PREDICTING COURIER NODE TRAJECTORY USING CHANNEL CHARACTERIZATION TO IMPROVE NETWORK LIFETIME IN UWSNS

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Candidate of **Master of Science in Computer Science (MSCS)** at the National University of Modern Languages do hereby declare that the thesis **Predicting Courier Node Trajectory using Channel Characterization to Improve Network Lifetime in UWSNs** submitted by me in partial fulfillment of MSCS degree, is my original work, and has not been submitted or published earlier. I also solemnly declare that it shall not, in future, be submitted by me for obtaining any other degree from this or any other university or institution. I also understand that if evidence of plagiarism is found in my thesis/dissertation at any stage, even after the award of a degree, the work may be cancelled and the degree revoked.

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ABSTRACT

Title: Predicting Courier Node Trajectory using Channel Characterization to Improve Network Lifetime in UWSNs

Underwater Wireless Sensor Networks (UWSNs) are essential for numerous applications, such as oceanic monitoring and military surveillance which require effective communications. The communication range and network lifetime are the major challenges for UWSNs, particularly due to limitations of acoustic wave-based communication. These limitations include low data rates and high latency and also include vulnerability to temperature and salinity. This research investigates the usability of Electromagnetic (EM) waves in short-range communications, detailing their benefits from higher data rates to lower delays but with limited range compared to acoustics. In response to these challenges, this research develops a comprehensive approach that merges environmental data from the National Centers for Environmental Information dataset, including temperature, salinity, and depth variations recorded between 1955 and 2012. Among others, Helmholtz, Stogryn, and Ellison Models are implemented and used to study the behavior of EM wave propagation in an underwater channel. It also involves the development of a trajectory prediction approach for AUVs or courier nodes towards optimizing the communication range with the least energy consumption. Using the proposed courier node trajectory prediction technique, the network achieved a 98% improvement in Network Lifetime and an 82% increase in successful Packet Delivery. Overall, the approach led to a 50% enhancement in network efficiency, ensuring longer and sustained energy usage throughout the simulation. This research thus proved that EM waves can be used in achieving efficient underwater communication based on accurate trajectory prediction and realistic channel characterization.

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LIST OF ABBREVIATIONS

DBR	-	Depth-Based Routing
EEDBR	-	Energy-Efficient Depth-Based Routing
ODBR	-	Optimized Depth-Based Routing
AMCTD	-	Adaptive Mobility of Courier Nodes in Threshold-Optimized Depth-Based Routing
iAMCTD	-	Improved Adaptive Mobility of Courier Nodes in Threshold Optimized Depth-Based Routing
SEECR	-	Secure Energy Efficient and Cooperative Routing Protocol
AUV	-	Autonomous Underwater Vehicle
mAUV	-	Micro Autonomous Underwater Vehicle
ASV	-	Autonomous Surface Vehicle
ALP	-	AUV Location Prediction mechanism
NCEI	-	National Center for Environmental Information
UWSN	-	Underwater Wireless Sensor Network
UASN	-	Underwater Acoustic Sensor Network
EM	-	Electromagnetic Waves
BER	-	Bit Error Rate
PDR	-	Packet Delivery Ratio
GNSS	-	Global Navigation Satellite System
UARA	-	Underwater Aggregation Routing Algorithm
OFDM	-	Orthogonal Frequency Division Multiplexing
QAM	-	Quadrature Amplitude Modulation
AODV	-	Ad-hoc On-Demand Distance Vector
GARP	-	Glider-Assist Routing Protocol
ODAC	-	Onshore Data Analysis Center
VAPR	-	Vector-Based Adaptive Packet Routing
DVOR	-	Depth Vector Optimized Routing
AURP	-	Adaptive Underwater Routing Protocol
BRP-ML	-	Bottom-Up Routing Protocol Based on Machine Learning

QELAR	-	Q-Learning Energy-Aware and Lifetime-Aware Routing
QL-EDR	-	Q-Learning-Based Energy-Delay Routing
NNR	-	Nearest Neighbor Regression
SNR	-	Signal-to-Noise Ratio
EMA	-	Exponential Moving Average
AR	-	Auto-Regression
DBCAR	-	Depth-Based Channel-Aware Routing Protocol
CARP	-	Channel-Aware Routing Protocol
DSPR	-	Directional Selective Power Routing
AoA	-	Angle of Arrival
DR	-	Directional Routing
VDBR	-	Variable Power Depth-Based Routing
PDO-DC	-	Prediction-Based Delay Optimization Data Collection
SEDG	-	Sleep Scheduling Energy-Density Grouping
DGS-AUV	-	Delay-Guided Scheduling for Autonomous Underwater Vehicles
UAWCN	-	Underwater Acoustic Wireless Communication Network
2ASK	-	Amplitude Shift Keying
IBFA	-	Improved Blowfish Algorithm
LSTM	-	Long Short-Term Memory
PUCOA	-	Pelican Updated Chimp Optimization Algorithm
REEFSM	-	Reliable and Energy-Efficient Framework with Sink Mobility
EERBCR	-	Energy-Efficient Reliable Balanced Cooperative Routing
DEADS	-	Delay-Efficient Adaptive Data Scheduling
ECC	-	Elliptic Curve Cryptography
CRL	-	Certificate Revocation List
GSO	-	Glowworm Swarm Optimization
SS-GSO	-	Smart Selection Glowworm Swarm Optimization
LEACH	-	Low-Energy Adaptive Clustering Hierarchy
ACO	-	Ant Colony Optimization
MFO	-	Moth Flame Optimization
RFID	-	Radio-Frequency Identification
VHF	-	Very High Frequency
ADVf	-	Advancement Factor

RPSOR	-	Reliable Path Selection and Opportunistic Routing
RELi	-	Reliability Index
SPi	-	Shortest Path Index
E2E	-	End-to-End
M2ARP	-	Multipath Malicious Avoidance Routing Protocol
FM-PRFES	-	Foldable Matrix-based Padding Rail Fence Encryption Scheme
EENS	-	Energy Efficiency Node Selection
CSO	-	Cuckoo Search Optimization
SCADA	-	Supervisory Control and Data Acquisition
GDTP	-	Grouping-Based Dynamic Trajectory Planning
EH-UWSN	-	Energy-Harvesting Cooperative Routing Scheme for UWSNs
SNRC	-	Signal-to-Noise Ratio Combination
Co-UWSN	-	Cooperative Underwater Wireless Sensor Network
IDBR	-	IoT-enabled Depth-Based Routing
AOPP	-	Anchor-Free Optimal Path Planning
RSSI	-	Received Signal Strength Indicator
SCAN	-	Sensing, Communication, and Networking
RL	-	Reinforcement Learning
RBCMIC	-	Region-Based Courier-nodes Mobility with Incremental Cooperation
EPRR	-	Energy Path and Channel Aware Reliable Routing
Co-EPRR	-	Cooperative Energy Path and Channel Aware Reliable Routing
EPACA	-	Energy Path and Channel Aware
CoEPACA	-	Cooperative Energy Path and Channel Aware

LIST OF SYMBOLS

α	-	Attenuation constant
β	-	Phase constant
γ	-	Propagation constant
ω	-	Angular frequency
σ	-	Conductivity of seawater
ϵ	-	Permittivity of seawater
μ	-	Permeability
ϵ_r	-	Relative permittivity
ϵ_0	-	Static permittivity
ϵ_∞	-	Infinite frequency
τ	-	Relaxation time
j	-	Imaginary unit
f	-	Frequency
T	-	Temperature
S	-	Salinity
ε_r	-	Static permittivity
ε_∞	-	Permittivity at infinite frequency
ε_s	-	Complex relative permittivity
ε_0	-	Permittivity of free space

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DEDICATION

This thesis work is dedicated to my parents and my teachers throughout my education career who have not only loved me unconditionally but whose good examples have taught me to work hard for the things that I aspire to achieve.

CHAPTER 1

INTRODUCTION

1.1 Overview

This research focus on the trajectory prediction of the courier node or autonomous underwater vehicle (AUV), specifically in the domain of Underwater Wireless Sensor Networks. To optimize the communication range, it is proposed to channel characterization. The motivation of this research is the difficult challenges of the underwater environment. Thus, this research discusses and focuses on understanding the benefits of electromagnetic waves over acoustic waves, keeping in mind the fact that in underwater communication acoustic waves were more dominant due to their short-range propagation. The research investigates continued predictions already made with Acoustic Wave for AUV Trajectories, filling the gap towards justification for actual deployment of electromagnetic waves (EM) waves in communication [1].

Such UWSNs are the emergent technological constructs dedicated to the establishment of effective onsite communication and information exchange in the marine environment. Sensor nodes are placed under the water, at different levels depending on the purpose to be served, which may range from environmental monitoring to military surveillance. Each sensor node has different sensors capable of measuring physical quantities such as temperature, pressure, and wave motion. Combining their efforts as a network, they try to ensure the collection and transmission of information in real-time. Acoustic signals that can travel through water are typically used for communication in UWSNs [1].

Courier nodes and AUVs have some resemblance, as they sense and pick up data from common sensor nodes and carry it forward to a surface base station (also known as a surface buoy or sink node). The same as the other can both buffer data over long time periods with the objective of minimizing energy consumption and improving network throughput. But their functionality and design are different. Autonomous Underwater Vehicles (AUVs) are self-operating robotic vehicles that can move around and do tasks in underwater environments without real-time help from humans. AUVs are larger in size and more complex; they can perform vertical and horizontal movements. In contrast, courier nodes are small-sized and allowed with a module for controlled vertical movement. Although AUVs are more expensive, it's worth noticing some of the advanced characteristics it holds. These include ability to act as a Mobile sink and a powerful acoustic modem with a higher transmission range but it does consume more energy. Reduced visibility, changing salinity, and unpredictability make underwater environments quite different and cause challenges for proper communication to be achieved [2].

Since underwater conditions such as visibility, salinity, and the state of underwater phenomena are very complicated and unstable, communication is very difficult. Signal propagation through water is fundamentally different from terrestrial signal propagation in that water is stronger in terms of increased signal attenuation, time-spreading effect on received signals, and bit error rate. All these make it difficult to establish reliable communication links, which may affect the overall performance of the network. Problems of node deployment and maintenance arise due to the harsh and corrosive nature of underwater conditions. Problems with sea tides and other sea activity add another dimension to the difficulty of planning and operating UWSNs [3].

The routing protocols act as the navigation system to steer the sensors toward the efficient fulfillment of their data delivery task through the underwater environment; this includes factors such as the water depth and the capabilities of the sensors. These are very important in realizing reliable and energy-efficient communication in an adverse underwater environment. There are two major schemes into which routing protocols, which are fundamentally important for effective data transmission, can be categorized:

- Localization-free
- Localization-based

As localization-free (or flooding-based) schemes, nodes do not know their locations or those of their neighbors; therefore, data packets are flooded in all directions [4].

In Underwater Wireless Sensor Networks (UWSNs), the preferable approach is localization-free rather than localization-based because of the unique challenges that are posed by the underwater environment compared to terrestrial sensor networks. Therefore, determining the positions of underwater nodes accurately becomes nearly impossible with conventional satellite-based systems. The localization-based methods mostly rely on anchor nodes or surface buoys for tracking the sensor nodes underwater; this therefore means added system complexity and deployment cost besides the energy overhead due to frequent location updates and synchronization. These systems would often fail in highly dynamic underwater conditions where node movement, water currents, and environmental noise disrupt the localization process. In contrast, localization-free routing protocols do not rely on position information; hence they reduce overhead and allow for simpler network designs. This is a useful feature for energy-constrained UWSNs, where the primary concern is to minimize energy consumption to extend the lifetime of the network. Moreover, localization-free protocols can achieve even better scalability and adaptability in large or sparsely deployed networks where infrastructure deployment for localization is not an option. Such underwater environments are typically prone to node failures and dynamic topology which helps in improving the robustness of the network [4].

Table 1.1: Comparison of Localization-Based and Localization-free Protocols [5]

Feature	Localization-Based	Localization-Free
Accuracy	High (with good localization)	Moderate
Energy Usage	High due to localization overhead	Lower
Infrastructure	Requires anchor nodes	No additional infrastructure
Complexity	High	Low

In a localization-free approach, estimating the trajectory of the courier node is much beneficial as it allows attaining maximal possible number of sensor nodes for communication without relying on accurate positional information. Since the underwater environment makes it very difficult and costly to acquire accurate node position because of signal attenuation, dynamic currents, and various obstacles to accessibility, localization-free strategies become even more practical and energy-friendly alternatives. If the network can make a prediction for courier node paths based on environmental and channel parameters (e.g., depth, salinity, temperature), then it can dynamically adapt itself to ensure coverage in active or critical areas. In this way, the courier nodes can travel optimally in the regions having a high density of nodes or demand for data so that packets can be efficiently collected and delivered. It further reduces the control overhead or additional infrastructure needed for node localization and hence conserves battery energy in energy-constrained underwater nodes. A well-approximated courier trajectory also aids in maintaining network connectivity as well as balancing energy consumption by avoiding certain nodes being overused. In fact, localization-free trajectory estimation maximizes mobile node utility strengthens communication reliability and considerably improves network lifetime hence being an excellent solution for real-time monitoring exploring and surveillance applications in underwater environments [4].

This research analyzes the localization-free scheme in the trajectory prediction of courier nodes (AUVs) for exploiting maximum communication range using electromagnetic and acoustic waves. It further compares two mediums and demonstrates short-range electromagnetic wave transmission advantages over others, even though these waves are not favorable for long-range underwater propagation. The research also studies the influences of water temperature, salt concentration, and pressure (depth) on electromagnetic wave propagation in UWSNs. In a nutshell, the aim is to estimate such a trajectory of the courier node, which allows maximum possible nodes at sea to communicate by using electromagnetic waves. The prediction of trajectory becomes a major building block for realizing the maximum range from electromagnetic waves, where estimations are based on underwater conditions: salinity, temperature, depth, and pressure.

Table 1.2: Comparison of Channel Characteristics [6]

Wave Properties	Electromagnetic Waves	Acoustic Waves	Optical Waves
Propagation Speed	High	Very slow	Very High
Impact of Environment	Minimal	High	High
Achievable Data Rates	High	Very Low	Very High
Network Coverage (Range)	Short	Very Long	Very Short

Using electromagnetic waves in UWSNs is very promising and offers benefits that can turn around the way underwater communication works. While formerly acoustic waves have dominated underwater communication because of their ease-of-use approach, recent research shows the drawback of acoustic waves concerning low speed, high propagation delay, and low data rate for real-time and shallow water applications. Electromagnetic waves just as radio waves are such a promising alternative. It is admitted that, in many respects, electromagnetic waves are better than acoustic waves, having higher data rates and the ability to go across the water–air and water–earth boundaries without shadow zones. Shadow zones are areas in underwater environments where acoustic or EM signals do not propagate due to reflection, refraction, or other environmental factors (for example, thermoclines and salinity gradients), essentially communication dead zones. Shadow zones are typically considered as being problematic but understanding them can help in route planning and node placement to avoid them or compensate for them thus making the communication networks more reliable [7].

Electromagnetic (EM) waves can help with the problem of shadow zones in underwater communication. They work better because they have a more direct, line-of-sight transmission path for travelling that is not much affected by things like temperature gradients and salinity layers which usually make sound waves bend and thus lost energy. In contrast to sound signals which are greatly affected by these conditions and normally bend away from such areas, radio waves generally maintain straighter paths of movement over short distances. This feature enables them to go into areas where sound waves may be stopped or bent away. In fact, the shadow zone is one striking reason why electromagnetic waves, including radio waves, are efficient in surmounting the challenges of underwater communication to attain improved velocity with less energy usage [6].

Electromagnetic waves, mostly at the radio frequency range, have very significant potential to improve Underwater Wireless Sensor Networks in various applications that are mostly over short ranges with high data rates. Shallow water environmental monitoring is one application that can benefit from real-time data availability on pollution, temperature, or salinity in the coastal zones. In underwater robotics and AUVs environments, radio-based EM communication provides a reliable means for command and control in confined environments where acoustic communication faces challenges [8].

This research considers the trajectories of courier nodes or AUVs in view of the characteristics of electromagnetic waves and the impact of environmental factors. Therefore, this research provides a basis for future technological improvements in underwater communication. It is the effort that brings different perspectives together in order to understand how the courier nodes or AUVs move and propagate electromagnetic waves under the water and study environmental factors that affect them with the main goal of maximizing communication range in challenging underwater conditions. While acoustic waves can achieve long-range communication. They also have a lot of limitations such as high latency, low data rates, and high energy consumption. On the other hand, low-latency and energy-efficient communication can be achieved by using EM waves though their range is much smaller. Therefore, this research focuses on maximizing the effective range of EM waves by efficient courier node trajectory prediction to improve overall network performance and improve network lifetime.

1.2 Motivation

This research is motivated to deal with the problems regarding underwater communication systems. Since the functionality of underwater sensor nodes is to work under various dynamically changing aquatic conditions, then their efficient data transmission and prolonged lifespan of the network becomes very important. Since the purpose of underwater sensor nodes is to operate in conditions that are dynamically changing and aquatic, then their efficient data delivery and prolonged network lifespan become very important. However, previous techniques while they made valuable contributions had specific challenges that resulted in excessive energy consumption or unreliable packet delivery or even high delay which challenged them to achieve optimal routing and energy efficiency. To predict future courier node trends from advanced channel characterization equipping such an idea with optimal routing decisions that reduces energy consumption at the same time extending overall network longevity is the main focus of this research. To develop undersea networks that can survive and stay for long periods, particularly with applications in environmental monitoring and surveillance, by providing concrete practical solutions to the specific challenges of UWSNs.

1.2.1 Architecture of UWSNs

Underwater Wireless Sensor Networks (UWSNs) architecture is designed to improve effective communication and information collection in environmentally harsh underwater conditions. Generally, it consists of a set of autonomous underwater sensors strategically located underwater within the aquatic environment for monitoring and data collection. The sensors used have underwater communication modules, power sources, and sensing capabilities. Sometimes the architecture includes a sink or surface station as a gateway between the underwater network and an onshore infrastructure. Underwater communication is mostly acoustic in nature; it uses sound signals for data transmission because the wireless reach is minimal when underwater. The architecture also involves mobile elements, AUVs or courier nodes, which can navigate through the water to collect data. The peculiarities of underwater channels which include signal attenuation, multipath propagation, and time variance make it necessary to tune routing and communication protocols. In modest terms, that is one part of UWSN architecture critical for responding to those challenges and ensuring something from strong, reliable communication toward environmental monitoring up to exploring all the mysteries beneath the waves [1].

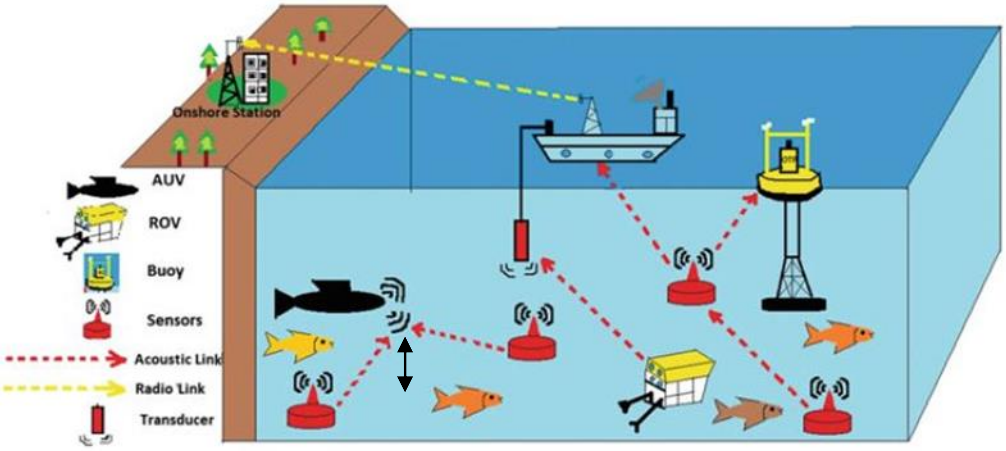

Figure 1.1: Underwater Wireless Sensor Networks [1]

The Figure 1.1 depicts the architecture of an Underwater Wireless Sensor Network (UWSN) which facilitates environmental monitoring, data collection, and underwater communication. A brief explanation of each component shown is as follows:

- ***AUV (Autonomous Underwater Vehicle):*** It is self-powered robotic vehicle that operates without any human intervention. It moves in the water collecting data by communicating with the underwater sensors.
- ***ROV (Remotely Operated Vehicle):*** ROVs are usually controlled from the surface ship. They are used for shallower tasks like inspection and repairs as well as deeper tasks related to sea exploration.
- ***Buoy:*** A float on the surface, acting as a communication relay between underwater sensors and the surface stations. It normally contains both acoustic and radio communication systems.
- ***Sensors:*** They are placed below the water surface and are used for monitoring environmental factors such as temperature, salinity, and pollution level. They communicate with AUVs, ROVs or surface stations through acoustic or electromagetic signals.
- ***Acoustic Link:*** It denotes the underwater communication methodology which utilizes sound waves for data transmission between sensors, AUVs and other underwater equipments.
- ***Radio Link:*** It denotes the wireless communication above the surface, typically from buoys or surface ship to onshore stations, used for long-range and high-speed data transfer.

