput Sci Rev*, 39, 2021.

[12] G. S. Spagnolo, L. Cozzella, and F. Leccese. Underwater optical wireless communications: Overview. *Sensors (Switzerland)*, 20(8), 2020.

[13] N. Brusselaers, H. Huang, C. Macharis, and K. Mommens. A gps-based approach to measure the environmental impact of construction-related hgv traffic on city level. *Environ Impact Assess Rev*, 98, 2023.

[14] A. Hussain and et al. Cr-nbeer: Cooperative-relay neighboring-based energy efficient routing protocol for marine underwater sensor networks. *Journal of Marine Science and Engineering*, 11(7):1474, 2023.

[15] U. Satija, N. Trivedi, G. Biswal, and B. Ramkumar. Specific emitter identification based on variational mode decomposition and spectral features in single hop and relaying scenarios. *IEEE Trans. Inf. Forensics Secur.*, 14(3):581–591, 2018.

[16] M. Ali and et al. Energy and path-aware-reliable routing in underwater acoustic wireless sensor networks. *Wirel Commun Mob Comput*, 2022, 2022.

[17] N. T. Nguyen, T. T. T. Le, H. H. Nguyen, and M. Voznak. Energy-efficient clustering multi-hop routing protocol in a uwsn. *Sensors (Switzerland)*, 21(2), 2021.

[18] M. I. Kalinin and S. A. Kononogov. Fundamental problems in metrology: Boltzmann's constant, the energy meaning of temperature, and thermodynamic irreversibility. *Measurement Techniques*, 48(7):632–636, 2005.

[19] A. Rajeswari, N. Duraipandian, N. R. Shanker, and B. E. Samuel. Efficient optimization algorithms for minimizing delay and packet loss in doppler and geometric spreading environment in underwater sensor networks. *Wirel Pers Commun*, 121(1):49–67, 2021.

[20] R. Diamant, R. Francescon, and M. Zorzi. Topology-efficient discovery: A topology discovery algorithm for underwater acoustic networks. *IEEE Journal of Oceanic Engineering*, 43(4):1200–1214, 2018.

[21] M. Bagaa, A. Chelli, D. Djenouri, T. Taleb, I. Balasingham, and K. Kansanen. Optimal placement of relay nodes over limited positions in wireless sensor networks. *IEEE Trans Wirel Commun*, 16(4):2205–2219, 2017.

[22] A. Ramasamy, J. R. A. Kumar, and M. S. Rajan. A secure and energy efficient sensor nodes in wireless sensor networks using improved ant lion optimization. *International Journal of Recent Technology and Engineering (IJRTE)*, 9(1):2200–2205, 2020.

[23] S. M. Shah, T. Hussain, B. Shah, F. Ali, K. Zaman, and K. S. Kwak. Ceer: Cooperative energy-efficient routing mechanism for underwater wireless sensor networks using clusters. *Computer Systems Science and Engineering*, 45(3):2587–2602, 2023.

[24] A. Khan and et al. Energy harvesting based routing protocol for underwater sensor networks. *PLoS One*, 14(7), 2019.

[25] A. Chaaf and et al. Energy-efficient relay-based void hole prevention and repair in clustered multi-auv underwater wireless sensor network. *Security and Communication Networks*, 2021:9969605, 2021.

[26] Y. Jing, Y. Xian, L. Xiaoyuan, and C. Cailian. Energy-efficient data collection over auv-assisted underwater acoustic sensor network. *IEEE Syst J*, 2018.

[27] N. Subramani, P. Mohan, Y. Alotaibi, S. Alghamdi, and O. I. Khalaf. An efficient metaheuristic-based clustering with routing protocol for underwater wireless sensor networks. *Sensors*, 22(2):415, 2022.

[28] R. S. Kumar and G. Sivaradje. Energy aware node deployment using ant lion optimization algorithm in underwater acoustic sensor network. In *Proceedings*

of the 2023 2nd International Conference on Smart Technologies and Systems for Next Generation Computing (ICSTSN), 2023.

[29] H. Liu, X. W. Zhang, and L. P. Tu. A modified particle swarm optimization using adaptive strategy. *Expert Syst Appl*, 152, 2020.

[30] H. Yan, Z. J. Shi, and J. H. Cui. Dbr: Depth-based routing for underwater sensor networks. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, volume 4982 LNCS, pages 72–86, 2008.

[31] A. Umar and et al. Deads: depth and energy aware dominating set based algorithm for cooperative routing along with sink mobility in underwater wsns. *Sensors*, 15(6):14458–14486, 2015.

