Packet Reliability Using Cooperative Routing in Underwater Wireless Sensor Networks

By

Hashim Khan

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Supervisor

Dr. Syed Ali Hassan

Department of Electrical Engineering

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Approval

It is certified that the contents and form of the thesis entitled "Packet Reliability Using Cooperative Routing in Underwater Wireless Sensor Networks" submitted by HASHIM KHAN have been found satisfactory for the requirement of the degree

Advisor : Dr. Syed Ali Hassan

Signature: ____________________

Date: 10-Apr-2021

Committee Member 1:Dr. Arsalan Ahmad

Signature: ____________________

Date: 13-Apr-2021

Committee Member 2:Dr. Hassaan Khaliq Qureshi

Signature: ____________________

Date: 12-Apr-2021

Committee Member 3:Dr. Safdar Abbas Khan

Signature: ____________________

Date: 09-Apr-2021

Dedication

I dedicate this thesis to my father Sher Azam Khan, mother Gul Bibi, mentors Hilal Afridi, Unsub Shafiq and Sajid Nawaz khan.

Certificate of Originality

I hereby declare that this submission titled "Packet Reliability Using Cooperative Routing in Underwater Wireless Sensor Networks" is my own work. To the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics, which has been acknowledged. I also verified the originality of contents through plagiarism software.

Student Name:HASHIM KHAN

Student Signature: _______________

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List of Abbreviations

Acronym	Description	Acronym	Description
UWSNs	Underwater Sensor Networks	TWSNs	Terrestrial Wireless Sensor Networks
CR	Cooperative Routing	bps	bits per second
EM	Electromagnetic	RF	Radio Frequency
BER	Bit Error Rate	N_t	Turbulence Noise
N_s	Shipping activity noise	N_w	Waves Noise
N_{th}	Thermal Noise	RTS	Ready To Send
CTS	Clear To Send	RE	Residual Energy
ToA	Time of Arrival	MIMO	Multiple-Input Multiple-Output
SISO	Single-Input Single-Output	FRC	Fixed Ratio Combining
MRC	Maximal Ratio Combining	PAR	Packet Acceptance Ratio
RSS	Received Signal Strength	TDoA	Time Difference of Arrival
ACK	Acknowledgment	RR	Routing Relay
TDMA	Time Division Multiple Access	ADV	Advertisement
QOS	Quality-of-Service	NACK	Negative Acknowledgment

Table 1: Acronyms with their descriptions.

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Abstract

Underwater wireless sensor networks (UWSNs) uses the wireless medium for communicating data in an underwater environment. Due to a lack of resources human being are exploring Oceans and Seas for resources. Optical signals have high propagation speed, high back-scattering by suspended particles and turbidity effect make UWSN not viable for long-distance communication. Radio waves due to the conductivity of water have high attenuation. Acoustic signals are used for communication because they are less sensitive to suspended particle than optical signal and have a low turbidity effect. Traditionally, research is done to improve the Packet Delivery Ratio (PDR) at the Sink via multi hoping from higher depth nodes. To summarize, our proposed protocol, Packet Reliability using Cooperative Routing (PRUCR) consider cooperative base routing technique to encounter the energy and drastic environment problem. The framework of UWSNs constitutes sink nodes, sensor nodes and surface station. The design of Packet Reliability using Cooperative Routing (PRUCR) protocols guarantees robust and reliable data delivery from the source nodes to the destination nodes. Furthermore, we studied the behaviour of PDR, delivery efficiency, Residual Energy (RE), Bit Error Rate (BER) and delivery efficiency. Towards the end, we concluded the potential research gaps to improve the performance of routing protocols.