- ***Transducer:*** Converts electrical signals into acoustic waves and also converts acoustic waves into electrical signals and hence enables signal transmission and reception underwater . It is essential both for underwater sensing as well as for communication.

Underwater Wireless Sensor Networks (UWSNs) constitute one of the most challenging technical infrastructures created to support uninterrupted communication and efficient data transfer in aquatic environments. Sensor nodes placed under the water are diverse in function, from environmental surveillance to tactical monitoring. Each sensor node is a carrier of various physical parameter sensors like temperature, pressure, or wave motion. As a combined result, these set the network on data acquisition and instantaneous utilization [1].

1.2.2 Applications of UWSNs

Underwater Wireless Sensor Networks (UWSNs) have various applications across different domains due to their ability to gather data in challenging underwater environments. Some of these underwater applications include [1]:

i. *Environmental Monitoring:* UWSNs are used to monitor the environment, gather data about the underwater ecosystem, and water quality, temperature, salinity, and marine life. This system is used in environmental impact assessment, ecological research, and pollution detection.

ii. *Oceanographic Research:* Modern underwater systems contribute to the collection of oceanographic data in real time regarding ocean currents and variations in temperature at different sea depths. Scientists can now better understand marine ecosystems, research climate change impacts, and keep track of geological phenomena using this information.

iii. *Underwater Surveillance and Security:* This would involve applications such as harbor protection, border control, and infrastructures all of which require

UWSNs representation of intruders, unauthorized underwater activities, and surveillance of critical underwater installations.

iv. *Underwater Archaeology:* Underwater Archaeology: UWSNs help in the exploration and documentation of underwater archaeological sites. They provide a non-intrusive way to collect data regarding submerged historical artifacts, shipwrecks, and ancient structures.

v. *Underwater Communication:* With the provision of reliable and efficient communication below sea level, this would involve applications such as autonomous underwater vehicles (AUVs) collaboration, diver communication, and exchange of data amongst submerged sensors. These networks are very important in enhancing such activities underwater.

vi. *Military and Defense Applications:* UWSNs have led to naval surveillance underwater mine detection and monitoring strategic maritime locations. Increasing the situational awareness of military forces in underwater environments.

The above applications prove that UWSNs are a very versatile tool in overcoming different challenges to improve knowledge of the underwater world in scientific, industrial, and security spheres.

1.2.3 Constraints in UWSNs

Underwater Wireless Sensor Networks have some actual constraints over the unique challenges of the underwater environment. Noteworthy constraints are as follows [7]:

i. *Limited Energy Resources:* Underwater sensor nodes work on battery power. In actual underwater systems, battery replacement or recharging is unrealistic. This gives the importance of energy efficiency and mandates developing energy-aware protocols and strategies.

ii. *Restricted Bandwidth and Data Rate:* The Acoustic channel mostly used for underwater communication suffers from less bandwidth and data rate compared to the terrestrial channel. This limitation drastically hampers the information from flowing at a faster rate; in general, it affects the whole network performance.

iii. *High Propagation Delay:* The speed of signal in water is lower than in air, which leads to higher propagation delays. This factor can restrict the real-time responsiveness for UWSN application that requires low latency in communication.

iv. *Changing Underwater Conditions:* The underwater environment is very unpredictable; water currents, temperature variations, and changes in salinity are some of the changes that characterize this environment. Stability of communication links and good localization is thus easily undermined by these dynamisms; hence the network becomes vulnerable to environmental uncertainties.

v. *Limited Connectivity:* There may sometimes be irregular or unreliable connectivity in underwater sensor networks due to some constraints such as obstacles in the water or marine life, which will limit or sometimes even eliminate the paths for communication between sensor nodes.

vi. *Underwater Channel Characteristics:* The underwater channel brings with it a number of challenges that include signal attenuation, multipath fading, and signal distortion. These reasons would compromise communication quality and impede accurate data delivery.

vii. *Node Mobility and Unpredictable Trajectories:* Some applications of UWSN involve mobile sensor nodes or vehicles with unpredictable trajectories. Tracking and predicting the movement in these applications will be a challenge for maintaining effective communication links and network connectivity.

viii. *Limited Computational Capabilities:* Underwater sensor nodes come with less processing power and memory capabilities. This then affects the level up to which algorithms can be implemented onboard and therefore the overall computational capabilities of the network.

Underwater sensor nodes come with low processing power and memory capacity. This, therefore, constrains the level to which algorithms can be implemented on board and thus the overall computational capabilities of the network.

Table 1.3: Challenges and Strategies used in UWSNs [7]

Problem	Strategy Used
Limited Energy Resources	Energy-aware routing protocols, energy harvesting techniques and efficient trajectory prediction.
Restricted Bandwidth and Data Rate	Use of electromagnetic (EM) waves for short-range efficient communication; data compression and efficient scheduling.
High Propagation Delay	Predictive routing, delay-tolerant networking and EM wave based short-range low latency communication.
Changing Underwater Conditions	Adaptive channel modeling, environment-aware protocols, and real-time sensing integration (e.g., NCEI datasets).
Limited Connectivity	Multi-hop routing, cooperative communication and mobile relay nodes (e.g., AUVs).
Underwater Channel Characteristics	Channel characterization models (e.g., Helmholtz, Stogryn, Ellison); robust modulation techniques.
Node Mobility and Unpredictable Trajectories	Trajectory prediction algorithms for courier nodes, localization-free routing and adaptive network reconfiguration.
Limited Computational Capabilities	Lightweight protocols; offloading computation to surface nodes or AUVs

1.3 Problem Background

Underwater Wireless Sensor Networks (UWSNs) face enormous challenges that greatly affect their performance and operational lifespan, especially when they are deployed for long-term monitoring applications in aquatic environments and data collection. Some major factors that worsen the conditions of underwater include limited bandwidth due to high signal attenuation, delay in signal propagation and changing channel conditions which attributes to temperature, salinity, and water current effects [7]. All these factors limit the effectiveness of underwater communications and make conservation of energy as well as surface data reception unreliable. Therefore, there is a need for autonomous courier nodes that help in transmitting data from underwater sensors to the sink node. However, unpredictable underwater currents coupled with energy constraints of battery-powered nodes makes the trajectory planning for these courier nodes a complex task [9]. Therefore, the proposed research predicts and optimizes the trajectory of the courier nodes as an effort to enhance the UWSNs lifetime. Modeling of underwater channel dynamics, which includes signal propagation, interference and fading effects forms the basis of the research toward the development of a predictive approach that could effectively predict the trajectory of the courier nodes for energy-efficient data transfer [10]. This trajectory prediction is based on real-time channel information and can boost the energy efficiency for ensuring timely and reliable delivery of data. The results of this research could greatly improve the performance and lifetime of UWSNs, making them much more reliable and useful for long-term monitoring applications.

1.4 Problem Statement

In Underwater Wireless Sensor Networks (UWSNs), acoustic waves are mostly deployed as the means of communication due to the very long network coverage range. However, the long-range acoustic waves come with some challenges like low achievable data rates and most importantly the enormous impact from the environment (noise, temperature changes, and etc.) [7]. To solve this issue, this research recommends using electromagnetic waves as the medium of transmission in UWSNs and this can be achieved by determining their optimal range that takes environmental effects into account [11]. The major aim of this research is to predict the most optimal trajectory for the Courier Nodes or AUVs to make sure that efficiency in communication is achieved, delays become minimal, and energy consumption is optimized [10]. This research uses the NCEI dataset to make predictions of optimal paths using electromagnetic wave propagation models for estimating path loss that could help to contribute to a better network lifetime in terms of efficient communication and energy savings. This research discusses electromagnetic waves as an alternative to acoustic waves in UWSN communication and involves the study of the range that can be obtained for these electromagnetic waves taking into account the environmental parameters like temperature, salinity, and depth. This allows for efficient communication where the courier node can interact with the sensor nodes within its range involving communication with maximum number of nodes and conserving maximum energy with the least possible transmission losses.

1.5 Research Questions

i. How to predict the trajectory of the courier node to maximize communication in UWSNs?
ii. How to use the channel characteristics to achieve maximum accuracy and efficiency using electromagnetic waves in UWSNs?

1.6 Aim of the Research

This research focuses on enhancing communication and prolonging network lifetime in UWSNs through prediction of optimal trajectories for courier nodes. The main idea is that by correctly predicting where courier nodes should move, they can communicate with the maximum number of sensor nodes and gather data as well as reduce energy use. This strategy is deeply connected with the analysis of underwater channel factors such as temperature, salinity, depth, and signal attenuation which have a strong influence on EM wave performance. By including this real-time environmental data, the study allows for more precise routing decisions, which will help to keep better communication links with less energy usage. The research also explores the usage of EM waves for short distance underwater communication which will give a more reliable and energy efficient alternative to acoustic waves in challenging underwater situations.

1.7 Research Objectives

i. To design and develop a comprehensive approach for predicting courier node trajectories in UWSNs, considering environmental factors and channel characteristics.

ii. To design and develop a channel characterization technique for improving network lifetime using an accurate and efficient courier trajectory with the help of electromagnetic waves.

1.8 Scope of Research Work

The scope of this research centers on improving the network performance and prolonging the network lifetime of Underwater Wireless Sensor Networks (UWSNs) through predicting the best paths of courier nodes. This study will focus on developing a model applying channel characterization techniques to optimize courier node mobility and ensure effective short-range communication by using electromagnetic (EM) waves. For this to happen, oceanographic parameters, such as seawater temperature, salinity, pressure, and depth which have a direct influence on channel characteristics namely attenuation, dielectric properties, signal scattering, and noise will be critically analyzed in this research because these factors play an important role in determining how EM waves propagate underwater [11]. By using real-time environmental data in the predictive approach, the courier nodes would be able to adjust their paths for maintaining reliable communication and also conserve maximum energy. This approach is designed to overcome the constraints of the traditional ways of underwater communication and also helps in making the network more durable and reliable in changing underwater conditions.

1.9 Thesis Organization

The rest of the thesis is organized to present a comprehensive study on the improvement of Underwater Wireless Sensor Networks (UWSNs), short-range, energy-efficient communication using electromagnetic (EM) waves. Chapter 2 contains a review of related literature that has been published in the area of Underwater Wireless Sensor Networks (UWSNs) and, in detail, research conducted to achieve efficient communication and network lifetimes. This chapter presents research that uses both acoustic and electromagnetic (EM) waves. The proposed research is based on this detailed literature review, and it helps in understanding new ways of enhancing UWSN performance. Chapter 3 presents the research with the following set of phases: Analysis Phase, Design and Development Phase, and Performance Evaluation Phase. In Chapter 4, the performance is evaluated in terms of network lifetime, energy consumption, packets received, and transmission loss at different water depths. A comparison with benchmark protocols is also presented to further validate and verify the effectiveness of the proposed methodology. The research is summarized in Chapter 5 by providing the major contributions and recommendations for future work that could further advance the field of underwater communication.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In the wide area of Underwater Wireless Sensor Networks (UWSNs), routing protocols are very important for communication and data transfer within difficult underwater settings. They are made with the aim of efficient energy use, better data reliability, and longer total lifetime of the network. Each one has a different way, giving particular features and focusing on certain goals to solve the problems of underwater communication.

2.2 Localization-free Routing Protocol

Localization-free routing protocols in Underwater Wireless Sensor Networks (UWSNs) allow the communication to take place between the submerged sensor nodes without knowing the exact physical location. While localization-based schemes work with accurate position information, in its absence, localization-free schemes become important, particularly in underwater environments where getting such information is difficult, expensive, or not feasible. Normally, localization-free protocols use proximity-based metrics or context-aware mechanisms for making forwarding decisions which in turn removes the dependency on complicated localization systems and makes UWSNs more adaptable and robust in dynamic and unpredictable underwater environments. By removing the complexity of keeping correct placement data, routing without location is a much better solution and can help the network to grow more easily, especially when nodes cannot be tracked or when resources in the network are low. Because of this, these routing protocols give a workable and trusted way for reliable communication in many underwater situations [8].

Following are the working mechanisms of several key routing protocols in Underwater Wireless Sensor Networks (UWSNs):

2.2.1 Depth-Based Routing (DBR)

This section introduces Depth-Based Routing (DBR) introduces a major advancement in switching from localization-based routing protocols to localization-free routing protocols in UWSNs. The basic idea behind DBR is to exploit sensor node mobility to enhance scalability in the underwater network. Sensor nodes' movement in the water, unlike terrestrial environments, is affected by ocean currents. DBR does intelligent work in using water pressure (depth) as a forwarding candidate selection criterion, abolishing the need to track with high precision the position of nodes that will be influenced by ocean currents, hence increasing scalability of the network [7].

In DBR, the static sink nodes are placed above the water level. In contrast, the sensor nodes are deployed at the network's bottom. To sense desired attributes, sensor nodes initiate a flooding-based data packet forwarding mechanism to the sinks. Forwarded data packets are those data packets with which the individual node attaches its depth and identity information. Holding time refers to a period for which a node that receives a data packet keeps it before forwarding it to the next node. At each node, the decision to forward the received packet is based on the depth information included: if it comes from a node of a greater depth, the packet is forwarded; otherwise, it is dropped. This further refines packet delivery ratios and lowers end-to-end delays by selecting relay nodes of shallowest depth. Although quite effective, DBR has its own challenges; it introduces redundant packets and high loads on nodes close to the sinks (low depth). This creates energy holes that deteriorate network performance in the latter phase of operation [7].

2.2.2 Energy-Efficient Depth-Based Routing (EEDBR)

The EEDBR protocol introduces a new approach by integrating both node depth and remaining energy into the process of forwarder selection, in order to balance out the fast depletion of low-depth nodes in DBR. Because of this, when a sender node has to choose who the forwarder should be, it goes for the lowest depth and highest remaining energy among its one-hop neighbors. This will disperse the consumption of energy throughout the network and, consequently, improve the creation of energy holes in DBR. But, note that EEDBR does not guarantee absolute data reliability at the final destination. Having one sender node for forwarder selection may add more chances for packet loss in case the link quality is not so good [7].

2.2.3 Optimized Depth-Based Routing (ODBR)

The Optimized Depth-Based Routing (ODBR) proposes a new approach to the initial assignment of energy where nodes are considered at different heights (depth) from the surface level of the water. Under this protocol, those nodes that are within close proximity to the water surface have much higher initial energy than those at a distance. This allocation is intended to seek an equitable consumption of energy such that eventually the overall lifetime of the network is prolonged. Yet, ODBR achieves optimal performance in areas such as shallow water regions and is likely not appropriate for scenarios with sensor nodes that are installed down on the bottom. Because the nodes at greater depths are the most energy-constrained, the effectiveness of the protocol in such areas is thereby limited [8].

Table 2.1: Comparison of Routing Protocols

Protocol	Routing Strategy	Problem Addressed	Advantages	Disadvantages
DBR [7]	Uses sensor nodes at the lowest depth, progressing from bottom to top, to transmit packets through a flooding approach	The mobility of nodes enhances scalability in underwater networks	Ensures fast data transfer and reduces the requirement for knowing exactly where the sensor nodes are located	Using up too much energy happens because extra packets are sent out and this makes the nodes at low levels run out of energy too quickly since they are often selected to send packets
EEDBR [7]	Addresses the issue of low-depth nodes in DBR by making sender nodes choose the forwarder based on how deep they are and how much energy they have left	Keeping the energy balanced and preventing nodes at shallow depths from dying	Making sure energy is shared fairly, and preventing nodes in shallow areas from running out of energy too quickly	Packets may not always be delivered reliably because when a sender node picks forwarder nodes and it sends only one copy of the data packets
ODBR [8]	Gives more energy to nodes that are close to the water's surface	Making sure energy is shared well and preventing nodes close to the water surface from running out of energy too soon	The network lasts a long time, and energy is used evenly	Doesn't function well in deep water areas because the nodes at the bottom need sufficient energy to sense characteristics
iAMCTD [2]	On-demand routing with depth-based thresholds	High energy consumption, end-to-end delay, and fast energy depletion in medium-depth nodes	Enhances network stability and throughput, reduces energy consumption, minimizes end-to-end delay and reduces unnecessary data forwarding	Complexity in weight function calculations and high overhead in sparse networks

SEECR [12]	Multi-hop routing with security and cooperative relay nodes	Security vulnerabilities, energy inefficiency, and transmission loss in UWSNs	Ensures security through defense mechanisms, reduces energy consumption, enhances network stability along with throughput and mitigates attacks	Computational overhead for defense mechanisms and relies on acoustic waves with high latency

2.3 Improved Adaptive Mobility of Courier Nodes in Threshold-Optimized Depth-Based Routing (iAMCTD)

In Javaid, et al. [2] the authors introduced a new protocol, iAMCTD, meant for filling all the observed shortcomings in the past routing approaches. Weight Functions and changes in Depth threshold are two modifications being added in this protocol towards bettering the stability period of the network. Where Weight Functions would be contributing towards load balancing by keeping a check on the count of eligible neighbors, variations in Depth threshold would regulate the eligible neighbors. This protocol enforces courier node mobility for enhanced throughput, with attention to various phases of network initialization, data forwarding, network adaptation, and control of the number of eligible neighbors. These different phases allow iAMCTD to point out what exactly is wrong with the network and, therefore, be in a position to give a full corrective remedy towards improved stability and throughput. It mainly targets the inadequacies of flooding and depth-based routing protocols since it is supposed to address the challenges at the medium depth nodes. Drawbacks of DBR and EEDBR include the problem of unnecessary forwarding of data, heavy loads on low depth nodes, and fast energy consumption of medium-depth nodes. It is a protocol that solves the issues of what type of problems relate to medium-depth nodes such as high end-to-end delay and transmission loss. The stability period is quite low with fast energy consumption.

The proposed system has several advantages. Firstly, it guarantees efficient courier node mobility in adverse underwater environments, therefore reducing end-to-end delay and conserving energy at low-depth nodes. It also implements an on-demand routing with threshold-optimized data forwarding that efficiently minimizes redundant data propagation within the network. The optimized movement of the sinks in later rounds plays an important role in preserving end-to-end delay, especially for delay-sensitive applications when sparsity conditions prevail. The protocol also helps in the detailed examination of the depth and controls overhead at both the physical and network layers. Thus, it offers a comprehensive solution to the major acoustic problems of the underwater communication environment [2].