[32] H. Gul, G. Ullah, M. Khan, and Y. Khan. Eerbcr: Energy-efficient regional based cooperative routing protocol for underwater sensor networks with sink mobility. *J Ambient Intell Humaniz Comput*, 14(5):6063–6075, 2023.

[33] H. Nasir and et al. Codbr: Cooperative depth based routing for underwater wireless sensor networks. In *Proceedings of the 2014 9th International Conference on Broadband and Wireless Computing, Communication and Applications (BWCCA)*, pages 52–57, 2014.

[34] U. Farooq and et al. Idbr: Iot enabled depth base routing method for underwater wireless sensor network. *J Sens*, 2021, 2021.

[35] S. Karim and et al. Gcorp: Geographic and cooperative opportunistic routing protocol for underwater sensor networks. *IEEE Access*, 9:27650–27667, 2021.

[36] K. Saeed, W. Khalil, S. Ahmed, I. Ahmad, and M. N. K. Khattak. Seecr: Secure energy efficient and cooperative routing protocol for underwater wireless sensor networks. *IEEE Access*, 8:107419–107433, 2020.

[37] K. Hao, H. Shen, Y. Liu, B. Wang, and X. Du. Integrating localization and energy-awareness. *Mobile Networks and Applications*, 23(5):1427–1435, 2018.

[38] M. Ismail, H. Qadir, F. A. Khan, S. Jan, Z. Wadud, and A. K. Bashir. A novel routing protocol for underwater wireless sensor networks based on shifted energy efficiency and priority. *Comput Commun*, 210:147–162, 2023.

[39] A. Sharma and A. Kakkar. Machine learning based optimal renewable energy allocation in sustained wireless sensor networks. *Wireless Networks*, 25(7):3953–3981, 2019.

[40] O. G. Uyan, A. Akbas, and V. C. Gungor. Machine learning approaches for underwater sensor network parameter prediction. *Ad Hoc Networks*, 144, 2023.

[41] Z. Zou, X. Lin, and J. Sun. A cluster-based adaptive routing algorithm for underwater acoustic sensor networks. In *Proceedings of the 2019 International Conference on Intelligent Computing, Automation and Systems (ICICAS)*, pages 302–310, 2019.

[42] S. A. Al-Ahmadi. Energy-aware framework for underwater mine detection system using underwater acoustic wireless sensor network. *Electronics*, 12(22):4598, 2023.

[43] S. Karim, F. K. Shaikh, K. Aurangzeb, B. S. Chowdhry, and M. Alhussein. Anchor nodes assisted cluster-based routing protocol for reliable data transfer in underwater wireless sensor networks. *IEEE Access*, 9:36730–36747, 2021.

[44] S. Pradeep, T. B. B. R. Bapu, R. Rajendran, and R. Anitha. Energy efficient region based source distributed routing algorithm for sink mobility in underwater sensor network. *Expert Syst Appl*, 233:120941, 2023.

[45] H. Gul, G. Ullah, M. Khan, and Y. Khan. Eerbcr: Energy-efficient regional based cooperative routing protocol for underwater sensor networks with sink mobility. *J Ambient Intell Humaniz Comput*, 14(5):6063–6075, 2023.

[46] K. Saeed, W. Khalil, S. Ahmed, I. Ahmad, and M. N. K. Khattak. Seecr: Secure energy efficient and cooperative routing protocol for underwater wireless sensor networks. *IEEE Access*, 8:107419–107433, 2020.

[47] V. Baranidharan, B. Moulieshwaran, V. Karthik, R. Sanjay, and V. Thangabalaji. Enhanced goodput and energy-efficient geo-opportunistic routing protocol for underwater wireless sensor networks. In *Smart Innovation, Systems and Technologies*, volume 224, pages 585–593. 2021.

[48] M. Memon, M. Salleh, M. Channa, and M. Rohani. Rmeer: Reliable multipath energy efficient routing protocol for underwater wireless sensor network.

International Journal of Electrical and Computer Engineering (IJECE), 8:4366, 2018.

[49] H. Tran-Dang and D. S. Kim. Channel-aware energy-efficient two-hop cooperative routing protocol for underwater acoustic sensor networks. *IEEE Access*, 7:63181–63194, 2019.

[50] Z. Zhou, W. Fang, J. Niu, L. Shu, and M. Mukherjee. Energy-efficient event determination in underwater wsns leveraging practical data prediction. *IEEE Trans Industr Inform*, 13(3):1238–1248, 2017.

[51] J. Qadir, A. Khan, M. Zareei, and C. Vargas-Rosales. Energy balanced localization-free cooperative noise-aware routing protocols for underwater wireless sensor networks. *Energies (Basel)*, 12(22), 2019.