Chapter 1

Introduction

Earth is recognized as a blue planet in the solar system as most of it is covered by oceans and water. The earth's surface covers about 140 million square miles with water which constitutes almost 70% of earth surface area [2]. The average depth of the ocean is four-kilometre, the main part of which is still unexplored. In deep oceans, underwater resources are not feasible to be explored by humans due to low visibility, high pressure, and unpredictable underwater events [3]. Therefore, scientists are paying more attention towards the exploration and monitoring of the underwater environment through modern UWSN technology. In terms of mobility of nodes and techniques of communication, UWSNs differ from Terrestrial Wireless Sensor Networks (TWSNs) in many aspects. UWSN generally consists of autonomous nodes in an underwater environment that sense data and are distributed spatially [4]. The sensed data can be used by a variety of applications for human advantage. Radio waves that are most widely used in the transmission medium are not feasible in UWSN's because of high attenuation and short propagation distance. Optical wave can't also be used as wireless transmission media in

UWSNs due to the strong backscattering effect by suspended particles and turbidity effect [2]. The acoustic signals are most widely used in underwater wireless transmission media. They are less sensitive to suspended particles as compared to the optical wave. UWSNs possesses many challenges using sound waves as the transmission medium. Sound waves are limited by low carrier frequency alongside high reflection and strong attenuation.

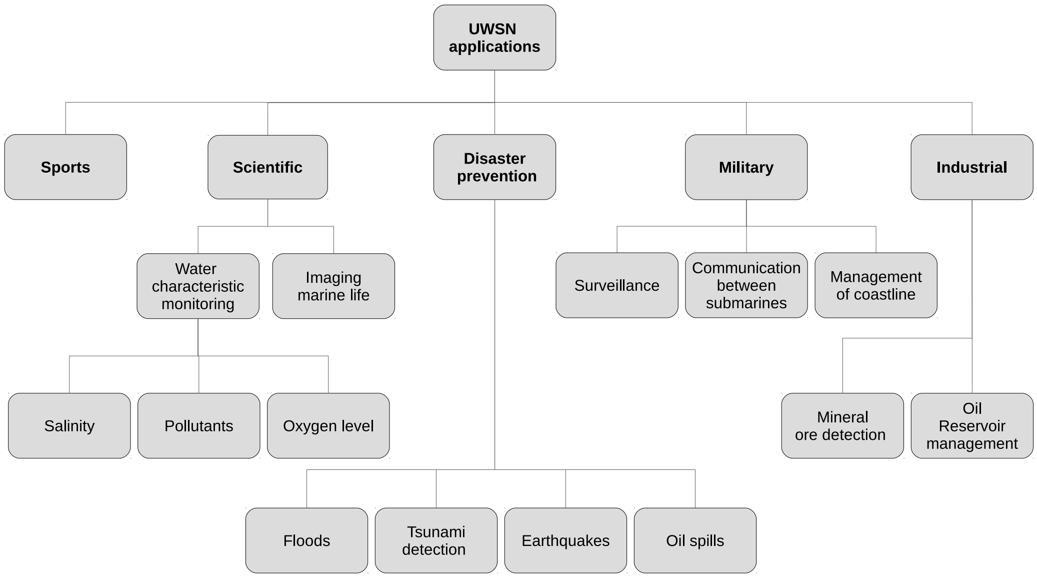

Figure 1.1: A snapshot showing various applications of underwater sensor networks under different categorizations.

UWSNs applications are used in a broad variety and becoming more important nowadays. Scientific application of UWSNs includes monitoring the characteristic of water i.e. salinity, oxygen level, and pollutants, etc. along with imaging marine life. The military application includes communication between the submarines, surveillance, and management of the coastline. The industrial application includes mineral ore detection and oil reservoir management. The disaster prevention application includes floods, oil spills, earthquakes, and Tsunami detection etc. UWSNs application also includes monitoring of water-based sports activities [4–6]. The classification of the broad variety of UWSN applications is shown in Fig. 1.1.