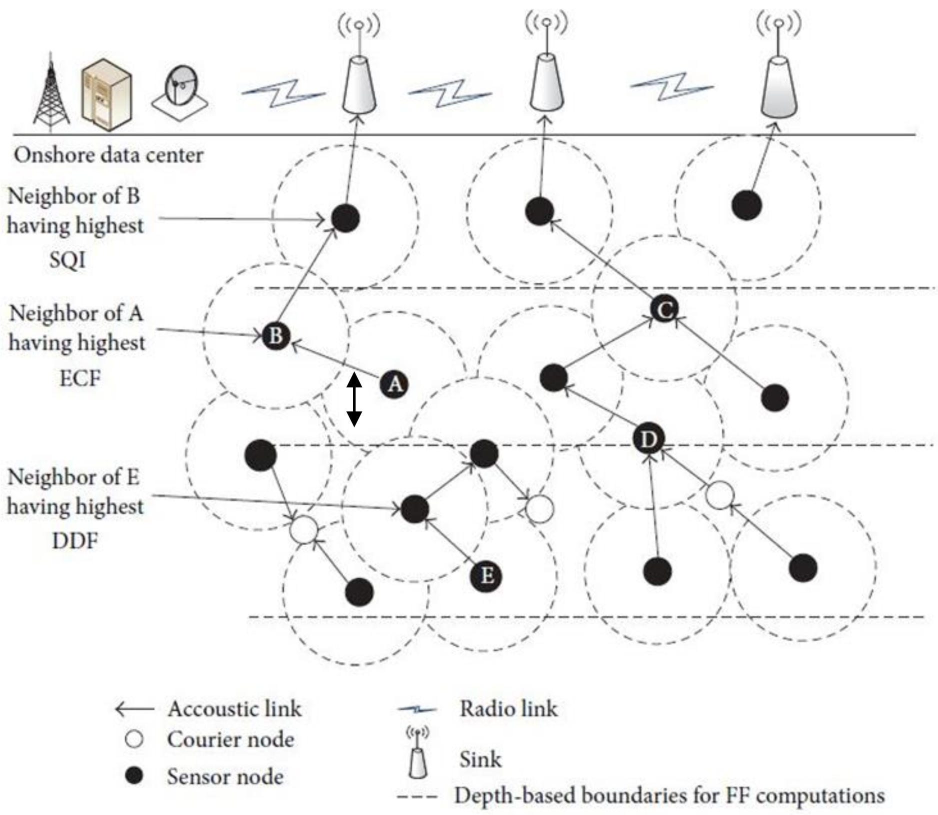

Figure 2.1: iAMCTD Architecture in UWSNs [2]

Alsalman, L. et al. [5] propose BRP-ML, Bottom-Up Routing Protocol for UWSNs based on Machine-Learning. This protocol tries to improve the performance of UWSNs by handling issues related to energy consumption, communication delay, and void regions which are caused by the failure of nodes. The protocol works in four phases: initialization, discovery, clustering, and data forwarding. Nodes are clustered using a modified K-means++ algorithm; selection of cluster heads is based on the levels of energy and closeness to the sink node. Q-learning is applied to determine energy-optimal routes to the sink with least possible latency. BRP-ML invokes Magnetic Induction technology for establishing low-latency communication that sustains above drawbacks from the usual acoustic and optical ones. For the longevity of the network, cluster heads are dynamically reselected after their energy falls below a certain set threshold, with the help of a reward function that gives a preference to routing decisions that steer away from void regions and packet loss. From the simulations, it can be noted that BRP-ML greatly outperforms previous-generation protocols such as QELAR and QL-EDR, by reducing latency by 18%, bettering energy efficiency by 16%, and at the same time prolonging network lifetime in terms of delivery rates and overall performance. Bridging clustering with reinforcement learning and BRP-ML offers a powerful, adaptive solution for UWSNs that holds great potential in real-world applications involving environmental monitoring, disaster detection, and underwater resource exploration.

In the paper by Wei, X et al. [9] various techniques are explored that can enhance reliable data collection for UWSNs (Underwater Wireless Sensor Networks), a key requirement for applications like environmental monitoring and resource management that have motivated a great deal of research. UWSNs are challenged in terms of impossibly high bit error rates, packet collisions, and routing voids in the underwater environment. The paper divided data collection into two models: hop-by-hop and Autonomous Underwater Vehicle (AUV)-aided collection. Hop-by-hop methods would be required to improve the link reliability and the routing protocols to address issues like packet loss and errors, using strategies such as redundancy, retransmission, and void-handling. AUV-aided collection incorporates mobility so that communication distances and path lengths can be shortened while achieving energy conservation, but it presents challenges like accurate navigation and path planning. The survey draws attention to the solutions that include geophysical and acoustic navigation and trajectory optimization algorithms for AUVs. In discussing the advancements, this paper emphasizes for further research requirement to lower energy consumption, guarantee fair data collection, and ensure system reliability. Such a comprehensive review would provide perspectives on what solutions exist at present and where innovation opportunities lie in UWSN evolution.

The research paper by Ali, M et al. [10] presents two routing protocols Path-Aware Reliable Routing (EPRR) and Cooperative EPRR (Co-EPRR), to enhance energy efficiency, reliability, and applicability of UASNs in real-world applications. EPRR can effectively reduce data propagation delays by choosing optimum routes considering parameters such as residual energy, shortest path, channel noise, and node depth to ensure reliable data delivery even in the presence of the challenges posed by underwater environments. Co-EPRR extends this work through cooperative routing: relay nodes also retransmit data to guarantee packet delivery in case of errors. Both protocols use physical distance metrics in place of the computationally expensive Euclidean distance for better scalability with reduced network overhead. Simulations indicate that EPRR and Co-EPRR excel the legacy counterparts such as DBR in terms of packet delivery ratio, energy consumption, and end-to-end delay. While Co-EPRR enhances reliability with retransmissions, it also slightly raises the concerns in terms of energy consumption and latency with respect to EPRR. The proposed protocols are in a position to be the preferred choice for underwater applications that operate under energy constraints and may be further improved by including energy harvesting techniques to prolong the lifetime of the network.

In the research by Isa Mohamed, H. et al. [11] the authors present a study on the electromagnetic (EM) wave propagation in seawater, with loss tangent, attenuation, and velocity as new parameters to overcome the limitations of underwater communication systems based on the acoustic and optical technologies. Although seawater has high conductivity, EM waves face high attenuation. The study classified seawater into good conductor, normal conductor, and good dielectric based on the loss tangent. MATLAB simulation results for low-frequency EM waves (less than 8 MHz) show minimal attenuation (about 62.83 dB/m), thereby making them suitable for short-range communication. At 10–100 MHz, corresponding frequencies are found to have moderate attenuation (70.24–221.6 dB/m), while very high frequencies above 50 GHz will evidently be of an extremely bulky property due to their extreme attenuation (~472.3 dB/m). The low frequencies show higher velocity: 3.21×10^3 m/s at 10 kHz, and 1.0154×10^7 m/s at 0.1 GHz. Hence, these are preferred for quick data transmission in applications such as UWSNs and AUVs, as the speed of propagation is directly proportional to the frequency. The study reveals that frequency planning is one of the prime factors for optimizing EM wave-based underwater communication systems. At low frequencies, the losses for short to intermediate distances are better than the unattainable energy losses for high frequencies. Thus, the study contributes important insights toward building more reliable underwater communication systems with the effective use of EM waves as an alternative to conventional technologies.

2.4 Secure Energy Efficient and Cooperative Routing Protocol (SEECR)

In Saeed, et al. [12] the authors presented a routing protocol for UWSNs, known as SEECR, emphasizing security, energy efficiency, and collaboration within the UWSN environment. It identified a security attack that could be launched against UWSNs and proposed a suitable defense mechanism outperforming the well-known UWSN routing protocol AMCTD. This work will improve network stability reducing transmission loss and hence minimize energy consumption, thereby making it suitable for resource-constrained underwater environments. SEECR works by relaying the multi-hop networking mechanism through cooperative relay nodes. It comprises an initialization phase, the movement pattern of the courier nodes, and a method to detect and remove attacker nodes. This defense requires computation only to the minimum, so it finds suitability for UWSNs having limited resources. The performance evaluation metrics prove that the SEECR approach outshines AMCTD. The approach of SEECR presents much greater alive node numbers, considerably cut transmission loss, better throughput, less energy consumption, and shorter end-to-end delay. The defense mechanism of SEECR reduces attacks to achieve stability and dependability for the network.

2.5 Autonomous Underwater Vehicles (AUV)

Han, G et al. [13] introduced another novel approach for optimizing data collection in UWSNs through AUVs. The AUV Location Prediction (ALP) spiral will plan a unique spiral path for the AUV to cover issues related to energy consumption and the uneven coverage of the network. It also requires time synchronization that enhances better communication between the nodes and AUV based on certain assumptions of the random distribution of nodes and acoustic communication. In comparison with other routing protocols, ALP surpasses them in terms of network lifetime, energy efficiency, and packet delivery ratio, though it results in somewhat higher average delay. It also throws a study into the ‘hot region’ issue whereby the trajectories of the AUV lead quickly to the depletion of the energy of nodes near it. A trajectory adjustment based on a mathematical model is thus called for. This mechanism helps periodically fine-tune the trade-off for improved energy utilization. The simulation results proved that the ALP is capable of improving the network performance to a greater extent through network lifetime extension and on the other hand can also reduce energy consumption yet maintaining a high packet delivery ratio. In summary, this study offers a unique approach to trajectory planning, energy management, and communication reliability in UWSNs, thus ensuring the effective operation of AUVs in gathering underwater data.

In Omeke, et al. [14] the authors contributed to the field of underwater data collection from a different perspective, emphasizing the critical role that can be played by autonomous underwater vehicles. Among the most critical challenges faced by AUVs is the relatively low capacity of their batteries, something that has encouraged a search for optimized paths. An advanced reinforcement learning - based algorithm for AUVs to make intelligent decisions by considering both geographical distance and energy consumption is what this paper is about. It proved the effectiveness of the algorithm in a very convincing manner, showing a good 50% improvement in energy conservation over and above the more conventional methods such as the Nearest Neighbor algorithm. In other words, this work pushes AUVs to a higher level of navigation performance, guaranteeing that they do so with efficient and thoughtful precision in their path along underwater terrain eventually yielding maximum operational durability, which is very important, and conserving critical energy resources for prolonged missions.

In Khan, et al. [15] the authors developed an in-depth perspective toward the optimization of data collection in an aquatic environment using autonomous underwater vehicles. Consequently, a novel AUV-based data-collection routing protocol for UWSNs is brought forward in this paper to offset the limitations of former data transmission mechanisms regarding two of the most critical challenges of the network, delay and energy efficiency. This goes through several steps that outline grouping sensor nodes into clusters and groups and implementing a Markov decision process for planning AUV pathing that is more reliable. Simulation results make the study adequate for verifying that the suggested protocol can be efficient and effective in improving throughput, energy efficiency, delay, and reliability. The results of this study can be applied to wider autonomous systems, especially in the optimization of trajectory plus data collection strategies by autonomous vehicles.

In another study, a paper presents the method for estimating the range of electromagnetic waves in seawater as based on the analysis of attenuation factors, including absorption and spreading losses. The paper sets out to model the relationship between temperature, salinity, and depth with the aforementioned quantity over the period 1955-2012 using global ocean data. A novel factor proposed is the introduction of the antenna polarization factor and its contribution to path loss. With an ultimate goal of predicting achievable ranges with high accuracy, the authors used a nonlinear least square approximation together with Lambert W function to solve for the nonlinearity of exponential decay. This makes it one of the models with such aspects as antenna gains, transmission power, and modulation schemes; it is highly relevant for underwater applications including communication, navigation activities by the military, and oil industry exploitation. Real-time NCEI real-time data are employed to characterize the seawater channel and evaluate performance. This study gives a detailed emphasis on the nonlinear nature of electromagnetic wave attenuation (especially in shallow waters) to be suitable for short-distance communication. Thus, the study gives a break to the complexities of underwater electromagnetic wave propagation; how it can have practical applications in practically all industries and their effect on understanding seawater as a communication medium [16].

Lilhore et al. [17] proposes a Depth-Controlled and Energy-Efficient Routing Protocol called the EEP Routing Protocol meant to address energy consumption, packet delivery, lifetime of the network, and transmission loss in problems related to UWSNs. Depth adjustments, and improved genetic algorithms make routing paths optimal for efficient multi-hop communication that guarantees consistent energy usage by replacing lower-energy nodes with higher-energy ones. Also, data fusion is incorporated in this protocol to optimize the cluster head and source node routes. Simulated with MATLAB, results indicate that EEP outperforms existing Depth-Based Routing (DBR) and Energy-Efficient Depth-Based Routing in metrics such as packet delivery ratio, energy consumption, packet drop ratio, network lifetime, and active nodes. By prioritizing energy consumption optimization and routing efficiency enhancements, the work detailed here fits into the broader goal of making the network sustainable and reliable over time. This research can help make the basis for future work on UWSN and the related problems, especially in optimizing courier node trajectories and providing a useful testbed for energy-efficient routing and trajectory prediction in underwater networks.

Another study investigates using electromagnetic waves for communication in UWSNs along with observing its behavior and applicability in the field. It mostly points to the bad factors on low connectivity, high packet loss, and thus environmental constraints with a proposal of EM communication especially in the low-frequency range as a viable alternative over acoustic and optical. To enable two key localization applications, innovative algorithms were introduced that address the challenges based on self-localization where nodes collaboratively determine their positions and navigation aid, where it helps underwater vehicles estimate their locations through node communication. The researchers performed simulations to study the feasibility of EM-based UWSNs using the Castalia simulator, which mimics real underwater conditions along with obstacles and device limitations. Simulations of point-to-point and broadcast communication are able to help explain the performance of the network in the presence of different scenarios. Applications for environmental monitoring, earthquake studies, and underwater robotics are just a few of the many possible uses of UWSNs in shallow water that are presented in this research. With the study integrating real channel measurements, advanced localization algorithms, and realistic simulations, it makes rather valuable contributions to the effort of developing centralized and distributed signal processing algorithms a milestone toward real-world EM-based UWSN implementations in different and challenging underwater scenarios [18].

A solution to address the self-localization challenges for micro autonomous underwater vehicles (mAUVs) operating in confined underwater environments. A low-cost, miniature system is developed for the mAUV domain that will perform all necessary signal processing related to self-localization. The proposed passive system operates on a one-way transmission of signals and can be easily extended for application among large numbers of mAUVs.

Therefore, its application within liquid-filled confined areas, such as in tank tests, particularly for large fleets of mAUVs, is possible. This paper discusses the drawbacks of existing approaches, including GNSS and vision-based methods, and the challenges of acoustic localization within such confined environments. It uses fixed beacons and localization based on a mobile receiver unit. This paper provides a theoretical background for spherical localization with reference to EM wave attenuation and the Extended Kalman Filtering and Particle Filtering signal processing algorithms implemented by theory declaration authors. Experimental results proved the system to be capable of determining both static and dynamic positions within restricted tank environments. While somewhat accuracy is constrained, the system still represented an improvement over prevailing methodologies and could find useful practical application for mAUVs in limited underwater spaces [19].

Su, R et al. [20] explore Autonomous Underwater Vehicles (AUVs) to enhance the operation of Underwater Sensor Networks, in this case, UWSNs in environmental surveillance and disaster management functions, among other applications. They pointed out some limitations of traditional UWSNs, especially high cost, energy consumption, and low localization accuracy. In this research, the AUVs are proposed as a dynamic anchor with stationary sensor nodes at the bottom of the sea that provide enhance localization benefits, data collection, and network lifetime. The information can be transmitted among others by optic, magnetic, and acoustic means to cater to these differential distance requirements. One great advantage of their proposed system is increased virtual anchor density that can be achieved by AUVs at such a low cost. The review also brings to light the challenges, which include the complexity of multi-modal communications, computation requirements for Time of Arrival measurements, and problems in AUV path planning. Such barriers notwithstanding, the paper proposes that indeed the incorporation of AUVs into UWSNs presents much potential for improved and effective underwater data collection. Further improvements in communication techniques, algorithm efficiency, path planning, and cooperation between several AUVs are needed to optimize and reap the benefits of this avenue.

In the paper by Zhan, A et al. [21] the challenges facing Underwater Sensor Networks (UWSNs) are discussed. A proposed solution is given for increasing their lifetime. UWSNs were perceived to be of a lot of importance in tasks related to monitoring water quality and collection of oceanographic data and pollution surveillance, composed of both sensors and vehicles. Unlike terrestrial networks, UWSNs find difficulty in maintenance because of characteristic facts about the underwater environment. A paper presents a three-dimensional hemisphere model for UWSNs and proves that by employing AUVs, Automatic Underwater Vehicles, the network lifetime can be significantly prolonged, with upper bound enhancement of 8 times in 3D UWSNs. The AUV only needs to stay within a two-hop radius of the sink. As such, this is a feasible and efficient solution. The authors propose UARA to maximize the network lifetime by deploying one AUV using the underwater aggregation routing algorithm. Simulations proved the point, finding that UARA can boost network lifetime to a very large extent for both dense and sparse underwater networks. The work places vast prominence in addressing the limited energy resources of underwater sensors, in what it claims to offer one practical approach towards maximizing efficiency and long-term service.

The following study discusses the underwater environment effects in the propagation of electromagnetic (EM) waves in seawater. This research justifies and motivates the investigation that EM waves should also be studied for short-range communication applications in UWSNs because of their possibility as a future substitute for acoustic waves. All channel characteristics for accurate channel modeling, such as attenuation, conductivity, permeability, and permittivity of seawater, are described. The two models called for use were the Helmholtz and Stogryn models for analyzing attenuation with respect to phase shift, where the Helmholtz model discusses the change of phase and attenuation of EM waves as they propagate through seawater while the Stogryn model gives these through empirical equations depending on temperature, salinity, and frequency. The results indicate that EM waves would undergo high attenuation in seawater, especially at higher frequencies, but then it can be suitable for short-range communication up to a distance in the order of meters for MHz frequency signals. The paper points out that attenuation is enhanced with increases in salinity and temperature, with the lower frequencies being better suited to underwater communication. These results are very important in terms of the trade-off on the optimization of energy consumption and the improvement of reliability on UWSNs communication and, hence, very valuable toward designing efficient communication strategies in underwater networks [22].

Another group of researchers have considered using electromagnetic waves for short-range and high-speed communication in UWSNs, focusing on the Ellison model to understand wave propagation at gigahertz (GHz) frequencies. Whereas acoustic waves have dominated long-range underwater communication and are now used more for short-range communication, they typically suffer from low data rates and high latency. This study uses the Ellison model for a different application in assessing the dielectric properties of seawater by taking into account the effect of temperature, salinity, and pressure. The model will help extract two key parameters which include attenuation constant and the phase constant that are important in understanding the interaction of EM waves with seawater and in finding a way for effectiveness communication. The results obtained show that attenuation increases with frequency; therefore, the gigahertz frequencies can only be used in short-distance communications despite their high rates of data transmission. Results from this study shows the effect of environmental parameters, namely temperature and salinity, on attenuation and phase constants which underpins that these parameters should be taken into due consideration while modeling UWSN communication channels [23].

Wang, J et al. [24] studied the feasibility of using electromagnetic (EM) waves for short-range underwater communication to address bandwidth and speed limitations of traditional acoustic wave systems. This work proposes OFDM over subcarrier allocation as a solution to address and improve the speed of communication in the underwater environment. It also discusses the modeling of seawater channels, with emphasis placed on challenges due to high attenuation, phase shifts, and frequency-dependent signal loss. An underwater channel is modeled using OFDM to keep these losses minimal. It is based on high attenuation, both phase shifts, and frequency-dependent losses due to highly conductive and dielectric properties of seawater. Simulation results proved that the subcarriers at lower frequencies undergo lower levels of attenuation due to which higher-order modulation can be allowed as compared to the subcarriers at higher frequencies which require lower-order modulation so as to keep the signal integrity. Improved allocation of optimized subcarriers enhances the dependability of the system and brings BER down by 3.2 dB as compared to the 16QAM standard. The proposed method increases the reliability and speed of underwater communication channels; this positions EM waves as an excellent substitute for the deployment of underwater sensor networks and information channels in real-time data transmission.

Another study describes a static multi-hop underwater wireless sensor network operating based on electromagnetic (EM) waves for a specifically shallow coastal environment with high sediment and aeration. The promising characteristic of EM waves over the conventional acoustic and optical communication in turbid or murky waters includes higher bandwidth, turbulence tolerance, and efficient air-to-water signal transmission. The network comprises 30 static sensor nodes and four intermediate routers using the AODV routing protocol. Sensor node energy consumption was achieved by scheduling sleep-wake periods and keeping it to a range of 40 meters at 100 bps. Simulations were conducted for grid topology variations, different node failures, and congestion scenarios to analyze network performance. Results showed that a squared grid arrangement performed better than other structures in terms of delay reduction and congestion prevention. The AODV Protocol did reroute traffic due to failed nodes and, therefore, maintained highly dependable performance by the network. The system also effectively provided for burst traffic, maintaining very low data loss and having a threshold throughput of 40KB. On the whole, therefore, it can be said that this study proved the possibility of using EM-based multi-hop UWSNs for shallow water coastal monitoring, ensuring reliable communication, energy efficiency, and failure tolerance in harsh underwater environmental conditions [25].

Frater, M et al. [26] proposed EM communications as one of the methods for swarm AUVs with comparison to the traditional acoustic techniques. The latency, interference, and reliability problems of underwater channels make the acoustic signals unsuitable. Electromagnetic signals, though restricted in range, have their own set of advantages in terms of throughput and efficiency. It explores simulation-based variations of network performance with network scale, load, and carrier frequency. Results indicated that the throughput of acoustic signals improved network scaling when the optimum node density and carefully chosen carrier frequencies were considered since EM signals offered as much as ten times more throughput than acoustic signals. This is because EM signals begin to sharply attenuate so as to reduce interference and allow much more efficient channel reuse. The researchers work brought out the benefits of employing EM communications for short-range applications, such as AUV swarms, where high throughput and low latency are much needed. Even though acoustic signals have much longer ranges, their feasibility is compromised since their throughput is low and they are prone to interference. It was also observed in the study that high carrier frequencies enhance the performance of the EM signal but reduce its range of communication. Further research and modeling work are proposed to validate these results, which will be highly valuable for improving research on underwater sensor communication in applications like environmental monitoring based on AUVs.