[52] R. E. Mohemed, A. I. Saleh, M. Abdelrazzak, and A. S. Samra. Energy-efficient routing protocols for solving energy hole problem in wireless sensor networks. *Computer Networks*, 114:51–66, 2017.

[53] K. Latif, N. Javaid, I. Ullah, Z. Kaleem, Z. A. Malik, and L. D. Nguyen. Dieer: Delay-intolerant energy-efficient routing with sink mobility in underwater wireless sensor networks. *Sensors*, 20(12):3467, 2020.

[54] M. Sajwan, S. Bhatt, K. Arora, and S. Singh. Gaer-uwsn: Genetic algorithm-based energy-efficient routing protocols in underwater wireless sensor networks. In *Lecture Notes in Networks and Systems*, volume 572, pages 151–159. 2023.

[55] B. Ramesh, B. N. Bhandari, and S. Pothalaiah. A hybrid technique to provide effective allocation based on mac with uwsn for energy efficiency and effective communication. *Multimed Tools Appl*, 82(19):28977–28996, 2023.

[56] R. Alkanhel and et al. Dedg: Cluster-based delay and energy-aware data gathering in 3d-uwsn with optimal movement of multi-auv. *Drones*, 6(10):283, 2022.

[57] N. Kapileswar and P. Phani Kumar. Energy efficient routing in iot based uwsn using bald eagle search algorithm. *Transactions on Emerging Telecommunications Technologies*, 33(1), 2022.

[58] SpringerLink. Smart-iout 1.0: A smart aquatic monitoring network based on internet of underwater things (iout). In *SpringerLink*. Accessed: Feb.

20, 2024, [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-030-05873-9$_1$6.

[59] S. Pradeep, T. B. B. R. Bapu, R. Rajendran, and R. Anitha. Energy efficient region based source distributed routing algorithm for sink mobility in underwater sensor network. *Expert Syst Appl*, 233, 2023.

[60] K. Sathish, C. V. Ravikumar, A. Rajesh, and G. Pau. Underwater wireless sensor network performance analysis using diverse routing protocols. *Journal of Sensor and Actuator Networks*, 11(4), 2022.

[61] J. Wang, J. Shen, W. Shi, G. Qiao, S. Wu, and X. Wang. A novel energy-efficient contention-based mac protocol used for oa-uwsn. *Sensors (Switzerland)*, 19(1), 2019.

[62] N. T. Nguyen, T. T. T. Le, H. H. Nguyen, and M. Voznak. Energy-efficient clustering multi-hop routing protocol in a uwsn. *Italian National Conference on Sensors*, 21(2):1–16, 2021.

[63] I. A. Alablani and M. A. Arafah. Ee-uwsns: A joint energy-efficient mac and routing protocol for underwater sensor networks. *Journal of Marine Science and Engineering*, 10(4):488, 2022.

[64] X. Xiao, H. Huang, and W. Wang. Underwater wireless sensor networks: An energy-efficient clustering routing protocol based on data fusion and genetic algorithms. *Applied Sciences*, 11(1):312, 2020.

[65] R. Dogra, S. Rani, Kavita, J. Shafi, S. K. Kim, and M. F. Ijaz. Eseerp: Enhanced smart energy efficient routing protocol for internet of things in wireless sensor nodes. *Sensors*, 22(16):6109, 2022.

[66] H. Alsamhi and et al. Dedg: Cluster-based delay and energy-aware data gathering in 3d-uwsn with optimal movement of multi-auv. *Drones*, 6(10):283, 2022.

[67] N. Subramani, P. Mohan, Y. Alotaibi, S. Alghamdi, and O. I. Khalaf. An efficient metaheuristic-based clustering with routing protocol for underwater wireless sensor networks. *Sensors*, 22(2):415, 2022.

[68] S. Karim, F. K. Shaikh, K. Aurangzeb, B. S. Chowdhry, and M. Alhussein. Anchor nodes assisted cluster-based routing protocol for reliable data transfer in underwater wireless sensor networks. *IEEE Access*, 9:36730–36747, 2021.

[69] S. Wang and Y. Shin. Efficient routing protocol based on reinforcement learning for magnetic induction underwater sensor networks. *IEEE Access*, 7:82027–82037, 2019.

[70] J. Luo, Y. Yang, Z. Wang, Y. Chen, and M. Wu. A mobility-assisted localization algorithm for three-dimensional large-scale uwsns. *Sensors*, 20(15):4293, 2020.

[71] R. Mani, A. Rios-Navarro, J.-L. Sevillano-Ramos, and N. Liouane. Improved 3d localization algorithm for large scale wireless sensor networks. *Wireless Networks*, 2023.

[72] S. Kaveripakam and R. Chinthaginjala. Energy balanced reliable and effective clustering for underwater wireless sensor networks. *Alexandria Engineering Journal*, 77:41–62, 2023.