1.1 UWSN Network

A UWSN is ad-hoc in nature with a large number of sensor nodes being deployed in a three-dimensional (3D) underwater environment at different depth levels. The main purpose of UWSNs is to collect data whenever an event occurs, the sensor nodes must be deployed in such a manner that the entire area, which is being monitored, is covered. Sensor nodes in UWSN possess the capabilities of sensing, processing and communicating with other sensor devices. Each sensor node contains a single antenna, battery and acoustic modem that has low bandwidth. Sensor nodes sense their surrounding information from the underwater environment and are considered homogeneous in terms of energy consumption. Multi-hoping is used by sensor nodes for delivery of sensed data toward surface sink using the acoustic link. The energy consumption of the UWSN is significantly higher as compared to the TWSN due the utilization of acoustic link between transmitter and receiver [4]. The surface sink is equipped with the radio and acoustic modem which floats on the water surface. It will forward the received data further over radio link towards the onshore sink as shown in Fig. 1.2.

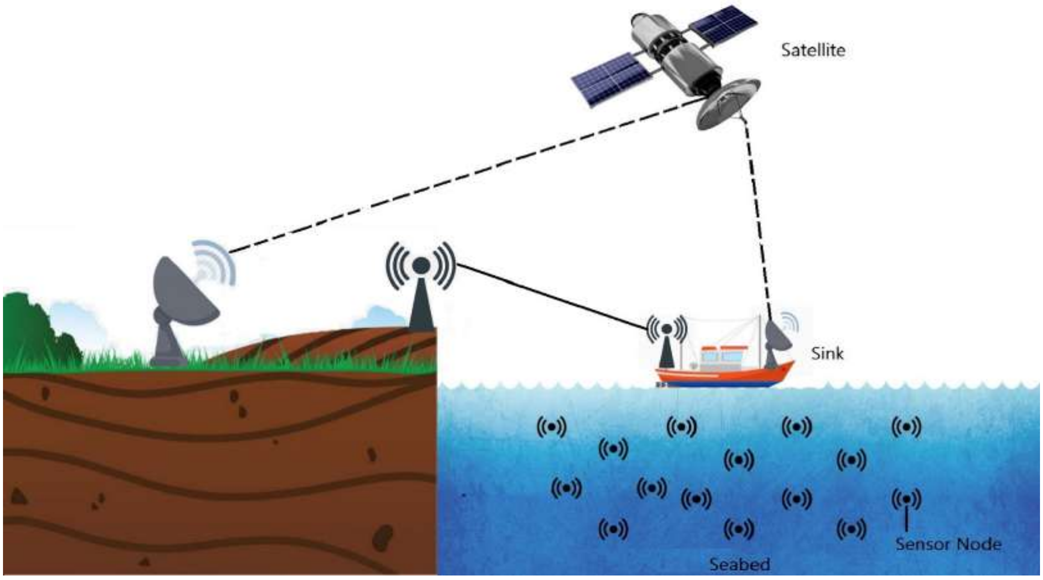

Figure 1.2: Network topology of an underwater sensor network showing various entities such as sensor nodes, sink node and ground stations.

A route between a sensor (or source) to the intended destination (or sink) is established for effective and reliable data transmission. The sensor nodes can communicate either by direct link or through a multi-hop path. In the direct link method, the data is sent directly from the source node towards the targeted sink. Whereas, in multi-hopping, the data packets are relayed by the intermediate nodes until they reach the sink. However, multi-hop incurs increased complexity to build a route, which also determines system performance such as network capacity and energy efficiency.

1.2 Thesis Contribution

The major contribution of this thesis work is to discuss the proposed PRUCR protocol contribution to the UWSN routing protocol which include the following;

- PRUCR protocol states that source node will broadcast the packet against its transmission range.
- Subsequently maximum of two nodes with least depth in transmission range will cooperatively broadcast the packet toward the destination node.
- We analyze the four different parameters and use them as a reference point for discussion.
- MATLAB emulator is used to check and evaluate the results.