A group of researchers proposed another solution for the improvement of communication within Underwater Acoustic Sensor Networks through Glider-Assist Routing Protocol (GARP). Challenges of conventional UASNs have been poor connectivity with long latency and energy limitations as a consequence of slow acoustic wave propagation and sparsely distributed nodes. GARP integrates Fuzzy Logic Algorithms and Kalman filtering for routing optimization. Underwater gliders, moving along semi-determined sawtooth paths, work as mobile relay nodes to fill the connectivity gap and enhance routing efficiency. In the application, static sensor nodes use fuzzy logic to derive routing tables based on parameters such as energy, buffer space, and link quality. These tables are collected by the gliders and sent to an ODAC, where their trajectories are re-optimized. Kalman filtering would be applied in predicting vertical trajectories for better glider movement. Simulations show in performance delivery ratio, latency, and network lifetime compared to existing protocols including VAPR, DVOR, and AURP. Gliders minimize routing voids and also the number of hops that further improves reliability of data transmission and network lifetime. GARP will equally distribute energy consumption and give better performance in high traffic or high-density network conditions. This research will present a promising energy-efficient routing solution for hybrid UWA where monitoring underwater networks and environmental applications are emphasized [27].

The research paper by Diao, B. et al. [28] proposed a Channel-Aware Routing Protocol with Nearest Neighbor Regression for UWSNs to explicitly handle the unreliable acoustic channels of UWSNs due to environmental fluctuations. Other approaches do not explicitly model the periodic nature of underwater noise; instead, an NNR algorithm can be adopted that realizes superior prediction of changes in SNR through time series analysis. The algorithm is highly computationally efficient due to its use of hash tables and compression techniques. In simulations and real-world trials (KW14 and KAM11), it outperforms EMA and AR conventional approaches in prediction accuracy. Incorporating it within the Depth-Based Channel-Aware Routing Protocol (DBCAR), this work enables SNR predictions, gradient trends, node depth, and residual energy to be used for optimization in routing that was performed in the research. DBCAR attains much better network efficiency; the packet delivery ratio is 39.7% higher than that of DBR and energy consumption is reduced by 26% compared to CARP. It also lowers end-to-end delays yet the retaining reliability of the network. In their work, advanced channel prediction is combined with intelligent routing to achieve UWSNs that are far more reliable, energetically more efficient, and perform much better in general, thereby setting a good strong base for future developments in systems of underwater acoustic communications.

The same applies to the Directional Selective Power Routing (DSPR) protocol proposed by Al-Bzoor, M et al. [29] to mitigate communication challenges in the Internet of Underwater Things, more especially limited bandwidth, high delay, and energy inefficiency. Because DSPR does not employ location-based forwarding it uses an angle of arrival (AoA) acoustic signals to determine optimal forwarding directions. It takes the readings of AoA and the residual energy of neighbors, dynamically adjusting the transmission power for proper selection of energy-efficient forwarders. That approach does reduce redundant transmissions and void regions but performs well when there is mobility at the nodes. Simulations place DSPR at above 90% packet delivery, far better than Variable Power Depth-Based Routing and Fixed Directional Routing in which sparse and dynamic networks bring down delivery rates below 50%. DSPR can save energy up to 30% more than DR and achieve eight times the energy saving compared to VDBR, thereby extending the lifetime of the networking infrastructure in energy-constrained underwater networking environments. While DSPR causes a slight increase in end-to-end delay due to selective power adjustments, the trade-off is more than compensated for by improved connectivity and efficiency. Indeed, the protocol proves its resilience in mobile networks, maintaining much higher delivery ratios than a similar alternative. This work positions DSPR as an effective, energy-efficient solution for environmental monitoring, disaster prevention, and undersea exploration applications within the Internet of Underwater Things, with immediate future work aimed at further reducing delays and optimizing power control.

In another study PDO-DC algorithm was presented by the authors for the optimization of solving delay challenges in AUV-based data collection in UASN. The proposed traditional technique became problematic due to the large travel distance and slow speed of AUVs. Then, Kernel Ridge Regression was applied to predict data with which the AUVs could estimate the information of particular nodes without going to the individual nodes. The network is initially clustered by a density-based approach where AUV will communicate with only the cluster heads. By predicting data and skipping predictable clusters, the proposed algorithm reduces AUV travel time towards the optimization of the data collection process. The operation was further optimized by merging clusters having similar prediction trends and proximity. The sleep scheduling mechanism will result in energy conservation by keeping the idle nodes in their dormant state. Simulation results have confirmed that this solution outperforms existing algorithms such as SEDG and DGS-AUV in energy consumption, network lifetime, packet delivery ratio, and delay. It minimizes redundant communications, optimizes paths for AUVs, and upholds high PDRs less energy is used and delays are shorter. Such efficient trade-off in energy conservation and collection speed makes PDO-DC a very promising solution toward applications over the UAWCNs in which the interest is in delay, which improves AUV path planning and predictive data modeling in UASNs [30].

Rauf, M. et al. [31] investigate electromagnetic wave propagation in seawater including the influence of surface waves on underwater wireless communication. Because seawater is conductive, reliable electromagnetic (EM) wave communication is quite a problem. It further explores how the depth of the transmitter affects signal strength and bit error rate to find out the optimum placement for reducing interference due to surface waves. Researchers conducted experiments in a synthetic saltwater tank using 2ASK modulation along with copper electrodes employed for transmission and detection. Numerical analysis using a complementary Finite Element Method evaluated wave behavior. Results showed breaches parallel to the coast induce salinity gradients that, in turn, generate electric fields which enhance signal levels. However, at a depth of 30 cm, the surface wave has decayed and shadowing has stabilized the propagation, hence improving the BER. Attenuation due to salinity of seawater increases after 30 cm. These results point to an optimal depth range when surface wave effects need to be balanced against quality of signal. The work presented here proves the promise of employment of EM waves for short-range underwater communication, for example, diver to diver messaging and unmanned underwater vehicle operations. It places the accent on depth optimization due to increasing reliability of the channel impulse response and hence paves the way for further improvements in future studies.

The research paper by Isa Kaveripakam, S. et al. [32] presents a novel approach towards optimal path selection and secure data transmission in energy-constrained Underwater Acoustic Sensor Networks (UASNs), considering packet loss and data security within high error environments that comprise a dynamically changing topology. Such a study introduces the application of an LSTM neural network in forecasting the energy levels of nodes to enable energy-efficient path selection. A hybrid optimization algorithm, Pelican Updated Chimp Optimization Algorithm (PUCOA), has also been presented that boosts path utility through integration of the energy, distance, and link quality metric. For secure data transmission, the Improved Blowfish Algorithm (IBFA) was provided, hence ensuring strong encryption for low-end nodes that would counteract attacks such as chosen-plaintext and ciphertext attacks. Experimental results show that the proposed model, LSTM+PUCOA, achieves better performance than the existing ones in terms of accuracy, in terms of precision, and even in terms of energy efficiency; on the other hand, IBFA guarantees confidential data transmission with little to no performance overhead. In this respect, therefore, this integrated framework will not only increase the operational lifetime and dependability of the network but also reinforce information security and make it very suitable for applications in rather hostile underwater conditions. It provides a synchronized, end-to-end amalgamation of advanced predictive, optimization, and encryption methodologies for enhancing performance and security in UASNs.

In the research paper by Ali, S. et al. [33] the authors offer the Reliable and Energy-Efficient Framework with Sink Mobility (REEFSM) proposed as a solution to address energy inefficiency and data unreliability in UASNs. In other words, the mobile sink nodes will be used for reducing the energy burden on intermediary nodes while at the same time achieving enhanced reliability in data delivery to the sink. Major innovations comprise adaptive duty cycling that dynamically adjusts states of the sensor nodes between active and sleep states and zonal network structure to have balanced coverage with reduced latency. Simulation results proved that the proposed REEFSM outperforms other protocols like EERBCR and DEADS, by consuming 43% less energy and further achieving a 35% better reliability factor of data delivery to the sink. Zero dead nodes were ensured, packet drops were minimized to near zero, and very high data accuracy was maintained, making sure network lifetime was prolonged and energy utilization maximized. REEFSM will offer stable communication in underwater environments; therefore, it proves to be reliable and energy efficient. The work presented herein represents the first steps towards such an enhancement in terms of autonomous path planning and energy harvesting for improved UASN performance from machine learning.

A Lightweight Key Management Framework for Underwater Wireless Sensor Networks (UWSNs) to simultaneously improve security and effectiveness in resource-constrained underwater environments. This can implement a combination of symmetric and asymmetric encryption with ECC for secure and efficient key generation and distribution. It includes a mechanism for revoking keys, such as Certificate Revocation Lists (CRLs), and authentication techniques that ensure only authenticated parties take part, thereby assisting in fortifying the system against any attack. Being lightweight, it reduces computational and communication overhead and makes it scalable and energy-efficient. Results obtained through simulation proved that the proposed framework can outshine existing methods in terms of energy consumption, memory usage, and most importantly scalability by also enabling quicker key distribution. All this, securely and efficiently. The solution can find its good usability in critical applications such as oceanography and environmental monitoring including some military purposes. It not only sets a solid foundation for further research in UWSNs but also has critical applications in oceanography, environmental monitoring, and military operations [34].

In this research paper by Bharany, S. et al. [35], an energy-efficient clustering protocol for UWSNs is introduced using an enhanced version of the Glowworm Swarm Optimization algorithm. UWSNs pose several problems including high energy consumption, operation with limited battery life, and environmental aspects concerning signal attenuation and propagation delay. The authors propose a new version of the GSO algorithm, specifically SS-GSO, to optimize the selection of a CH based on residual energy, transmission energy, and node distance to balance the energy usage and redundancy in data transmission. The simulation results indicate that SS-GSO performs much better in terms of energy consumption, packet delivery rate, and clustering time than LEACH, ACO, and MFO under all scenarios. It also results in a longer network lifespan, which makes the proposed solution quite promising regarding enhancement of underwater data collection systems in fields such as environmental monitoring and marine exploration.

Another group of researchers explored the possibility of using electromagnetic (EM) communication in UWSNs as a suitable alternative to acoustic signals, which have continuously been hindered by immense propagation delay, multipath problem, and noise in the shallow water channel. Electromagnetic signals would travel much faster have bandwidth high and would interfere less thus giving much advantage over acoustic signals in shallow water, but attenuation is still a major challenge for EM communication, more so in high frequencies due to the high conductivity of seawater. The study shows that although high-frequency EM signals have a lot of signal loss in seawater, their usability for short-range transmission in freshwater environments is possible with low-level attenuation. The paper further gives an account of antenna dimensions where high-frequency EM signals enable much smaller antennas that would be advantageous for sensor networks. Long-distance communication could be realized with low-frequency EM signals, though this would be a very difficult task. The results are of good use in working out alternative means of communication for UWSNs and where further experimentation might be undertaken to overcome limitations relating to existing underwater communication systems [36].

The paper by Jiang, S. et al. [37] considers electromagnetic (EM) waves for fresh water communication in underwater environments. It states that as acoustic and optical communication systems experience issues of time delay and short distances, EM waves can be used since their propagation is much faster with minimized interference and better resistance to reflection and refraction. Attenuation in water is largely due to the high conductivity of water. Although, it is through this research that it has been found that fresh water, being less conductive than seawater, helps EM waves to attenuation less. A plane wave incidence is what the researchers demonstrated in their study on transmission and path losses, with losses minimized for the most suitable frequencies between 3-100 MHz for depths to about 5 meters.

The range of shortwave radio and VHF bands falls within these practical applications for underwater communication in fields like robotic systems, environmental monitoring, and RFID systems. It also implied the possibility of developing compact antennas for these frequencies; thus, EM communication can be perceived as a promising choice for UWSNs.

Rehman, Z et al. [38] proposed a novel methodology for Underwater Wireless Sensor Networks (UWSNs) using the static courier nodes along with depth-based routing that further enhances energy efficiency and prolongs network lifetime. Underwater harsh conditions make UWSNs major challenges in terms of highly energy-hungry, propagation delays, and bandwidth constrained. In this solution, the authors proposed using static courier nodes with more energy reserves that play the role of the intermediaries to decrease the load on energy-constrained sensor nodes. Divided into three regions based on depth, the courier nodes are to be located at specific depth thresholds. Consequently, sensor nodes send their data to the nearest specific depth of a courier node, which forwards to the sink only once, therefore minimizing redundancy in transmissions while balancing energy consumption. Simulations proved that this protocol results in an improvement in throughput, cuts down energy consumption, and provides more stability, as it stops sensor nodes near the sink from failing early on. The proposed approach guarantees a better lifetime for the network and improved stability compared to conventional methods like Depth-Based Routing (DBR) and Energy-Efficient DBR (EEDBR). While keeping the courier node's energy advantage in practice, it will give the efficient and sustainable solution of underwater communication, which is important for marine monitoring or underwater exploration applications.

Reliable Path Selection and Opportunistic Routing (RPSOR) protocol to challenge energy inefficiency, packet loss, and void hole formation in UWSNs. RPSOR enhances over WDFAD-DBR-based routing methods by consolidating three metrics: the Advancement Factor (ADVf), Reliability Index (RELi), and Shortest Path Index (SPi). Through these metrics, the protocol will choose optimal forwarders based on depth, energy levels, and a position close to the sink. The RPSOR protocol uses opportunistic, not greedy, approaches towards energy consumption and void hole avoidance to further enhance the packet delivery ratio. Where needed, mobile sinks are also incorporated to ease congestion at densely populated regions.

From the simulations, it is evident that RPSOR presents an improvement on PDR with a significance level of 18.45% and also cuts down energy usage by 44.30% and reduces E2E delay by 3.93%, especially in dense networks. For sparse networks the end-to-end delay proves to be challenging. Efficient and reliable, RPSOR is proposed as a solution for underwater communication with the possibility of future improvements in terms of sparse network delay and sink mobility optimization [39].

Natarajan, V et al. [40] proposed a framework for achieving secure communication in UWSNs. The framework is based on two main approaches: Multipath Malicious Avoidance Routing Protocol (M2ARP) and Foldable Matrix-based Padding Rail Fence Encryption Scheme (FM-PRFES). M2ARP achieves routing at the level of multipaths to avoid malicious nodes and thus enhances network security, ensuring reliable data transmission. It achieves lightweight encryption and, in fact, strikes the right balance between security and energy efficiency by encrypting data in a symbolic zigzag pattern. Further, it has Energy Efficiency Node Selection (EENS) of stable nodes and Cuckoo Search Optimization (CSO) of optimal cluster heads. The results obtained from the simulations are impressive: Packet delivery ratio is 94.03%, throughput is 93.61%, and energy consumption is 28.24 J, with an added advantage of reducing end-to-end delay to 18.24 ms. These improvements prove resilience of the developed SCADA system against attacks such as jamming and spoofing, balancing low energy usage. This work introduces a perspective energy-efficient approach for UWSNs to implement a secure communication channel for applications in marine monitoring, disaster management, and resource exploration. Subsequent works should concentrate on network reconfigurations and real-time threat intelligence to further enhance the potential of such systems.

A research group introduced the problem of trajectory optimization for data flow from sensors in the water environment to solve the problem of energy constraints and no data on node positions. For instance, old static path methods would be useless in marine life tracking because it involves changes in relatively unknown sensor positions. The approach can then be called planning-while-detecting to adjust the AUV path as signal sensors are detected. An algorithm came as Grouping-based Dynamic Trajectory Planning (GDTP), which further enhances the efficiency where sensors have overlapping communication areas by clustering them to allow the AUV to collect data from multiple nodes in one trajectory with reduced energy consumption. Simulations prove that GDTP can dramatically improve efficiency in data collection and energy usage, even in dense or changing networks. The study emphasizes the capacity of GDTP in revolutionizing the process of collecting underwater data and making it more flexible, efficient, and real-world applicable for environmental surveillance and marine exploration [41].

Another paper by Ahmed, S et al. [42] presents an EH Cooperative Routing Scheme, namely EH-UWSN, proposed to cope up with the limited energy resources and communication problems of UWSNs. It includes energy harvesting; hence, sensor nodes could charge themselves from the environment, which substantially increases the lifetime of the network and reduces energy consumption induced by data delivery. This approach employs cooperative communication, where relay nodes also assist in forwarding data to maximize energy resource usage while maintaining reliable communication. A method known as Signal-to-Noise Ratio Combination (SNRC) is thrown at the sink to improve data aggregation plus lower transmission loss. The simulation results revealed that EH-UWSN achieves better performance in all the evaluated metrics compared to the existing protocol, Co-UWSN, in terms of network lifetime, energy consumption, packet delivery ratio, and network stability. It proved to be promising since it consumes less energy by three times, dropping fewer packets and having the system more reliable; hence, a promising solution for sustainable underwater communication. This architecture provides a strong and energy-efficient base that can be employed in real-life applications for underwater monitoring, exploration, and surveillance.

Farooq, U et al. [43] propose a novel IoT-enabled Depth-Based Routing (IDBR) to enhance the efficiency of UWSNs in terms of eliminating the drawbacks that characterized the traditional DBR. While DBR relies only on depth information, which leads to high energy consumption and reduced network lifetime, IDBR takes advantage of the Internet of Things, where intelligent sink nodes perceive as data relays forward information to a base station, thereby using cloud services for processing and storage. Therefore, it reduces computational energy at underwater nodes thereby achieving energy efficiency. In addition to that, IDBR applies energy threshold values to make those nodes with enough energy prioritize packet forwarding, thus achieving more efficiency. Simulations prove that IDBR performs better than DBR. It accomplishes this by cutting down energy consumption to 27.7% and retaining more active nodes; hence, extending stability in the network. The increase in end-to-end delay resulting from cloud and sink interaction, though minimal, is justified by the overall improvement in energy efficiency and lifetime of the network. Hence, it can be considered to be an endurable solution for the practical realization of underwater applications, including but not limited to environmental monitoring, observing marine life, and disaster control.

A novel technique for node localization in UWSNs using AUV and an Anchor-Free Optimal Path Planning model is proposed in this paper. Increasing the efficiency of traditional path planning models is not possible due to the changing underwater environments and the irregular deployment of nodes and because of this the efficiency of the network could not be maximized. By using AOPP model, which optimizes AUV path considering most energy consumption and improved node localization accuracy. It involves the partitioning of the field into zones from which to dynamically pick energy-efficient cluster heads. Data is acquired by the AUV and assisted in node localization by measuring RSSI values. Unsettled nodes realize their positions by taking the average of three distance estimates to neighboring nodes by a tri-alteration method. Simulation results show that AOPP, under all possible scenarios, outperforms the existing traditional models such as SCAN and Spiral. It does so rather remarkably when the network is sparse or semi-dense, where it offers low localization errors and high node settlement. Simultaneously, it can plan more energy-efficient paths. From this study, AOPP can be said to improve underwater localization with less error; it stands as a practical solution for marine scientific research and environmental monitoring, and also for underwater exploration [44].

This research paper by Fu, Q et al. [45] proposed a novel trajectory optimization approach for ASVs, underwater data muling applications though Reinforcement Learning based methods. The ASVs reference is for the primary challenges related to data collection from Autonomous Underwater Vehicles (AUVs) over vast mission areas impaired by limited ranges of communication and energy constraints. The proposed "nearest-K" RL algorithm will choose the K AUVs that are the closest in their prescribed visit by ASV, hence equaling fair data transmission and minimizing travel distance. The reward function of the algorithm keeps track of better data transmission opportunities for all while minimizing the overall travel distance. This is coupled with an AUV association strategy that makes multiple ASVs work in cooperation towards an enhanced efficiency in much larger networks. It is demonstrated by simulation results that the RL-based approach surpasses traditional heuristic methods by achieving better fairness, reduced energy consumption, and shorter travel paths. More importantly, the number of ASVs deployed makes data collection much more evenly distributed and lowers latency. In this work, the promise of RL to enhance underwater data collection is shown, offering a scalable and energy-efficient solution for applications such as ocean monitoring and marine exploration.