[73] J. Wu, X. Sun, J. Wu, and G. Han. Routing strategy of reducing energy consumption for underwater data collection. *Intelligent and Converged Networks*, 2(3):163–176, 2021.

[74] H. H. Rizvi, S. A. Khan, R. N. Enam, M. Naseem, K. Nisar, and D. B. Rawat. Adaptive energy efficient circular spinning protocol for dynamic cluster based uwsns. *IEEE Access*, 10:61937–61950, 2022.

[75] Q. Wang, J. Li, Q. Qi, P. Zhou, and D. O. Wu. An adaptive-location-based routing protocol for 3-d underwater acoustic sensor networks. *IEEE Internet Things J*, 8(8):6853–6864, 2021.

[76] T. A. Alghamdi and N. Javaid. A new joint geo-opportunistic routing scheme in duty cycled internet of underwater things. *International Journal of Web and Grid Services*, 19(1):58–78, 2023.

[77] Q. Wang, J. Li, Q. Qi, P. Zhou, and D. O. Wu. A game-theoretic routing protocol for 3-d underwater acoustic sensor networks. *IEEE Internet Things J*, 7(10):9846–9857, 2020.

[78] J. Luo, Y. Yang, Z. Wang, Y. Chen, and M. Wu. A mobility-assisted localization algorithm for three-dimensional large-scale uwsns. *Sensors*, 20(15):4293, 2020.

[79] X. Wei and et al. A co-design-based reliable low-latency and energy-efficient transmission protocol for uwsns. *Sensors*, 20(21):6370, 2020.

[80] J. Kim. Fast path planning of autonomous vehicles in 3d environments. *Applied Sciences*, 12(8):4014, 2022.

[81] L. Yan, Y. He, and Z. Huangfu. An uneven node self-deployment optimization algorithm for maximized coverage and energy balance in underwater wireless sensor networks. *Sensors*, 21(4):1368, 2021.

[82] G. Xu, N. Zhang, M. Xu, Z. Xu, Q. Zhang, and Z. Song. Outage probability and average ber of uav-assisted dual-hop fso communication with amplify-and-forward relaying. *IEEE Trans Veh Technol*, 72(7):8287–8302, 2023.

[83] W. Jiang. Graph-based deep learning for communication networks: A survey. *Comput Commun*, 185:40–54, 2021.

[84] D. Anuradha, N. Subramani, O. I. Khalaf, Y. Alotaibi, S. Alghamdi, and M. Rajagopal. Chaotic search-and-rescue-optimization-based multi-hop data transmission protocol for underwater wireless sensor networks. *Sensors*, 22(8), 2022.

[85] Z. Mohammadi. Modified relay node placement in dense 3d underwater acoustic sensor networks. In *Proceedings of the 2022 9th Iranian Joint Congress on Fuzzy and Intelligent Systems (CFIS)*, 2022.

[86] G. Liu. A q-learning-based distributed routing protocol for frequency-switchable magnetic induction-based wireless underground sensor networks. *Future Generation Computer Systems*, 139:253–266, 2023.

[87] Haseena Gul, Ghufran Ullah, Muzammil Khan, and Yosra Khan. Eerbcr: Energy-efficient regional based cooperative routing protocol for underwater sensor networks with sink mobility. *Journal of Ambient Intelligence and Humanized Computing*, 14:6063–6075, 2023.

[88] Amara Umar, Nadeem Javaid, Ashfaq Ahmad, Zahoor Ali Khan, Umar Qasim, Nabil Alrajeh, and Amir Hayat. Deads: Depth and energy aware dominating set based algorithm for cooperative routing along with sink mobility in underwater wsns. *Sensors*, 15:14458–14486, 2015.

[89] Shanmugam Pradeep, Tapas Bapu Bathey Ramesh Bapu, Radhika Rajendran, and Ramachandran Anitha. Energy efficient region based source distributed routing algorithm for sink mobility in underwater sensor network. *Expert Systems with Applications*, 233:120–141, 2023.

[90] X. Wei et al. A co-design-based reliable low-latency and energy-efficient transmission protocol for uwsns. *Sensors*, 20(21):63–70, 2020.

List of Publications

Article Published in IEEE Access Journal

1. 3D Dynamic Topology with Energy-Aware Forwarding in Underwater Acoustic Networks

Article Published in Scientific Report Journal

1. IoT-Based Framework for Optimizing Energy Efficiency and Reliability in Acoustic Sensor Networks Using Mobile Sinks.

Article published in PeerJ Computer Science Journal

1. Acoustic Sensors data transmission integrity and endurance with IoT-enabled location-aware framework