1.3 Thesis Organization

The remainder of this thesis is organized as follows: In Chapter 2, we give the background of and literature review related to the UWSN. Chapter 3 addresses the Underwater Acoustic channel model, the objectives we want to achieve and the proposed approach. Chapter 4 focuses on the PRUCR protocol design including the proposed algorithm and simulation results. Finally, Chapter 5 concludes the thesis and gives some future directions.

Chapter 2

Background and Literature Review

This chapter explains the characteristics of carrier waves in Section 2.1. Routing protocols for UWSNs have peculiarities compared to TWSNs, which make UWSN routing protocol design challenging. Section 2.2 explain the UWSN channel characteristics in detail. UWSN routing protocols have been classified into three main categories that are localization-based, localization-free, and cooperative routing. Section 2.3 discusses the main routing protocols discussed so far for UWSNs and highlights their advantages and performance issues.

2.1 Classification of Carrier Waves

The following section explains and defines carrier waves which included acoustic, RF, and optical waves as given in Table 2.1.

Parameters	**Acoustic**	**RF**	**Optical**
Data rate	5 b/s to 20 kb/s	Up to 100 Mbps	Up to 1 Gbps
Attenuation	Depends on frequency and distance	Depends on conductivity and frequency	Depends on distance
Tx Distance	20 Km	100 m	10-30 m
Turbidity Effect	Low	Low	High
Speed	1500 m/s	3×10^8	3×10^8
Cost	High	High	Low

Table 2.1: Comparison between different modes of communication in UWSNs.

2.1.1 Acoustic Waves

Acoustic waves are mechanical in nature and require a medium for transmission. In water, the speed of sound is approximately 1500m/s [7], whereas in air medium, it is 340m/s. The speed of sound is impacted incredibly by the temperature, pressure, depth and water's salinity [8, 9]. The acoustic signal absorption in water is three order of magnitude lesser than the absorption of electromagnetic (EM) signal. The acoustic signal operates below 30 KHz and has a very limited bandwidth [10]. Although some signals can move considerable lengths, large frequency sound is attenuated much more quickly than low frequency sounds [11]. The acoustic signal attenuation is primarily dependent upon frequency and distance, has low turbidity effect and is limited by the low carrier frequency and provides data rate between 5 b/s and 20 kb/s. These signals can communicate over long-distances up to 20 km [12] and are less sensitive to the suspended particles.

2.1.2 Radio Frequency (RF) Waves

RF waves are non-mechanical. The speed of EM waves in the RF range is four orders faster than acoustic waves in water. RF waves propagation is acceptable with low frequency, whereas the sensitivity of RF signals to refraction and reflection is less in the shallow water. EM/RF has very little effect by suspended particles and the data rate of the RF signal in short distance, i.e., up to 10 meters, is around 100 Mbps [13]. To communicate over a long distance, extremely low-frequency RF signal is required. However, the cost for extremely low frequency is large due to large antenna size and high transmission power [14, 15]. High frequency is also not feasible because attenuation increases with the increase of RF wave frequency. The water absorbs and disperses almost all EM frequencies, where the EM signal absorption in seawater is around $45\sqrt{f}$ (dB/km), where f is the operating frequency [16]. The electromagnetic range for 1 MHz frequency is around 10 meters, however, the propagation rate of the electromagnetic wave is smaller at low frequencies [12]. High-frequency RF waves lead to high signal attenuation which restricts communication range. Moreover, the salinity in water causes conductivity which eventually increases RF signal attenuation. The RF signals are not preferred for long-distance communication for the above reasons.

2.1.3 Optical Waves

Optical waves are non-mechanical and their speed is about four to five times higher than the acoustic waves prorogation speed in fluids [17]. Optical signal provides higher data rate, power efficiency, and low latency. These waves are not considered a good option for communication over long distances. Optical communication between receiver and transmitter requires a line of sight hence it is a point-to-point communication instead of omnidirectional communication [18] [19]. Due to water current, nodes position can change and it can lead to disconnection of the transceivers. Low cost lasers and diodes can be used to build optical wireless transceivers. The carrier wavelengths have absorption, scattering and multi-path fading effect due to their interaction with water molecules. The optical signal range in an underwater environment is between 10 and 30 meters and attenuation is directly proportional to the distance. The primary disadvantage of optical communications is their water turbidity reliance. Scattering can be caused by salt ions and particles, and the direction of the photons changes due to scattering [20].