Region-Based Courier-nodes Mobility with Incremental Cooperation over Underwater Wireless Sensor Networks (RBCMIC) A new contribution comes with a study on Region-Based Courier-nodes Mobility with Incremental Cooperation under one of the most critical issues facing UWSNs having low energy efficiency due to high energy consumption and poor link reliability: RBCMIC. It employs mobile courier nodes within predetermined vertical regions for data collection and relaying information from sensor nodes to the surface sinks. This work defines logical regions based on the depth of the network to enable the thresholding of depths and, hence, reduce the number of direct transmissions and achieve a much better load balancing in terms of energy consumption. It takes advantage of incremental cooperative routing in which relay nodes help forward data and retransmit it, thereby achieving more reliability with less energy wastage. The performance evaluation indicates that RBCMIC protocol far outruns other approaches such as DEADS and DBR with 20% better energy efficiency, 89% better end-to-end delay, and long network lifetime. These improvements make RBCMIC a promising solution for sustainable underwater monitoring and communication. Future research could focus on region formation and adaptive node selection to further optimize performance [46].

Researchers present two novel routing protocols for UWSNs in a research paper with the goal of energy efficiency and reliable communication without the necessity of node localization. The Energy Path and Channel Aware (EPACA) provides forwarding node selection based on energy metrics, including residual energy, history in handling packets, distance, and bit error rate to achieve minimum energy consumption. It guarantees energy-efficient data flow from underwater nodes to surface sinks while maintaining low latency. A cooperative routing mechanism that allows data packets to be sent over many paths improves reliability because it can counteract adverse channel effects that may lead to packet loss is introduced on top of EPACA in the Cooperative Energy Path and Channel Aware (CoEPACA). Simulation results prove that both protocols have been able to outperform existing techniques in terms of energy efficiency, packet delivery ratio, and most importantly, network lifetime. EPACA does better in terms of reducing the energy budget and latency. In turn, CoEPACA provides a lot of improvement in terms of reliable packet delivery since it works on cooperative transmission. These steps will offer sturdy solutions for underwater usage in marine monitoring and disaster prevention. These results can be further extended with the integration of mobile sinks and opportunistic routing to achieve more scalability and efficiency [47].

2.6 Summary

Research on EM Wave Communication for UWSNs bring forth some enhancement techniques for reliable data transmission and improved network performance. Concepts, like channel characterization and analysis of path loss, indicate a clearer picture of the behavior of EM waves in water enabling optimized frequency choice and minimal signal attenuation. Multi-hop communication and relay node deployment maintain energy efficiency while extending the range of communication. Meanwhile, optimization in terms of courier node trajectories has led researchers to consider predictive algorithms and mobility models that factor unpredictable changes in the underwater environment. Techniques like trajectory planning based on the metrics of energy and data density can guarantee efficient data collection. These would minimize redundant node visits and at the same time maintain a balance in energy consumption throughout the network. By integrating these adaptive strategies and cooperative mechanisms of routing, these studies have successfully enhanced network lifetime, reduced node failures and ensured sustained data flow for long-term underwater operations.

CHAPTER 3

METHODOLOGY

3.1 Overview

This research proposes to use electromagnetic waves in short-range and efficient communications with the ultimate goal of extended network lifetime. Choosing a near-optimal path to reach the maximum number of nodes and using electromagnetic waves to communicate short ranges in an energy-efficient way is expected to work excellently toward the goal of enhancing overall network lifetime. The research predicts the trajectory that courier nodes should follow to maximize range and exploit channel characteristics to the highest possible accuracy and efficiency using electromagnetic waves in UWSNs. The objectives of the research include coming up with an improved methodology in UWSNs for channel characterization that would bring about better trajectory prediction through the use of electromagnetic waves.

3.2 Operational Framework

This research adopts a structured operational framework comprising Analysis, Design and Development, and Performance Evaluation that systematically address the challenges pertaining to underwater electromagnetic (EM) wave communication and optimization of courier node trajectories for Underwater Wireless Sensor Networks (UWSNs).

3.2.1 Analysis Phase

The first phase is based on the evaluation of existing methods and limitation identification. The majority of the existing routing protocols and trajectory prediction approaches are based on acoustic communication since it is quite obvious that present routing protocols and trajectory prediction techniques are based on acoustic communication [4]. The major disadvantages of acoustic communication are higher latency, lower data rate, and also changes dependence on the environmental conditions [7]. Thus, the same drawbacks critically affect the energy consumption and network lifetime in turn. From this reason, it justifies the development toward a more energy-efficient approach that can lower energy consumption, extend the range of communication, and improve network performance. Thus, it lays down a base for optimized trajectory prediction in EM waves over acoustic communication to ensure dependence reliable and efficient operation of UWSNs.

3.2.2 Design and Development Phase

This phase is the creation phase for innovative solutions for trajectory prediction and channel characterization:

- ***Trajectory Prediction:*** An overall approach to prediction the trajectory of the courier node is presented. This approach is supported by EM wave propagation models, namely the Helmholtz, Stogryn, and Ellison models. In the Helmholtz model, a stratified ocean representation enables the examination of both the attenuation and propagation of waves. Wave absorption due to salinity, temperature, and frequency-dependent environmental factors is computed by the Stogryn model. Dielectric properties of seawater are included in the model by which a precise prediction of the behavior of waves can be made. These models provide accurate trajectory planning.

- ***Channel Characterization:*** The research makes use of the NCEI dataset, which is rich in real-time environmental data related to factors such as temperature, salinity, and depth averaged over several decades. The data is used to build up a path loss matrix at different depths and frequencies through which to quantify attenuation of EM waves. Up to 5500 m depth and in the frequency range from 2 MHz to 40 MHz. The channel characterization technique continuously adapts to changes in the underwater environment for optimal energy efficiency and reliable communication.

3.2.3 Performance Evaluation Phase

In the final phase, developed models and techniques are validated by running extensive simulations in a 3D MATLAB-based environment (100 m × 100 m × 100 m). The simulation, which involves 100 sensor nodes, 3 courier nodes, and 1 sink node, is executed for 5000 rounds. The following performance metrics are to be analyzed as the main indicators of the proposed methodology efficiency:

- ***Network Lifetime:*** Monitored by checking how many nodes died over the simulation rounds to see how long the network survived.
- ***Packets Received:*** How much data is actually successfully transmitted.
- ***Transmission Loss:*** To ensure reduced loss of data during communication.
- ***Energy Consumption:*** The evaluation includes adjustments to the trajectories of courier nodes so that energy usage is minimized.

The research encourages for short-range efficient communications over electromagnetic waves with an end goal to extend the lifetime of the network. To further increase the network lifetime the research pursues by predicting optimal communication paths for courier nodes and adopting short-range, energy-efficient communication. The proposed methodology has its foundation in predicting courier node trajectories so that communication ranges are maximized and entangled with exploiting channel characteristics toward attaining the highest possible correctness and efficiency in UWSNs. This involves giving an overall design of a proper trajectory prediction technique and coming up with a method to characterize a channel that gives the most accurate and precise results with electromagnetic wave use.

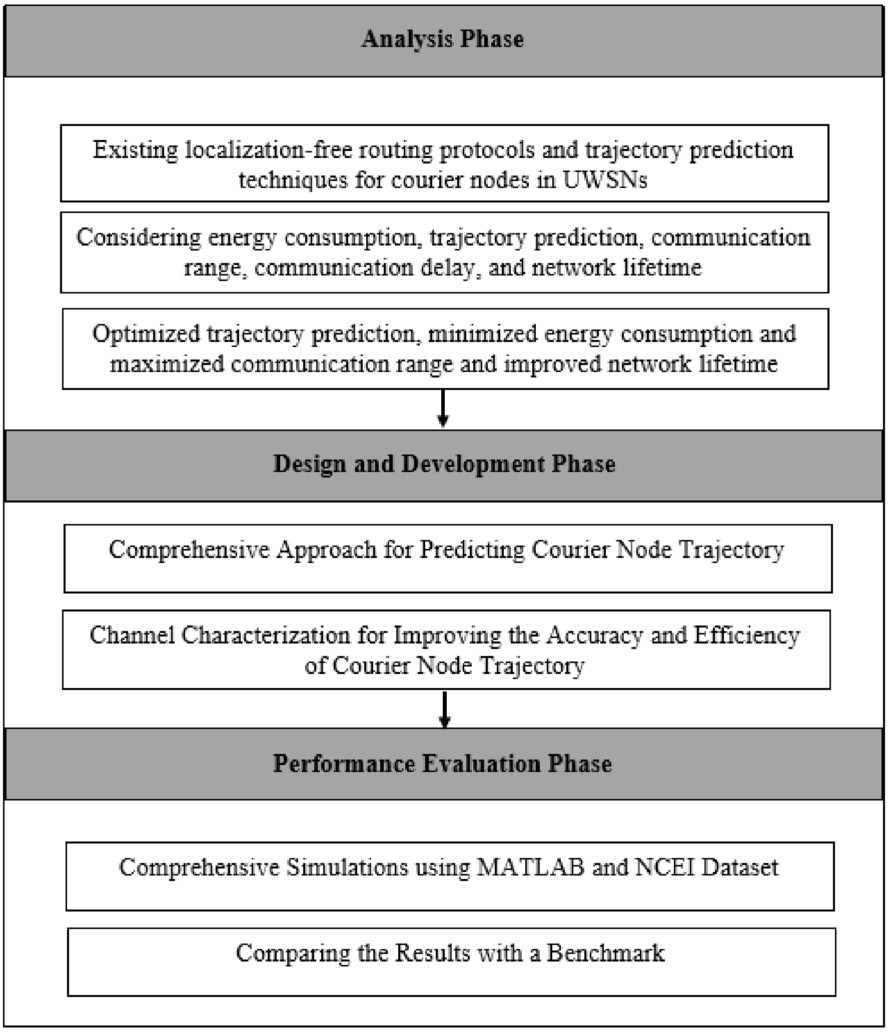

Figure 3.1: Operational Framework of the Research

3.3 Research Design and Development

Environmental monitoring, underwater archaeology, and naval defense are possible areas of application for Underwater Wireless Sensor Networks (UWSNs). Unlike terrestrial networks, UWSNs rely on acoustic communication because of long propagation distances. Acoustic communication has several challenges regarding low data rate, high latency, and vulnerability concerning environmental parameters like temperature, salinity, and noise level. Such limits to the efficiency and lifetime of UWSNs call for alternative means of communication.

Limitations of acoustic communication such as low data rates, high latency, and energy inefficiency due to slow sound propagation are also considered by UWSNs. Degradation of the signal quality because of long-distance acoustic transmission channels eventually leads to reduced lifetime for the network. The research includes in its work three key models of EM wave propagation: Helmholtz, Stogryn, and Ellison, which take into account temperature, salinity, and pressure due to real-time environmental data from the National Centers for Environmental Information (NCEI) dataset. In the final phase, a channel characterization technique is used that adjusts to changes in the environment and confines EM wave communication to short ranges so that energy consumption is minimized. Framework validation is carried out by simulations on a 3D environment with 100 sensor nodes, three courier nodes, and one sink node. Simulated performance metrics were network lifetime, packets received, transmission loss and energy usage. The results of this study will offer an improved solution for communication in UWSNs with enhanced performance and energy sustainability, acting as a basis for further research in underwater communication technologies. Figure 3.2 shows a block diagram of the proposed methodology.

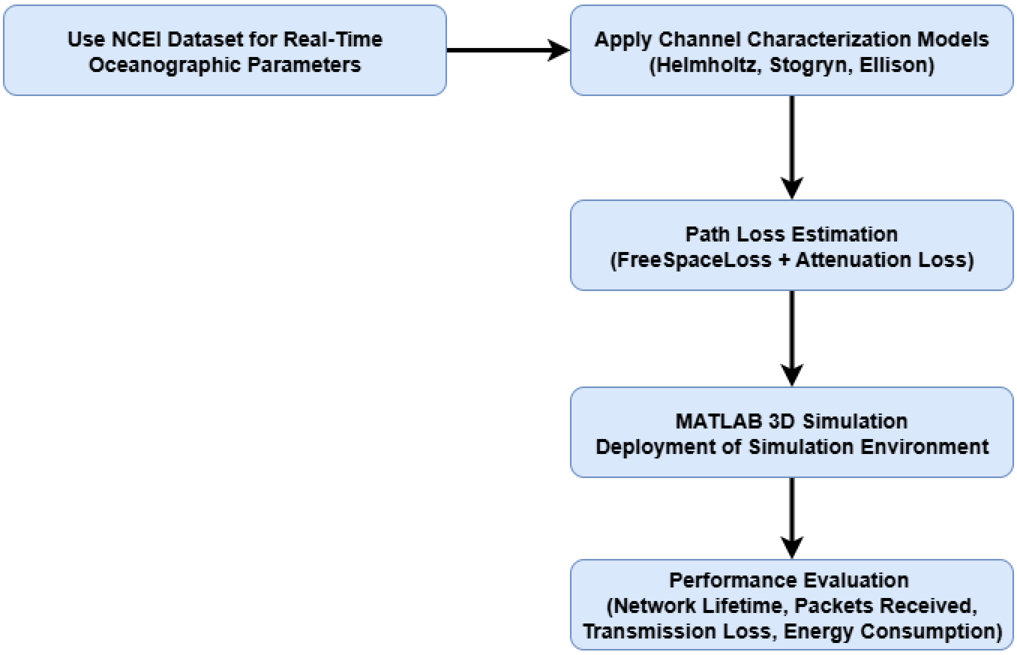

Figure 3.2: Block Diagram of the Proposed Methodology

3.3.1 Channel Characterization

Models developed by Helmholtz and Stogryn are critically important for gaining insight into the propagation of electromagnetic (EM) waves underwater. Such models are useful for determining attenuation, phase shift, and dielectric properties of seawater factors that are important in the process of short-range underwater communication system optimization. The Helmholtz model basically treats the problem of EM wave propagation within a conducting medium such as seawater. It derives expression for the attenuation constant (α) and phase constant (β) corresponding to a given complex propagation constant (γ). In general, the form of the propagation constant γ is:

$$\gamma = \alpha + j\beta = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)} \tag{3.1}$$

Here, α = attenuation constant (Np/m), β = phase constant (rad/m), j = imaginary unit, ω = angular frequency ($2\pi f$), μ = permeability of seawater, σ = conductivity of seawater and ϵ = permittivity of seawater. In this model, the EM wave will be estimated to propagate within a highly conductive medium such as seawater by determining the attenuation constant (α) and phase constant (β) that are derived from the complex propagation constant ($\gamma=\alpha+j\beta$). The model will include angular frequency (w), permeability (μ), conductivity (σ), and permittivity (ϵ) of seawater [22].

Attenuation Constant α:

$$\alpha = \sqrt{\frac{\mu\omega}{2}}\left[\sqrt{\sqrt{1+\left(\frac{\sigma}{\omega\epsilon}\right)^2} - 1}\right]^{\frac{1}{2}} \tag{3.2}$$

Phase Constant β:

$$\alpha = \sqrt{\frac{\mu\omega}{2}}\left[\sqrt{\sqrt{1+\left(\frac{\sigma}{\omega\epsilon}\right)^2} + 1}\right]^{\frac{1}{2}} \tag{3.3}$$

The Stogryn model supplements the Helmholtz model by explaining the dielectric properties of seawater. It computes the relative permittivity ($\boldsymbol{\epsilon_r}$) and conductivity (σ) as a function of such environmental factors as temperature, salinity, and frequency. In this equation, static permittivity ($\boldsymbol{\epsilon_0}$) plus that at infinite frequency ($\boldsymbol{\epsilon}_\infty$), and relaxation time ($\tau$) help realize that at higher frequencies, seawater acts as a better dielectric material [22].

$$\epsilon_{\mathrm{r}} = \epsilon_\infty + \frac{\epsilon_0 - \epsilon_\infty}{1 + j\omega\tau} \tag{3.4}$$

It can be derived from the equation of conductivity that the conductivity increases with temperature and salinity; that is, regions of higher salinity will cause greater signal attenuation.

$$\sigma = f(T, S, f) \tag{3.5}$$

In this equation, σ stands for conductivity, f denotes frequency, T is temperature, and S represents salinity.

Combining Helmholtz and Stogryn models gives a complete structure in the explanation and prediction of EM wave propagation in seawater. The Helmholtz model deals with the general problem of attenuation and phase velocity of waves due to physical parameters of the medium, while the Stogryn model places more emphasis on how environmental factors such as salinity and temperature affect the dielectric properties of the medium. These will yield accurate estimates for transmission ranges and frequencies to be adopted by EM waves to be energy-efficient in underwater propagation. Results obtained had shown that the propagation of EM waves is being greatly influenced by environmental conditions; thus, the proper frequency selection becomes very important in balancing energy efficiency and communication range. Consequently, such models can show that though reaching limited ranges, EM waves could be very well applied for short-range communication within UWSNs as an alternative to acoustic communications.

Another critical model used for the characterization of dielectric properties of seawater, the Ellison model which gives valuable information on the electromagnetic wave propagation in underwater environments. Therefore, it is important for the research that is focused on improving the performance of Underwater Wireless Sensor Networks (UWSNs) by offering a mathematical framework to understand the interaction between EM waves and seawater. The model represents seawater's complex relative permittivity, or (ε_r). This comprises real and imaginary parts that correspond to storage energy and induced losses during wave propagation, respectively. The main equation of the Ellison model is as follows:

$$\varepsilon_r(f,\ T,\ S) = \varepsilon_\infty + \frac{\varepsilon_s(T,S)-\varepsilon_\infty}{1+j\omega\tau(T,S)} \tag{3.6}$$

Here, ε_∞ would represent the permittivity at infinite frequency, basically representing the intrinsic capacity of the medium to store electrical energy at very high frequencies. ε_s (T, S), static permittivity dependent on temperature and salinity, is taken as a parameter that expresses the response function of the medium to the low-frequency electric fields. j is the imaginary unit that introduces the phase shift between the electric field and polarization. The angular frequency is what determines the rate at which the wave oscillates, given by ω=2πf. The relaxation time τ would give a measure of how fast water molecules realign themselves with respect to the electric field, and it depends on seawater conductivity, which governs the loss of energy as heat. Lastly, ε_0 is the permittivity of free space, a constant medium property related to field propagation [23].

The Ellison model is also applied to channel modeling primarily when UWSNs are to be considered since modeling the levels of attenuation and phase constants are critical. Attenuation is a measure of signal loss with distance, and the phase constant is used to measure the number of changes in the phase of a wave during propagation. This model assists in finding the Path Loss estimate, a fundamental quantity comprising both attenuation loss and free-space loss that is essential in predicting precisely how EM waves will behave in differing underwater conditions. With temperature, salinity, and frequency as components, it allows for a more realistic model of the underwater communication environment. From its practical application point of view, the Ellison model helps in optimizing the trajectories of courier nodes in UWSNs. It allows the prediction of optimal paths that will be taken by Autonomous Underwater Vehicles (AUVs) or courier nodes with the least energy consumption and maximum efficiency in communication by predicting path loss. This, therefore, guarantees that the nodes will take routes with minimal signal degradation, hence the overall performance gain of the network. It also helps to estimate the optimal frequency range for high data rates by EM waves with minimal energy loss, which agrees with the aim of improving network lifetime using short-range communication in an energy-efficient manner.

3.3.2 Trajectory Prediction

One of the key building blocks for efficient and reliable communication in UWSNs is the accurate prediction of courier node trajectories. Real-time environmental data from the National Centers for Environmental Information (NCEI) dataset will be integrated in full; this dataset includes a wealth of information on underwater conditions, such as temperature, salinity, and profiles of depth. With the help of such a dataset, changes in underwater environmental conditions are dynamically responded to by the model so that it always offers energy-efficient and, most importantly, communication-effective predictions of paths. Unlike with the models based on machine learning, which often require large volumes of training data, substantial computational resources, and considerable time for processing, this research uses an approach that is more straightforward in analysis. Such an approach removes the necessity for large-scale training but retains correctness and adaptability in predictions of trajectories. The simplicity of the calculation of path loss inspired the research approach and is determined as the sum of attenuation loss and free-space loss. Attenuation loss is the energy absorbed by the water medium due to its salinity, temperature, and frequency-dependent nature; in free space, loss tracks how EM waves naturally diverge over distance.