2.2 Underwater Channel Characteristics

In this context, to better design the UWSN routing algorithms, the numerous challenges faced by UWSNs that are distinct from TWSNs are discussed below and outlined in Fig. 2.1.

The communication in UWSN is done using acoustic channel between the sensor nodes. Acoustic communication is affected by two types of noise: ambient and human-made noise. Human activities are the reason behind human-made noise but on the other hand, natural activities are the cause of ambient noise [21]. Interference in UWSNs is also higher due to reflections from the bottom, the surface, impurities and aquatic life [22]. The energy consumption of sensors in UWSNs is higher than in TWSNs. The battery cannot be recharged because of large size of nodes that are positioned in the deep ocean with harsh underwater conditions. However, energy-efficient routing protocols can increase the network lifetime. The data is collected from multiple sensor nodes, combined and then forwarded towards the sink using aggregation. The aggregated information is more reliable compared to individual readings of sensor nodes. As a result, reliability of data also increases by aggregation.

The UWSNs are ad-hoc in nature and hence they do not have any prior information about the location of sensor nodes. Equipping the sensor node with the GPS receiver is the simplest solution, however, this method does not work underwater because of high RF attenuation. GPS at 1.5 GHz band is unable to propagate due to high frequency and quick absorption in underwater [4]. Another way to determine the underwater sensor nodes location information is through message exchange. A major disadvantage of this approach is the need to exchange periodic messages. As sensor node location changes with the water current, the sink needs to broadcast Hello packets at regular intervals hence the sensor nodes update their location information. Thus, energy consumption increases and the lifetime of network decreases.

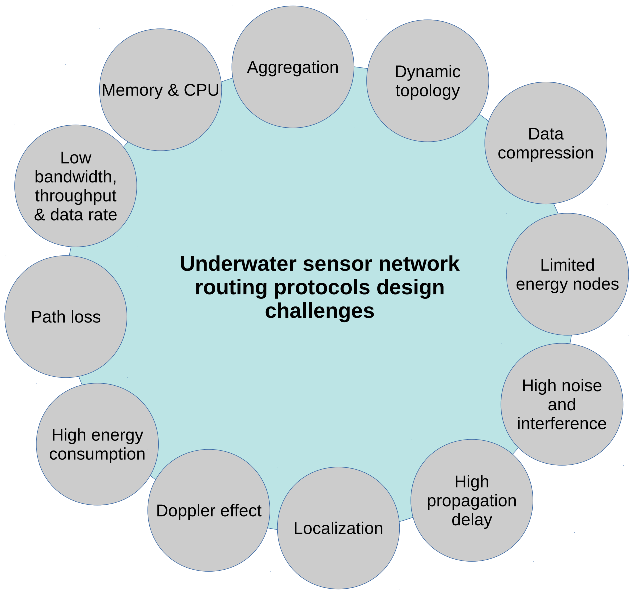

Figure 2.1: A depiction of various challenges faced for UWSN protocols.

The network's lifetime has a direct link with the energy consumption. Low energy consumption implies a long network lifetime and vice versa. The sensors in UWSNs consume more energy for transmission and reception of packets compared to TWSNs [23]. Communication links are also more unstable due to the random motion of nodes and the Bit Error Rate (BER) is higher compared to terrestrial network. On the other hand, attenuation is also a great factor and the acoustic wave speed can change in underwater environment. Because of these issues, it is more often that re-transmission occurs, which consumes more energy.