These calculations are used with further details from Helmholtz, Stogryn, and Ellison electromagnetic wave propagation models to explain the effect of environmental factors on the behavior of EM waves. In the Helmholtz model, the ocean is assumed to be stratified, and its influence on the propagation of the waves taken into account. Attenuation as described by Stogryn, is due to the water properties, and Ellison defines the dielectric properties of seawater regarding how electromagnetic waves will interact with the medium. Real-time environmental data are used in concert with these propagation models so that courier nodes can dynamically choose energy-minimizing routes while maintaining optimal communication quality. Such an adaptive feature is extremely important in the changing underwater channel, where phenomena such as temperature, salinity, and depth variations can greatly affect the propagation characteristics of EM waves. Besides this, the path prediction improves the efficiency of the entire network because the courier nodes become capable of anticipating and responding proactively to environmental changes. With this prediction ability, there is less need for reactive adjustments, and therefore communication paths can be made more reliable. The ensuing of the optimization does not only conserve energy but also extends the operation period of the network since sensor nodes experience less depletion in their batteries. The trajectory prediction approach unifies analytical methods, propagation models, and the NCEI dataset to achieve a solution that is innovative, adaptable, and efficient all at once for UWSNs. Considering the constraints of underwater communication and optimizing paths for courier nodes, the methodology applied presents a considerable leap forward in underwater network technology.

3.4 Simulation Framework

The simulation framework builds the success of evaluating the proposed methodology relating to the prediction of courier node trajectories and performance improvements in UWSNs. Here, the main objective is to evaluate the EM wave-based communication channel in terms of improving network lifetime, energy consumption of the solution, and data transmission efficiency. MATLAB has been selected as the major tool for simulation because of its wide capabilities in making mathematical models, manipulating matrices, and expressing the results of different data operations. MATLAB simulation for the underwater wireless sensor network, along with the channel characterization models from which the Path Loss estimate can be calculated, is very important for replicating the electromagnetic (EM) behavior in an actual underwater environment. This is fundamental to the assessment of the network operation, especially through the impact on network lifetime. Because the simulation can relate to conditions similar to that of underwater, it ensures an accurate and thorough evaluation of the network to keep communications reliable and energy usage minimized, and hence make energy-efficient communication far more long-lasting in practice.

3.4.1 Simulation Environment

The simulation framework provides a foundation for evaluating the proposed methodology in predicting courier node trajectories and enhancing the performance of

Underwater Wireless Sensor Networks (UWSNs). Green dots lying at their positions denote the static underwater sensor nodes deployed randomly within the network area for monitoring environmental parameters or data collecting purposes in aquatic environments. It consists of three mobile courier nodes shown in black, yellow, and red colors responsible to fetch the data collected by sensor nodes and transmit them towards the central sink node represented by a black star. The network area is divided into four regions, while the sink node changes its position at the start of the simulation and moves to the region with the maximum number of alive nodes. This ability of the sink node to change position optimizes data aggregation since it reduces the distance of communication and also reduces energy consumption which extends the lifetime of the network. By dynamically relocating, the sink node would thus play a very critical role in maintaining network consistency to enable efficient data collection over all regions. The sink node is the endpoint for final data aggregation where information collected by sensor nodes is merged for subsequent processing and analysis. The figure illustrates the spatial distribution of nodes, which practically emphasizes the difficulty of communicating in an underwater 3D space. The energy consumed during data transmission is also influenced by the proximity of the courier nodes to the sensor nodes and the sink.

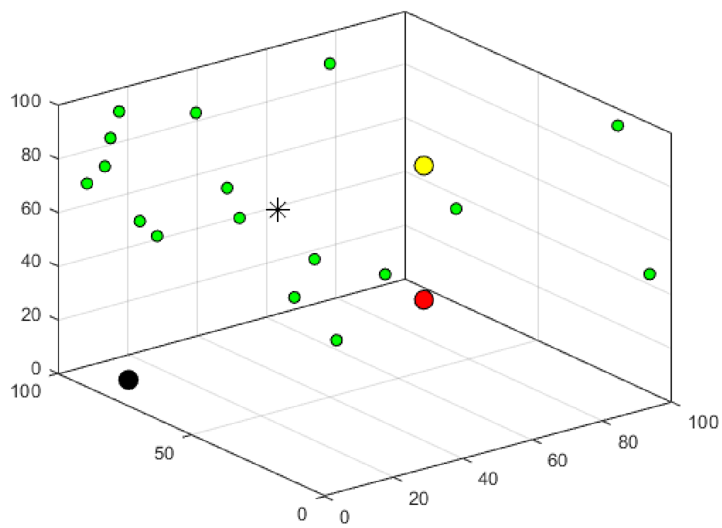

Figure 3.3: Illustration of network architecture

3.4.2 Simulation Process

This simulation environment imitates a 3D network area to be a real-time underwater communication scenario. A total of 100 sensor nodes are randomly deployed within the given area. The simulation is carried out for 5000 rounds to allow for the assessment of network performance in a variant environment. The courier nodes adjust the paths dynamically, taking into account real-time estimate of the path loss and energy availability which ensures that they follow the optimum path for data collection and transmission. By using MATLAB for ensuring visualization, the simulation is able to present real-time interaction effects between mobile and static nodes, providing some insight into how wave propagation within EM waves is influenced by conditions at the bottom of the sea.

3.4.3 Performance Metrics

Various performance metrics such as network lifetime, energy consumption, and packets received are used to evaluate the efficiency of the proposed methodology. All of these metrics give a comprehensive analysis of the benefits of using EM waves for short-range underwater communications.

i. Network Lifetime:

It is measured as the time span from the beginning of the simulation to the point of termination of 5000 rounds. It is an important parameter for Underwater Wireless Sensor Networks (UWSNs) since sensor nodes have limited energy, and replacing them underwater is a challenging task. Longer network lifetimes show that there is effective energy management through optimal communication and resource efficiency. This study presents the optimal trajectories for courier nodes, achieving minimal consumption of energy and thus extending the period of the network's operability.

$$Network\ Lifetime\ =\ Total\ number\ of\ nodes\ dead\ after\ all\ rounds$$

ii. Packet Delivery:

The number of packets received by the sink node from the courier nodes which were collected from the sensor nodes. It is a very important parameter that decides the performance and reliability of the network. This assures that most of the data reaches the sink node without any loss, and UWSNs need their data integrity preserved. Packet delivery may be affected by the factors of signal attenuation, interference, and node mobility. Improved trajectories of courier nodes due to the proposed method and proper exploitation of EM waves leads to a minimal underwater impairments and maximum packet delivery.

$$Packets\ Received\ =\ Total\ number\ of\ successful\ transmissions$$

iii. Transmission Loss:

Signal strength decreases along with the electromagnetic wave traversing in the underwater environment, which is referred to as transmission loss (TL). It has a direct impact on the efficiency and reliability of communication in UWSNs. Transmission loss depends on salinity, temperature, depth, and frequency. Especially for short distances, one has to aim to minimize transmission loss. The methodology of the proposed research achieves optimized trajectories of courier nodes together with adjustments of transmission parameters based on channel characterization models. Through correct prediction of the behavior of EM waves in underwater conditions, this methodology ensures reduced signal degradation, which brings an improvement in the performance of the network and extends operational lifetime.

$$Transmission\ Loss\ (TL)\ =\ 10\ *\ log_{10}(d)\ +\ (\alpha\ *\ d)$$

Where d = distance between transmitter and receiver, α = attenuation per meter (depends on frequency)

iv. Energy Consumption:

It measures all communication activities performed including transmission, reception, processing of data, and movement of the courier node. In UWSNs, it depends on factors such as the range of communication, transmission power, and environmental conditions, such as salinity and temperature. The methodology introduced, where short-range communication works using electromagnetic (EM) waves, will aim to cut down the energy consumption. This metric will consider how the communication protocol and trajectory prediction work in reducing unnecessary energy expenditure that consequently optimizes performance regarding the sustainability of the network.

$$E\_TX = Power * Transmission\,Time$$

$$E\_RX = Power * Reception\,Time$$

$$E\_total = E\_TX + E\_RX + EDA + E\_idle$$

Where EDA = energy for data aggregation, E_idle = idle energy consumption per round

Table 3.1: Simulation Parameters

Parameter	Value	Description
Network area	100m x 100m x 100m	3D underwater environment
Number of nodes	100	Total number of sensor nodes
Transmission range	10 – 40 m	Range for EM wave communication
EM wave frequency	2 – 40 MHz	Frequency of EM waves
Simulation rounds	5000	Total number of simulation rounds

3.4.4 Assumptions and Limitations

The simulation framework is based on particular assumptions and constraints for concentrated analysis. It is assumed that nodes have the same hardware and equal initial energy levels at their disposal. It is further assumed that environmental parameters such as temperature, salinity, and depth change gradually based on the corresponding NCEI dataset. The simulations involve short-range EM wave communication; long-range acoustic communication has not been taken into account. The simulation also does not explicitly model the effect of underwater currents and obstacles on UWSN behavior. Despite these limitations, the framework provides a rather realistic and strong environment for analyzing how effective the proposed methodology might be in influencing UWSN performance.

3.5 Summary

This research presents a comprehensive approach for improving communication in Underwater Wireless Sensor Networks using electromagnetic (EM) waves for short-range and energy-efficient communication. A three-phased, structured approach has been taken, including Analysis, Design and Development, and Performance Evaluation. In the analysis phase, the limitations of acoustic communication in terms of high latency and energy inefficiency are considered, and a motivation factor for an EM wave-based alternative is set. The Design and Development phase is comprised of a trajectory prediction approach based on the three models which include Helmholtz, Stogryn, and Ellison to study the behavior of EM waves in varying environmental conditions regarding temperature and salinity and by using the NCEI dataset for real-time environmental data. The estimated path loss using the channel models and NCEI dataset provides a real time attenuation estimation of the EM in the dynamically changing underwater environment. The methodology is implemented using a MATLAB-based 3D simulation tool for network lifetime, energy consumption, packets received, and transmission loss. The main emphasis of this research is regarding optimization of trajectory planning for courier nodes to enhance the network lifetime period while maintaining efficiency.

CHAPTER 4

PERFORMANCE EVALUATION

4.1 Overview

The performance evaluation section presents a review of the UWSN through the following major metrics: Network Lifetime, Sink Packets, Transmission Loss, and Energy Consumption with the help of the figures. Insights of different frequency conditions and courier node trajectory into the effectiveness and reliability of EM wave-based communication are provided by each metric. Network Lifetime tracks the dead node numbers versus the number of rounds of the network. Packets Received is an indicator to find out how much efficient or reliable is the communication of data from the source sensor nodes to the sink node. Energy Consumption studies how much energy efficient the proposed methodology is, Node is monitored from data transmission and reception ends, which shows the proposed methodology's energy efficiency. Finally, Transmission Loss is measured to assess signal attenuation and communication losses in varied underwater environmental conditions. All these metrics together give a complete perception of the network performance in different conditions to find out the efficiency and feasibility of the proposed approach.

4.2 Results and Analysis

This research studies the effectiveness of Underwater Wireless Sensor Networks when using electromagnetic (EM) waves in short-range communication, to improve the efficiency of the network and increase its lifetime. The study redesigns the approach by incorporating real-time environmental data and channel characterization models, plus optimized courier node trajectories specifically for underwater communication, to overcome these issues. A set of experiments are designed to assess UWSN performance in three underwater environments: shallow water (5–100 m), medium water (100–500 m), and deep water (>500 m) using a MATLAB-based 3D simulation framework. This confined model of underwater space is 100 m × 100 m × 100 m and comprises of 100 static sensor nodes, three mobile courier nodes, and one sink node. It includes three propagation models: the Helmholtz model for stratified wave propagation, the Stogryn model for attenuation loss, and the Ellison model for dielectric properties of seawater. A Path Loss matrix, which has already been calculated in advance and is based on data from the National Centers for Environmental Information (NCEI) dataset, including depths in the range 5–5500 m and frequencies 2–40 MHz, is followed by the model to predict courier node trajectories dynamically during 5000 simulation rounds. The research showed that shallow water is a perfect choice for EM wave propagation due to some factors such as low depth, low absorption, and stable environmental factors. The lowest energy consumption, least transmission loss (3.38 dB), and highest packet delivery were on record in low-depth water. Medium-depth water recorded moderate energy consumption and transmission loss. High attenuation and energy inefficiency due to the greater depths and environmental variability, particularly in deep water, presents a lot of challenges to EM wave propagation.

The results demonstrate better performance of EM waves in shallow waters, where good conductivity and low attenuation provide benefits for efficient communications. Results obtained for medium and deep water scenarios further support earlier evidence that increased depths pose more of a challenge, with deep water presenting much higher energy consumption (up to 3.8 kJ) and transmission loss (3.48 dB). The research shows the importance of using low-frequency EM waves due to being less sensitive to underwater absorption, and by keeping an optimum transmission range, which in this experiment is kept at 40 m. By optimizing courier node trajectories using the Path Loss estimate, there are visible improvements in data reliability, energy efficiency, and lifetime of the network, thereby validating the feasibility of EM wave-based communication in underwater networks.

4.2.1 Network Lifetime

The network lifetime performance shown in Figure 4.1 below is a measure of how the three experiments performed, which were conducted for diverse underwater environments concerning water depth: shallow water, medium water, and deep water. These experiments relate the number of dead nodes to the number of rounds over which the simulation is conducted, which is 5000 in this case. The experiments were conducted to study the effect of environmental conditions such as depth, salinity, and attenuation over the lifetime of UWSNs when employed for EM wave communication. In this experiment, 2–40 MHz frequency is used for performance analysis to study frequency-dependent behavior. The results showed that with the increase in the number of rounds of simulation, the number of dead nodes also increased, which noted the dependency between energy consumption, attenuation, and the environment on underwater communication systems.

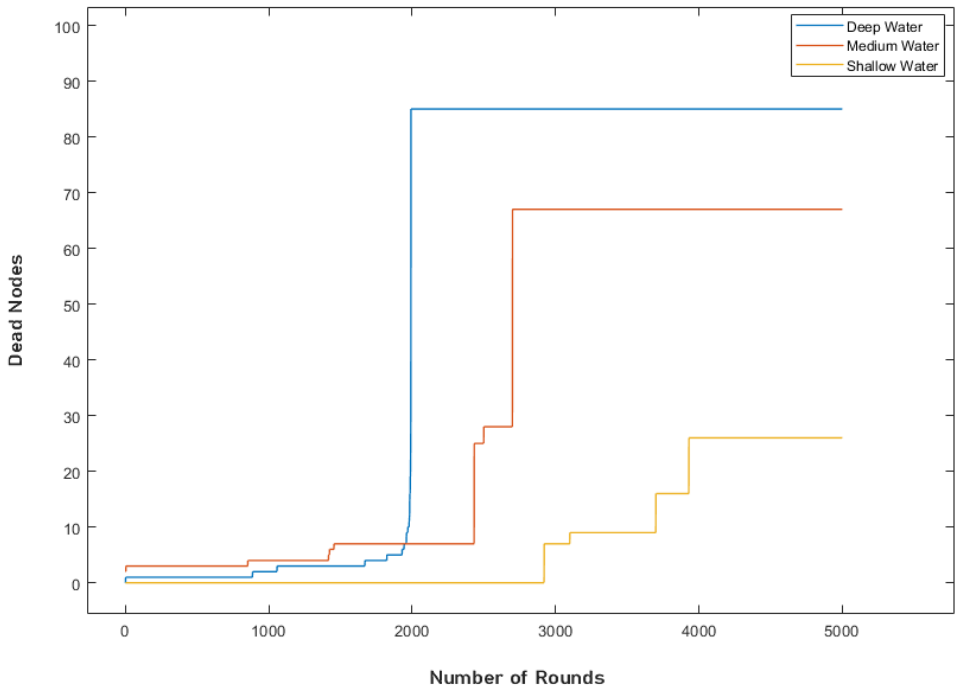

Figure 4.1: Network Lifetime using EM waves in UWSNs

The deep water experiment shows the shortest network lifetime out of the three scenarios. There is a slow increase in the number of dead nodes in the initial stages, with 2 nodes at 900 rounds, 3 nodes at 1100 rounds, 4 nodes at 1600 rounds, and 5 nodes at 1800 rounds. After about 1800 rounds, the network enters a phase of very fast increase in node mortality, with 85 nodes dead by 2000 rounds. This drastic rise is due to heavy losses in terms of attenuation and energy demands when moving into deep water. Higher salinity, pressure, and temperature gradients at greater depths result in greater resistance to EM wave propagation, leading to substantial energy depletion in the sensor nodes. The fast node failure observed after 1800 rounds shows once again the point that it is very difficult to work in this harsh underwater environment, where stability of communication cannot be maintained due to high consumption of energy and degradation of signals.

On the other hand, from the results of the medium water experiment, it shows improved results in terms of longer network lifetime. In this case, the first 4 nodes die by 900 rounds, and that remains constant until about 1500 rounds after which node deaths rise gradually, with 25 nodes dead by 2400 rounds and a maximum of 67 nodes dead by 2700 rounds. The better performance is realized in medium water due to modest environmental conditions where attenuation is much reduced and energy consumption is low compared to deep water. Although medium water offers lower resistance to the propagation of EM waves, it is more demanding in terms of energy consumption at greater depths than in shallow water.

The shallow water experiment shows the best performance and the longest network lifetime. In this case, the first node death does not occur until about 2800 rounds, much later than in the medium and deep water experiments. By round 2900, 7 nodes are dead; this increases to 9 nodes by 3100 rounds and 16 nodes by 3700 rounds. At about 4000 rounds, the maximum number of dead nodes, 26, is observed. The superior performance of shallow water is due to minimal attenuation, lower pressure, and reduced temperature gradients. In short, less resistance against the propagation of EM waves and less energy lost. All these features make the conditions favorable for the network to sustain operation for a much longer duration. This point is confirmed by the considerably delayed onset of node failures plus the lesser number of dead nodes overall throughout the simulation.

The experiments also bring out the importance of frequency and transmission range in determining network performance. Underwater, EM waves show much more effective propagation at lower frequencies than at higher ones. Lower frequencies encounter less resistance and attenuation in seawater leading to an extended lifetime of the network. Though the simulation is for frequencies in the range 2–40 MHz, from the graph it is clear and evident that with more rounds, the performance of the network started deteriorating until a rising number of dead nodes. This is practical evidence to show that lower frequencies are far better suited for underwater communication. The reason behind this statement is that the seawater at lower frequencies is more conductive. The transmission range is another effective factor in the performance of the network. Therefore, in this simulation, it is set at 40 meters to balance energy consumption with efficiency of communication. If this range is longer, it would make the nodes spend more energy in communicating and hence reduce the lifetime of the network since nodes would deplete their energy reserves much quicker. The experiments ensured effective communication without heavily draining the energy of the sensor nodes by maintaining the suitable 40-meter transmission range.

The performance differences between the three experiments can be explained based on the impact of environmental conditions, frequency, and transmission range. It is such that deep water conditions impart the heaviest attenuation and energy requirements leading to quick failures of nodes hence shorter network lifetime. Medium water is a modest environment, offering relatively lower attenuation and loss of energy compared to deep water, and therefore it allows for slow deaths of nodes and longer longevity in network applications. Shallow water presents optimistic conditions for EM wave propagation with minimal attenuation and energy consumption. Thus, network performance is extended considerably in such an environment. The fact that node failures are delayed and a smaller number of nodes die in the shallow water experiment displays the effectiveness of EM waves for short range communications.

4.2.2 Packets Received

The Figure 4.2 illustrates the number of packets received by the sink node at the end of three underwater communication experiments run in different scenarios, shallow, medium, and deep, versus simulation rounds. The following graph charts sink packets against simulation rounds for a total of 5000 rounds. It provides a graphical representation of the variance of successful packet numbers regarding environmental conditions and network performance parameters.