Acoustic waves use the frequency between a few Hz and tens of kHz because this chunk can be used to communicate over a large distance. Because of limited frequency used for data transmission and noise in underwater environment, the throughput decreases, thereby, the transmission rate hardly exceeds 100 kbps [24]. This is a major constraint which is considered while designing efficient routing protocols because during route discovery, maintenance and recovery, large amounts of information is exchanged. The data rate of acoustic channel is more than 100 kbps when distance is less than 1 km. However, the achievable data rate is reduced to 50 kbps when distance is between 1 to 10 km, and for distance up to 20 km, the maximum achievable data rate is only 10 kbps [25].

In UWSNs, the sensor nodes are deployed without any proper planning. Topology changes due to water current and subsequently new sensor nodes join the network whereas some nodes become inactive. The movement of nodes depends on the speed of water that varies with time [21]. Another reason of the topology change is that the sensor nodes are susceptible to failure because of corrosion and pollution, such as, algae collection on camera lens [26]. Further, the performance of routing protocols is affected by such frequent network changes. However, in TWSNs nodes movement is restricted and topology changes primarily when new nodes join the network or some nodes become dead.

The path loss impact can be decreased by reducing the distance traversed and increasing the power of transmission. Therefore, multi-hopping technique is preferred to relay the packet toward the surface sink rather than traversing single direct link [21].

2.3 Routing Protocols for UWSNs

The design of routing protocols and the behaviour of acoustic waves for UWSNs have been studied for decades. For the reliable delivery of data at the destination and discovery of the network, routing protocols play an essential role. As illustrated in Fig. 2.2 we treat the three categories separately in different sections. In this section, Section 2.3.1, localization-based routing protocols are discussed along with their advantages and disadvantages. In the subsequent Sections 2.3.2 and 2.3.3, localization-free and cooperative routing protocols are presented, respectively. The protocols introduced in the three sections are outlined in Fig. 2.2. In the Section 2.3.1, as shown in the figure, we consider four representative localization-based routing protocols.

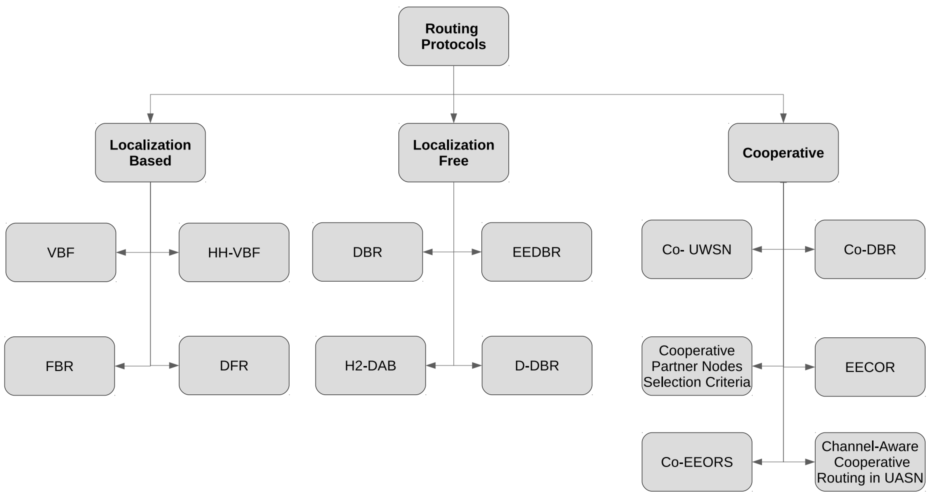

Figure 2.2: Hierarchy of UWSNs routing protocols.

2.3.1 Localization-based Routing Protocols

The protocol enlisted in this category assume that every nodes knows about their position in the network.