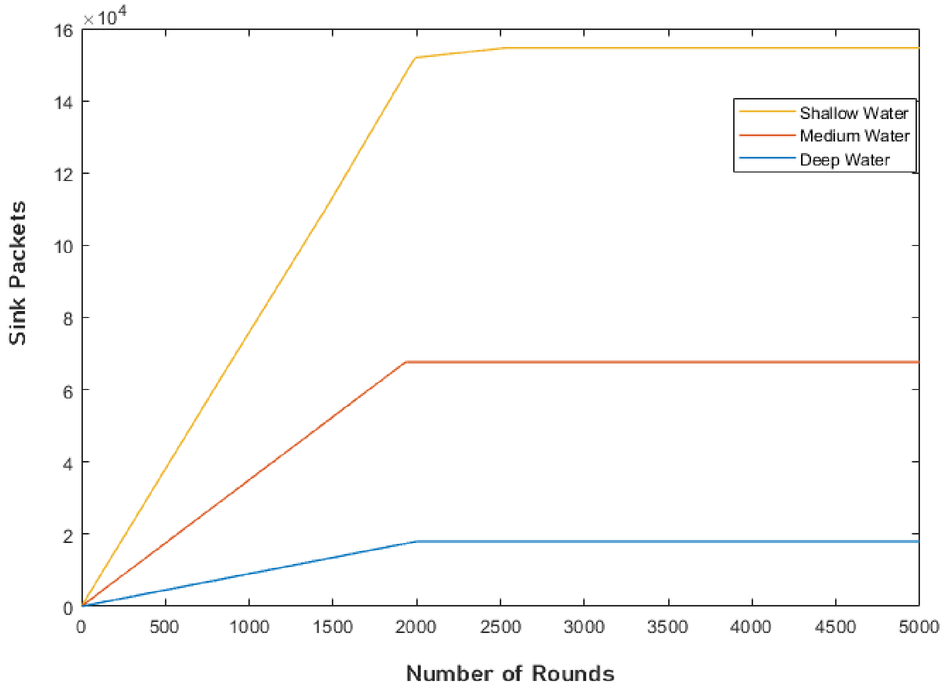

Figure 4.2: Packets Received in UWSNs

The deep water experiment shows the least number of packets received, which is approximately 18,000 at around 2000 simulation rounds. Performance of the network in deep water is hence limited by very challenging propagation conditions for electromagnetic (EM) waves at such depths. Typically, deep water environments have higher attenuation and absorption, attributed to increased salinity, pressure, and temperature gradients in them. These effects reduce the signal strength of transmission and increase energy consumption for communication. Further, because EM waves do not propagate well in deep water, energy is wasted since communication is inefficient due to inadequate connection between the sensor nodes and courier nodes.

In medium water, the number of packets received sees a marked enhancement over deep water, with about 67,000 sink packets successfully received at about 1,900 rounds. In terms of the nature of the environment, medium water conditions are more favorable for EM wave propagation due to low attenuation and absorption. Therefore, interaction between the sensor nodes and the courier nodes is good, resulting in a high packet delivery rate. The improvement is due to the relatively balanced underwater environment in medium water where conductive properties of seawater are less severe than in deep water, thus resulting in enhanced signal reliability with reduced energy expenditure. Performance in medium water therefore still does not reach the levels observed in shallow water due to signal propagation and energy consumption challenges in the moderately deep environment.

In the performance analysis, the shallow-water scenario proves to be the best, with a total of 154,000 packets received at about 2500 rounds. This is because the EM waves can propagate much more easily in shallow water as compared to other depths. Attenuation and absorption in shallow water are greatly reduced for EM waves, which makes the communication between nodes more efficient. In shallow water, the courier node's trajectory becomes more efficient since the reduced depth allows EM waves to propagate with minimal loss of signal strength. Low-frequency EM waves propagate better in shallow water because their absorption is much less than at higher frequencies. Hence, communication offers improved delivery of packets with better network life time.

The results demonstrate how efficiency in UWSNs is influenced by environmental conditions. In the deep water experiment, high attenuation and absorption of EM waves made it necessary to increase the transmission power for communication, which led to fast energy depletion and consequently less packet delivery. While medium water is less challenging than deep water, because EM waves are partially attenuated and absorbed, they still restrict communication efficiency. The favorable conditions characteristic of shallow water makes this the level with optimum communication; the energy expenditure is minimal, and the greatest number of sink packets are received. This result is due to some other equally important features, such as using a fixed transmission range of 40 meters. For deep and medium water, it might be possible to further improve the communication by expanding the transmission range, but the energy consumption will also increase and the network lifetime would be reduced. Therefore, the 40-meter range is selected. It balances reliable communication with the energy consumption rate, especially in shallow water, where short distances make good node communication interaction possible.

4.2.3 Transmission Loss

The Figure 4.3 shows a comparison of transmission loss for three underwater experiments carried out in shallow, medium, and deep water, denoted by the yellow, red, and blue curves, respectively. The x-axis denotes the simulation round number, with a maximum value of 5000, and the y-axis represents transmission loss in decibels (dB). The chart visibly demonstrates how the loss changes for diverse underwater conditions and with individual simulation rounds.

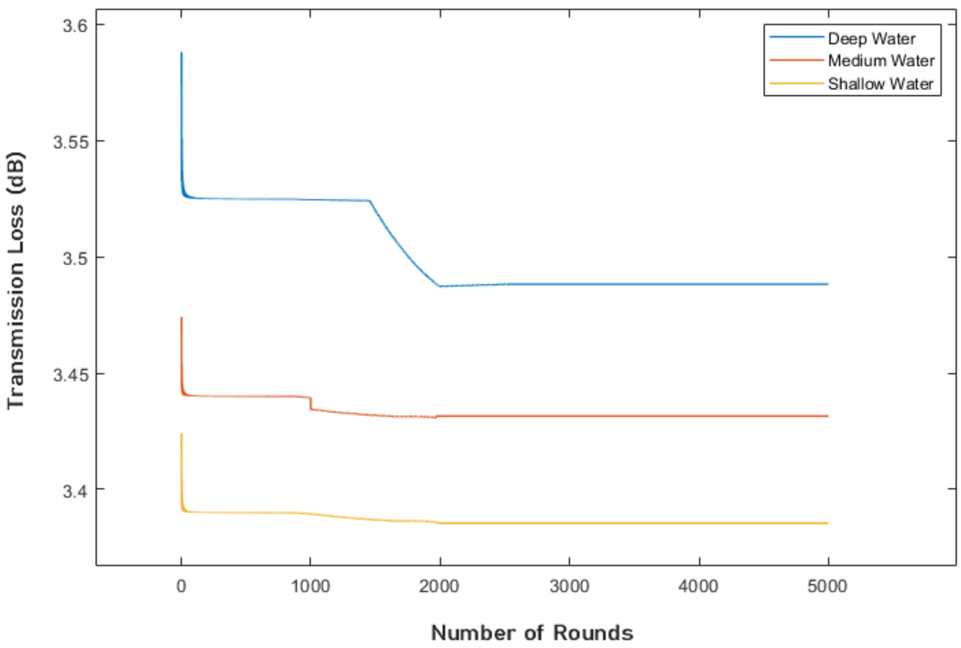

Figure 4.3: Transmission Loss of the Network in UWSNs

The deep water experiment began with the highest transmission loss of 3.58 dB. Such high loss at the initial stage demonstrates inefficiencies in the courier node's trajectory and energy utilization; thus, network performance is far from adequate. With the advancement of the simulation, the transmission loss started slowly decreasing. It took about 1500 rounds for the transmission loss to stabilize at 3.52 dB, as a result of more optimal trajectory planning for the courier node, which enhanced efficiency both in terms of energy consumption and communication. After further reductions, the transmission loss is recorded at 3.48 dB when rounds stood near 2000.

The loss of transmission at medium water occurred less drastically than deep water, beginning at a maximum of 3.47 dB. Initially, the transmission loss is relatively high, somewhat of a correspondence to similar inefficiencies in the early stages of simulation. However, it decreased steadily and for about 1000 rounds it maintained a transmission loss of 3.43 dB. Thereafter, some fluctuation set in before it went back to stabilizing at 3.43 dB from around 2000 rounds onwards. This behavior gives an indication that of the three environments, the medium water gives room for better communication efficiency with less attenuation compared to deep water, hence lower losses and improved network performance.

The shallow water experiment showed results at their best, with the lowest and most stable transmission loss compared to the other two experiments. The initial transmission loss in shallow water is 3.42 dB, and it gradually lessened over time. By about 1900 rounds, the transmission loss stabilized to 3.38 dB and remained constant for the rest of the simulation. The low, steady transmission loss of shallow water is an indication for better electromagnetic (EM) wave propagation characteristics in such an environment. The less attenuation and absorption at a reduced depth coupled with optimized courier node trajectory supported the observation of efficient communication.

Results show the key dependence on underwater environmental conditions for transmission loss in wireless sensor network. The deep water experiment showed the highest transmission loss because of challenging conditions at greater depths. Higher salinity, pressure, and temperature gradients further enhance the attenuation of EM waves, leading to more energy consumption and higher transmission loss. With further simulations and optimization of the trajectory of the courier node, the transmission loss reduced, indicating better communication efficiency. Medium water conditions, which are less challenging than deep water, prove challenging. The reduction of transmission loss in medium water compared to that of deep water can be attributed to an improved propagation of the EM wave in these conditions, although some degree of the attenuation and absorption still persisted. Shallow water is found to be the most suitable environment for underwater communication. The very low and constant transmission loss recorded in shallow water drives the point home on how efficient EM wave propagation can be in low-depth regions. Lower attenuation, alongside favorable physical properties and an optimized courier node trajectory, led to efficient communication and usage of energy. Such stability and efficiency proves shallow water depths as the best conditions for UWSNs, especially when the emphasis lies on energy efficiency and high communication reliability.

4.2.4 Energy Consumption

The Figure 4.4 shows a comparative energy consumption in joules in an underwater wireless sensor network over 5000 simulation rounds for shallow water, medium water, and deep water scenarios. It justifies how many joules are expended on a run to simulate varying dynamics for the three scenarios shallow, medium, and deep water. It reveals the relationship between performance variation of EM wave propagation characteristic and environmental condition.

The deep water experiment has the highest energy consumption of the three scenarios due to extreme attenuation and absorption of EM waves under such conditions. Attenuation is already quite high due to high salinity, pressure, and colder temperature when compared to surface water. The conductivity of the seawater in these depths enhances the absorption of the signal, forcing the nodes to use much more transmission power to send out their data. Energy consumption in deep water rises sharply to a peak value of about 3.8 kJ at 1800 rounds and then falls off rapidly as nodes deplete their energy reservoirs. This is a more noticeable pattern for the energy-intensive deep water environment, where the medium's conductivity hinders the efficient signal transmission.

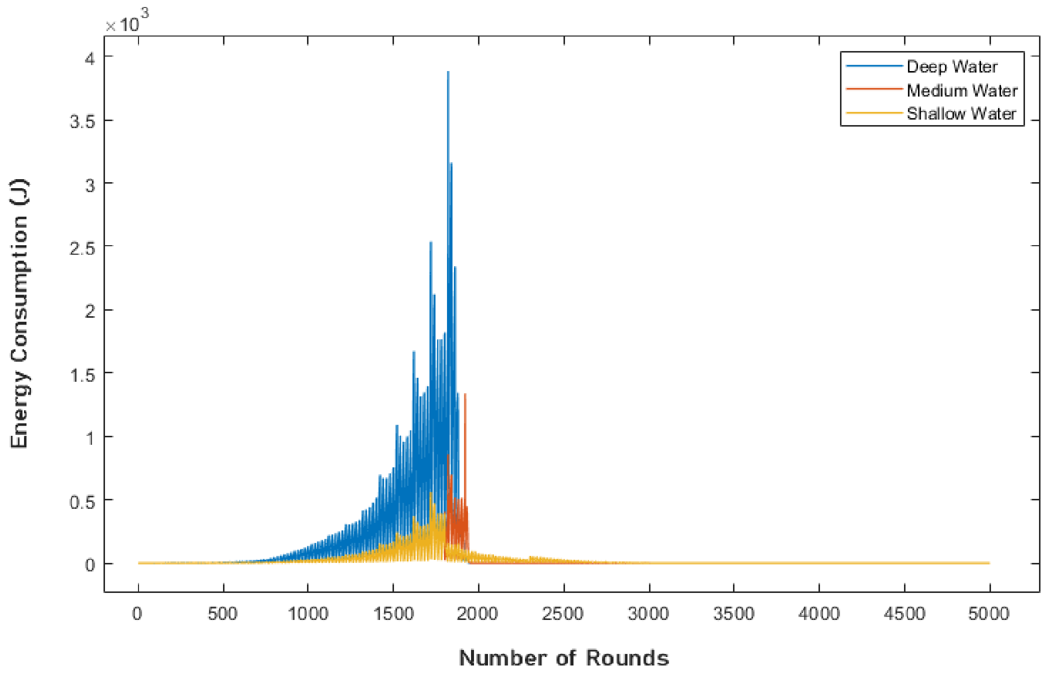

Figure 4.4: Energy Consumption of the Network in UWSNs

In Contrast, the medium water experiment depicts a moderate energy expenditure that peaks at about 1.5 kJ at around 1900 rounds. Attenuation in the medium water environment is much less than in deep water since absorption is not as drastic, offering much less resistance to the propagation of EM waves. Thus, relatively good communication efficiency can be achieved but at the cost of somewhat higher energy expenditure by the network than in shallow water due to the moderate resistance offered to signal propagation. Though the waves do continue to propagate, they require much larger transmitting power for further distances to maintain integrity for signal quality and data delivery reliability. The performance of the network in the medium water experiment falls between those of shallow water and deep water as energy usage continues to increase but not as sharply as in deep water, meaning that the network can survive extended operation compared to the harsher deep water environment.

Shallow water, on the other hand, presents the lowest energy consumption, peaking at about 0.6 kJ and observed at around 1700 rounds. Low salinity, pressure, and temperature gradients make shallow water favorable in addition to little attenuation and absorption of EM waves; therefore, nodes can communicate effectively with much lower power requirements. All this eventually translates into prolonged operation of the network since it maintains functionality for a longer duration. From the findings, shallow water is evidently the most conducive for underwater communication since it demands little energy, thus allowing for long-lasting performance and durability.

Using 40-meter transmission range is found ideal to ensure optimum communication performance while keeping energy usage minimal in all three scenarios. In deep water and medium water environments, further increasing power output to have a longer transmission range made things worse by fetching even more energy requirements. With all three scenarios having their simulation rounds scaling up energy consumption, it goes to show the real-time environmental challenges faced during the network operation as energy reservoirs are run out of energy over time. From the results above, oceanographic environmental conditions bear a lot of influence on energy efficiency in underwater networking. Medium water provides a compromise balanced midpoint energy-intensive setting; shallow water represents the optimum condition for effective and sustainable communication. Shallow water is much better because it requires extremely low energy demands that are also observed to make the network operation last longer and perform better. From the observation of the experimental results, EM waves at lower frequencies can perform much better in all three environments because such frequencies face less attenuation and have less power demands to maintain communication over the same range of transmission.

Table 4.1: Parameters and Impact on Network Performance

Parameter	Value	Impact on Performance
Frequency Range (EM Waves)	2 – 40 MHz	Using lower EM frequencies resulted in a minimum transmission loss of 3.38 dB in shallow water

Depth Range	Shallow (5–100 m), Medium (100–500 m), Deep (>500 m)	In shallow water, first node dies at 2800 rounds and 154,000 packets are received vs. only 18,000 in deep water
Depth Points	5 m to 5500 m (101 depth points)	Depth analysis enabled mapping where energy consumption peaked as in shallow water with max energy usage of 0.6 kJ
Transmission Range	10 – 40 meters	Transmission remained efficient; 3.38 dB and longest lifetime achieved in shallow water
Simulation Rounds	5000	Allowed observation until 85 nodes dead by 2000 rounds in deep; 26 dead by 4000 in shallow
Path Loss Estimation	Based on NCEI dataset (5–5500 m depth, salinity, temperature)	Enabled fine-grained prediction: transmission loss ranged from 3.38 dB to 3.48 dB across depths
Environmental Dataset Used	NCEI (1955–2012) real-time averaged ocean data	Optimized courier trajectory resulted in an improved network lifetime with 26 nodes dead in shallow water by the end of 5000 rounds

Table 4.2: Comparison of Results at Different Depths

Metric	Shallow Water (5–100 m)	Medium Water (100–500 m)	Deep Water (>500 m)
Network Lifetime	First node dies at 2800 rounds; 26 nodes dead by 4000 rounds	First 4 nodes dead by 900 rounds; 67 nodes dead by 2700 rounds	5 nodes dead by 1800 rounds; 85 nodes dead by 2000 rounds
Packets Received	154,000 packets received by 2500 rounds	67,000 packets received by 1900 rounds	18,000 packets received by 2000 rounds
Transmission Loss	Lowest and stable: 3.38 dB	Moderate and stable: 3.43 dB	Highest and reducing: 3.48 dB
Energy Consumption	Lowest: Peaks at 0.6 kJ at 1700 rounds	Moderate: Peaks at 1.5 kJ at 1900 rounds	Highest: Peaks at 3.8 kJ at 1800 rounds
EM Wave Performance	Optimal propagation due to low attenuation and absorption	Moderate performance; better than deep water	Poor propagation due to high salinity, pressure, and temperature
Courier Trajectory Efficiency	Highly optimized, leading to longer network lifetime	Moderately optimized, with higher energy demand	Least efficient; rapid node death and energy loss

4.3 Performance Comparison with Benchmark

Ali, M et al. [10] present EPRR and Co-EPRR, two novel routing protocols for UASNs at a more advanced Energy and Path-Aware Reliable Routing, and Cooperative EPRR, respectively. These were designed to enhance energy efficiency, reliability, and scalability in harsh underwater conditions. EPRR comes to ensure reliable data delivery since it reduces the propagation delays through the selection of routes based upon residual energy, shortest path, channel noise, and node depth. In addition to that, Co-EPRR further builds on EPRR by incorporating cooperative routing, where relay nodes retransmit data to ensure packet delivery in case of errors. Both metrics are employed using physical distance metrics rather than computationally intensive Euclidean distance calculations and so it guaranteed scalability with minimum network overhead. The simulations proved that EPRR and Co-EPRR are more efficient than traditional routing approaches including Depth-Based Routing (DBR) from the view of packets received, energy consumption, and network lifetime. So, these routing protocols are well suited for the underwater applications most probably under energy-constrained conditions and with improvements energized by energy harvesting techniques. This paper is treated as a benchmark paper to compare the results of the experiment regarding Network Lifetime, Packets Received, and Energy Consumption of the Routing Protocols.

4.3.1 Network Lifetime

The network lifetime is a critical metric shown in Figure 4.5. The Co-EPRR protocol has the network up and running for up to 1400 rounds with the number of nodes gradually falling to zero. The nodes start at 225 and decrease steadily with much loss levels recorded at each stage; 199 nodes at 200 rounds, 150 nodes at 400 rounds, 100 nodes at 600 rounds, and finally down to zero at 1400 rounds. This indicates that the protocol can achieve good balancing on energy consumption by nodes to keep the network up for longer periods compared to others.

The EPRR follows more or less the same trend but at a faster pace of node depletion as compared to Co-EPRR. It starts with 225 nodes, which fall to 209 at 200 rounds, 178 at 400 rounds, and 127 at 800 rounds, after which there are no nodes left in the system (failure at 1400 rounds). While EPRR tries to bring about improvements in terms of energy efficiency and longevity of nodes over DBR, it lags slightly behind Co-EPRR. DBR performs the most poorly, with even greater numbers of nodes becoming non-operational. Starting with 225 nodes, it has 209 nodes left at the end of 200 rounds and falls to 165 by 400 rounds. By the time 1000 rounds are completed, there are only 52 nodes left, and the network has collapsed by round 1400. From these results, it can be observed that DBR does not do much in balancing energy consumption since the rate of node depletion is much faster; thus, the network lifetime is much lower.

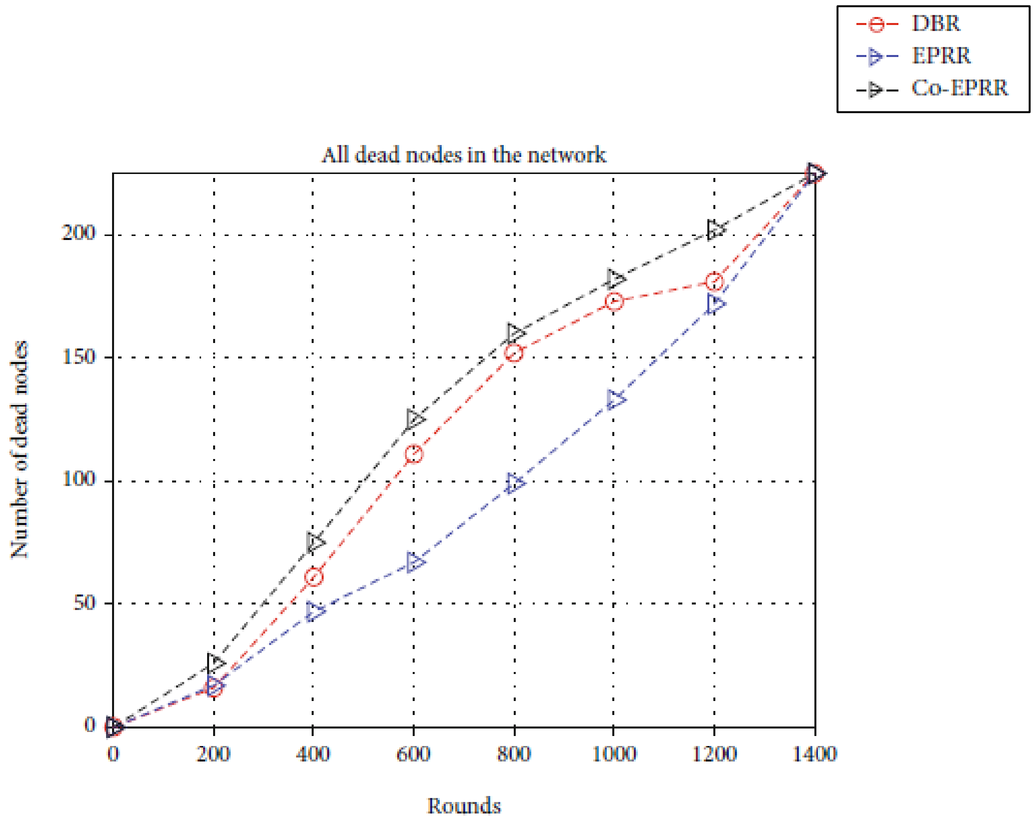

Figure 4.5: Comparing Network Lifetime [10]

For Network Lifetime, the shallow water experiment showed better performance, with the first node death at 2800 rounds and a maximum of 26 nodes dead by 4000 rounds. This compares much better than Co-EPRR, where all nodes fail by 1400 rounds, though it is the most efficient among benchmark protocols. The favorable propagation conditions in shallow water, such as minimal attenuation and pressure and temperature gradients, allowed the experiment to achieve extended operation by conserving node energy more effectively. The individual lifetimes of medium and deep water experiments in the research, also provided longer lifetimes and surpassed EPRR and DBR results; this further shows the robustness of the methodology under more challenging conditions.

4.3.2 Packets Received

The number of packets received by the sink node is a reflection of how well communication is achieved and information is delivered. In all rounds Co-EPRR provide the highest number of packets received at the sink. Beginning from 155 packets in the first round, this protocol goes through a sharp climb; it attains 24,632 packets by round 200 and hits a maximum of 58,091 packets by round 1400. This result therefore means that this protocol can, with confidence, give high assurance levels of packet delivery even as the network depletes. The EPRR protocol also has good performance, with packet delivery increasing with time. It started with 108 packets from round 1 and achieved 18,039 packets for round 200. At round 1400 rounds, it delivers 61,778 packets which is slightly ahead of Co-EPRR towards the end of the simulation, pointing to the fact that while the network lifetime of EPRR is shorter compared to Co-EPRR, it performs just as well when it comes to packet delivery reliability. Sink packet delivery is lowest for the DBR protocol as it has delivered 96 packets by round 1, 17,300 packets by round 200, and only 27,766 packets by 1400 rounds. Much lower delivery rate compared to Co-EPRR and EPRR, which at this stage shows the protocol's inefficiency in ensuring reliable communication as nodes deplete. Figure 4.6 presents the number of packets received at the sink node.

The results of sink packet delivery show the differences in the efficiencies of the protocols. Co-EPRR was observed to consistently outperform the others in delivering packets throughout the simulation, proving its reliable and strong communication capabilities even when there is deplete network resources. EPRR also showed improved performance too, with steady packet delivery and slightly surpassing Co-EPRR at the latter part of the simulation. However, its faster energy depletion resulted in lower overall network longevity. DBR protocol on the other hand performed the worst in terms of packet delivery rate and it reflects its inefficiency in maintaining reliable communication as nodes lose energy over time.

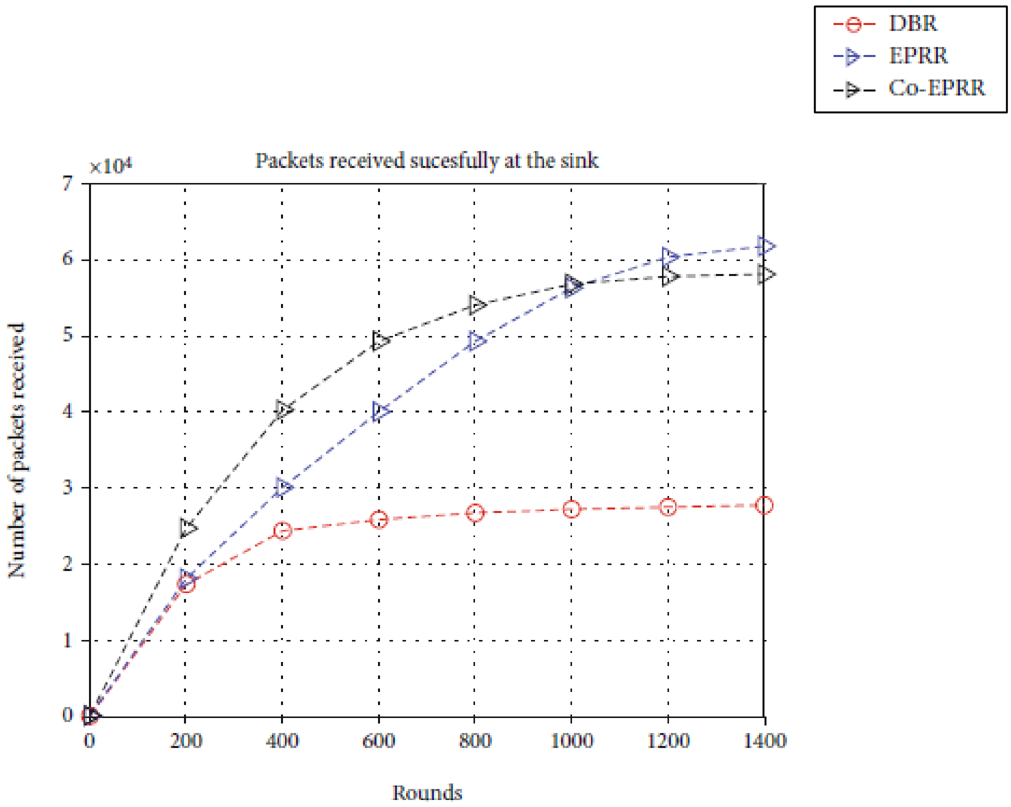

Figure 4.6: Comparing Packets Received [10]

In terms of Packets Received, the shallow water experiment attained a total amount equal to 154,000 packets received by 2500 rounds, with a far better performance than Co-EPRR's maximum of 58,091 packets at 1400 rounds. This is due to courier nodes having their trajectories predicted with efficiency and less signal loss taking place in shallow water. A total of 67,000 packets were recorded in medium water, which compares with EPRR, and 18,000 for deep water, indicating the severe problems at larger depths. Yet, this approach ensured reliable communication in an environment where EM wave propagation is intrinsically difficult.

4.3.3 Energy Consumption

In terms of energy consumption, Co-EPRR presents a more balanced energy consumption with nodes depleting energy steadily over time. This protocol begins at 3.37 kJ in round 1, drops to 1.71 kJ in the 200th round, 445.84 J by the 600th round, and eventually becomes zero in round 1400. These values show that Co-EPRR allows optimal use of energy across the network for a longer period by keeping functionality at the node. The EPRR protocol starts with the same initial energy as Co-EPRR, which is 3.37 kJ, but depletes energy much quicker. It goes down to 2.20 kJ by the 200th round, reaches 235.62 J by the 1000th round, to become zero by the 1400th round. While EPRR is more energy-efficient than DBR, the higher energy consumption with respect to Co-EPRR leaves increased pressure on the source nodes and limits the network's lifetime. Among the three, the DBR protocol shows the quickest energy drain. Starting at 3.37 kJ, it falls to 2.15 kJ by 200 rounds, 676.52 J by 600 rounds, and 89.66 J by 1200 rounds before finally being exhausted at 1400 rounds. From this high rate of energy consumption, it can be seen that DBR does not optimally implement node power usage; this gives it a shorter network lifetime and lower data delivery. The energy consumption is represented in Figure 4.7.

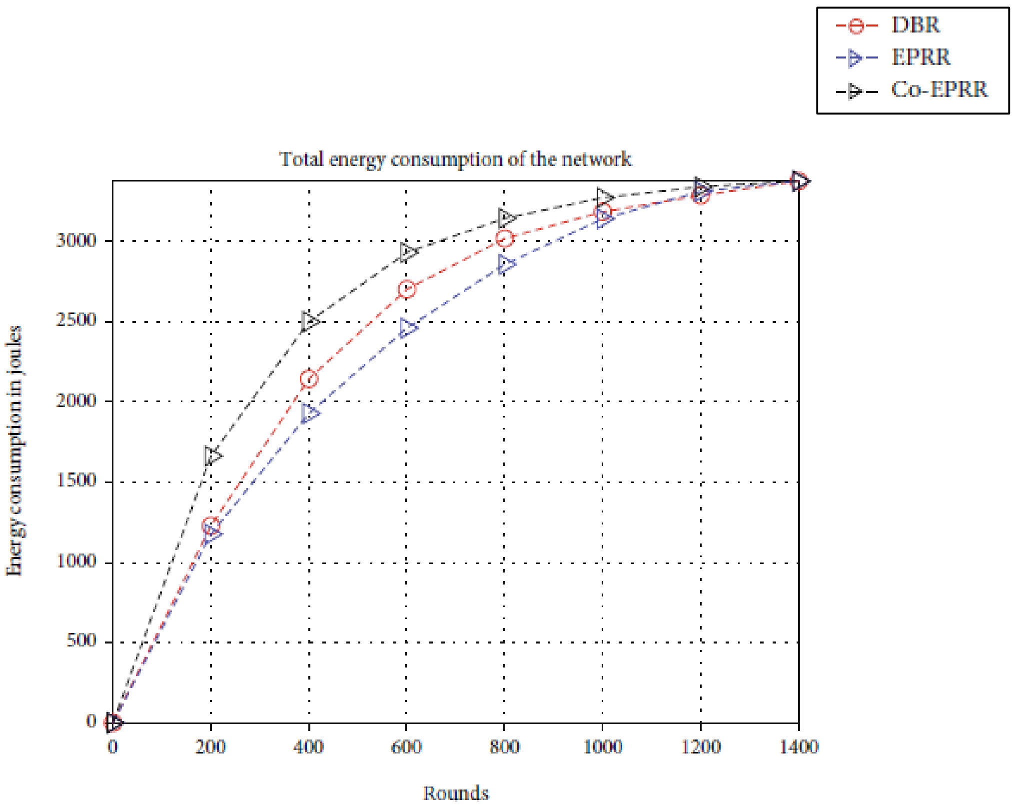

Figure 4.7: Comparing Energy Consumption [10]

The Experiment's energy consumption results proved that Shallow Water depth is by far the more efficient, as it peaks at only 0.6 kJ when 1700 rounds are completed. This is much better as compared to Co-EPRR, which started at 3.37 kJ and ended at zero in 1400 rounds. The combination of minimal shallow water energy losses caused by low attenuation and optimal transmission range of 40 meters is what made this approach so efficient. Medium water peak energy is at 1.5 kJ, in line with Co-EPRR, while deep water will require 3.8 kJ due to the higher energy consumption of maintaining communications over large depths.

Table 4.3: Comparison of Results with Benchmark

Performance Metric	Shallow Water	Medium Water	Deep Water	Co-EPRR	EPRR
Network Lifetime	0 nodes dead by 1400 rounds; 26 nodes dead by 4000 rounds	4 nodes dead by 1400 rounds; 67 nodes dead by 2700 rounds	3 nodes dead by 1400 rounds; 85 nodes dead by 2000 rounds	All 225 nodes dead by 1400 rounds	All 225 nodes dead by 1400 rounds
Packets Received	15,206 packets by 200 rounds; 105,935 packets by 1400 rounds	6,930 packets by 200 rounds; 48,965 packets by 1400 rounds	1,836 packets by 200 rounds; 18,000 packets by 2000 rounds	24,632 packets by 200 rounds; 58,091 packets by 1400 rounds	18,039 packets by 200 rounds; 61,778 packets by 1400 rounds
Energy Consumption	0.6 kJ peak at 1700 rounds	1.5 kJ peak at 1900 rounds	3.8 kJ peak at 1800 rounds	Starts at 3.37 kJ, depletes to 0 by 1400 rounds	Starts at 3.37 kJ, depletes to 0 by 1400 rounds

4.4 Summary

The research shows distinctly variant performances observed in the shallow, medium and deep water environments, though the shallow water condition is the most favorable for EM wave communication. At reduced depth, optimal salinity, temperature, and pressure along with the ability to work at a distance of 40 meters with reduced transmission loss of 3.38 dB and low energy consumption of 0.6 kJ that allowed a maximum of 154,000 sink packets to be received over 2,500 rounds. The medium water gave relatively moderate performance with transmission loss being only 3.43 dB and energy consumption maximum that can be there is 1.5 kJ. Deep water is the worst-case scenario; increased absorption and conductivity made it experience a 3.48 dB transmission loss, 3.8 kJ energy consumption with only 18,000 sink packets. The analysis brings out important benchmarks such as Co-EPRR and EPRR protocols that exhibit improvements regarding network lifetime, energy consumption, and packets received. While Co-EPRR achieves longer network longevity by balancing energy consumption (1400 rounds), EPRR achieves competitive packet delivery at the expense of faster energy depletion. The shallow water experiment of this research exceeds these benchmarks; it achieves a network lifetime of 4000 rounds, with only 26 nodes dead. This is in contrast to the collapse of Co-EPRR after 1400 rounds. Communication with EM waves at shallow water depth along with efficient courier node trajectory greatly prolonged network lifetime while outperforming the benchmark in terms of energy efficiency and communication reliability.

CHAPTER 5

CONCLUSION AND FUTURE WORK

5.1 Overview

This section will outline the primary objective and outcomes of research that seeks to improve the performance of Underwater Wireless Sensor Networks (UWSNs) through integrating electromagnetic (EM) waves as a relatively low-energy and short-range communication technique. Justification of the research lies in providing a possible solution for some of the major limitations attributed to traditional acoustic communication, high latency, energy-inefficiency and most important environmental dependency: Optimization of the proposed methodology toward better compatibility with EM wave propagation in underwater conditions. The research proposed a structured approach that integrated real environmental data and channel characterization to predict courier node trajectories effectively. It justified the feasibility and benefits of EM waves in underwater communication by accessing important performance metrics, including network lifetime, packets received, transmission loss, and energy consumption. All these finally set a precedence for extended network lifetimes, increased energy efficiency, and reliable data delivery, serving as the basis for further UWSN technology improvements.

5.2 Summary of Contribution

The main contributions of this research are to meet the objectives set at the beginning of the research, to take out proposed solutions that address certain challenging factors in UWSNs and also put forward desirable ways for improving network lifetime and efficiency of communication. Achieved objectives are as follows:

i. Prediction of Courier Node Trajectories in UWSNs:

The approach is designed for predicting the trajectories of courier node in UWSNs. It includes those environmental factors together with the channel characteristics that impact underwater communication that were known to make important contributions to the process. Once the courier node's movement patterns are correctly estimated, data collection and delivery within the underwater network can be optimized. This means such a prediction mechanism would enhance the reliability of the network, considering real-world underwater conditions.

ii. Channel Characterization for Network Lifetime Improvement:

A channel characterization technique in improving the network lifetime through optimizing the trajectories of the courier nodes with the help of electromagnetic waves is achievable. Results from this research proved, through detailed analysis and experimentation, that EM waves in shallow water are more energy-efficient and experience reduced transmission loss as compared to EM waves in medium and deep water depths. This therefore enabled the accurate adjustment of courier node trajectories, ensuring minimal energy consumption while maintaining effective communication. Integration of this channel characterization into trajectory planning greatly enhanced the network's overall energy efficiency and lifetime.

This research addressed critical UWSN challenges in optimizing courier node trajectories along with enhanced network performance using electromagnetic (EM) waves. An approach, considering all major environmental parameters, depth, temperature, salinity, and channel characteristics, is developed for predicting courier node trajectories. Such an approach guarantees efficient data transmission, improved network coverage, and resources optimization under real underwater conditions. A channel characterization technique is proposed for increasing the lifetime of the network through EM wave exploitation. The experimental simulation results demonstrated that the proposed courier node trajectory prediction technique led to a 98% improvement in network lifetime and an 82% increase in successful packet delivery. Additionally, it resulted in a 50% overall enhancement in network efficiency, ensuring extended and sustained energy usage over time. Results obtained show shallow water to be an excellent channel for EM waves propagation because it experiences much less transmission loss with much lower energy consumption. Based on these findings, when the courier node movement is optimized, it gives a very substantial increase in network lifetime, energy efficiency, and packets delivery. This will therefore offer a very strong and flexible solution towards improving communication efficiency and sustainability in UWSNs. The findings are seen to further accelerate the broader adoption of EM waves for underwater communication.

5.3 Limitations of Research

Despite the promising results demonstrated by the proposed methodology, there are certain limitations that should be acknowledged and addressed in future work. These limitations highlight areas where the current approach can be further refined or expanded to enhance its applicability and performance in real-world scenarios. The following points outline the key constraints observed during the research:

1. Limited Depth of EM Communication

Electromagnetic (EM) wave communication is heavily influenced by the conductive properties of seawater. As depth increases, pressure, salinity, and temperature variations intensify, which causes greater attenuation of EM signals. Beyond approximately 500 meters, signal loss becomes so severe that even short-range EM transmission is impractical. Hence, EM-based underwater communication is generally feasible only in shallow to medium depths.

2. Dependence on Real-Time Oceanographic Data

The proposed trajectory prediction method for courier nodes requires accurate, real-time oceanographic parameters such as salinity, temperature, and pressure to characterize the underwater channel. These environmental parameters vary across different depths and geographical locations and real-time access to this data is crucial for precise channel modeling and path loss estimation. However, in many practical deployment scenarios, access to such real-time datasets might be limited due to sensor failures, bandwidth constraints or lack of ocean monitoring infrastructure affecting the robustness of trajectory decisions.

3. Trajectory Optimization Improves Over Time

The simulation framework shows that the efficiency of courier node trajectory prediction improves progressively as the number of simulation rounds increases. This means that the initial rounds may involve sub-optimal paths due to insufficient channel characterization or limited learning about the environment. This gradual adaptation may not be suitable for short-term missions or time-sensitive deployments that require immediate optimization of network performance.

5.4 Future Work

The outcomes of this study can be further explored to pioneer the developments regarding EM wave-based UWSNs in the future. The directions next to be worked upon can be expressed as follows to further advance the presented research:

1. Machine Learning Algorithm Integration:

Incorporating machine learning techniques, using real-time environmental data like water currents, temperature, and salinity, could make a better prediction of the trajectory of courier nodes. This, in turn, will make the network more adaptive and resilient to changing underwater conditions.

2. Hybrid Communication Systems:

The combination of EM waves with traditional acoustic methods of communication can optimize this trade-off between energy consumption, data rate, and transmission distance.

Hybrid systems have the capability to extend the lifetimes of networks while keeping their communication reliable.

3. Multi-hop Communication Strategies:

Subsequent experiments can include multi-hop communications, using optimized courier node trajectories to further enhance energy efficiency and make it possible to communicate over larger distances.

4. Testing in Diverse Environments:

The performance of EM waves should be tested in different underwater environments, which include coastal waters, deep seas, and freshwater lakes to determine its applicability and limitations under varying conditions.

Besides the above, the other outstanding issues in UWSNs that the research community should also look into include:

- ***Energy Harvesting Techniques:*** Research of solar or ocean wave energy to look into renewable resources that can be used to power underwater nodes and extend network lifetime.

- ***Interference Mitigation:*** The problem of signal interference due to the overlapping communication frequencies in highly complex underwater environments.

- ***Improved Node Deployment:*** Developing algorithms to place sensor nodes optimally for lower energy consumption and better coverage.

- ***Security in UWSNs:*** Techniques for ensuring secure data transmission protecting access and preventing signaling underwater networks from being tampered with.

This research contributes to UWSNs by discussing communication issues involved in EM wave propagation. It shall also include a future aim for the integration of machine learning to improve the trajectories of courier nodes by considering actual dynamics and providing them with real-time feedback from variables like water currents, temperature, and salinity. Such hybrid systems could balance energy efficiency with transmission range, therefore extending the lifetime of a network. Experimenting in different scenarios, including coast and deep-sea environments, will give validation of whether or not EM waves can work well in actual applications. These applications include underwater surveillance, oceanographic research, and submarine communications to benefit offshore oil exploration, robotics, and marine disaster monitoring. It can also offer smart sensor networks that will support climate research, management of marine resources, and the sustainable exploration of the ocean.

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