Vector-Based Forwarding Protocol (VBF)

VBF, proposed in [27], is a localization-based routing protocol which assumes that every sensor node carries the position information of itself, destination and all forwarders. Control messages are not used for information gathering in this protocol, and a single sink is assumed in the network. A virtual routing pipe is created using the node position information of the source and the destination. Each header field of a packet comprises the position information of the source, forwarder and destination node along with the range and radius of routing pipe. The nodes present in the pre-controlled radius of the routing pipe along the routing vector are selected as forwarders. The nodes that are present in the virtual routing pipe are considered as potential forwarders and participate in the routing process. The packet is discarded by the nodes that are present outside the virtual routing pipe. The main advantage of VBF protocol is in dense networks, PDR increases, because there are more number of potential forwarders. On the other hand, the main drawbacks of the VBF protocol include low PDR in sparse networks, because the virtual routing pipe has few nodes. If a void region is present in routing path, VBF protocol cannot discover a path to send the packet towards the destination and packet will get discarded. On the top of that, VBF protocol is not capable of recovering the void region. Increasing the radius of virtual pipe can avoid the creation of a void in a sparse network. In addition, the packet forwarding

Table 2.2: Localization-based and localization free routing protocols comparison

Parameter/Protocol	VBF	HH-VBF	FBR	DFR	DBR	EEDBR	H2-DAB	D-DBR
Sink	Single	Single	Multiple	Single	Multiple	Multiple	Multiple	Multiple
Hello or control packets	✗	✗	✓	✗	✗	✗	✓	✗
Receiver-based	✓	✓	✗	✓	✓	✓	✓	✓
Localization-free	✗	✗	✗	✗	✓	✓	✓	✓
Hop by Hop communication	✗	✓	✓	✓	✓	✓	✓	✓
Communication overhead	Medium	High	High	Low	Low	Medium	Medium	Medium
Network Lifetime	Low	Low	Medium	Medium	Medium	High	Medium	Medium
Energy consumption	Medium	High	Low	High	High	Low	Medium	Low
Packet delivery Ratio	Low	Medium	Medium	Medium	High	High	High	High
Delay	High	Medium	Low	Medium	Low	Medium	Medium	Low
Performance	Low	Medium	High	Low	Medium	Medium	Medium	High
Reliability	Low	High	Medium	High	High	High	Medium	Medium

does not allow the balance of energy as the nodes near the virtual routing pipe are used more frequently.

Hop-by-Hop Vector-Based Forwarding Protocol (HH-VBF)

HH-VBF, proposed in [28], is the extended version of VBF, in which every forwarding node calculates its vector towards the sink, so that the data is forwarded towards the destination using multiple virtual pipes. In this protocol, the network topology is also assumed to have a single sink, and periodic control messages are not exchanged. The sparse network has more paths for delivery of packet compared to VBF routing protocol. The HH-VBF has the advantage of finding the data delivery path, given that there is a single node present in the communication range of the forwarding path. Also, the PDR of HH-VBF is higher in comparison to the VBF in sparse networks. In contrast, HH-VBF may suffer from high propagation delay due to large computation at every hop. It has more packet overhead because of computation at every hop and hop by hop transmission. It also inherits the problem of finding accurate radius threshold of the routing pipe.

Focused Beam Routing (FBR)

FBR protocol in [29] assumes that every node has its own information as well as the information of destination location, and does not need the intermediate nodes' location information. The network comprises of multiple sensor nodes and sinks. Multiple power transmission levels are used for data transmission. The usage of dynamic transmission power increases routing robustness as per the requirement of the network. Control messages, Ready-To-Send (RTS) and Clear-To-Send (CTS) are used to forward the data packets. If a node does not receive CTS packet in response to RTS, it increases the power level until it receives one. In a sparse network, it is not a good option for routing because high transmission power levels increase energy consumption. The prominent advantage of this protocol is that it multicast the RTS packets in particular cone of an angle. The sender node increases the power level until maximum if it does not receive CTS. After the maximum power level is achieved and no neighbor is found, the angle is shifted either left or right to cover the entire region. A major disadvantage of this routing protocol is the assumption of a fixed sink position. The sender rebroadcasts the RTS packet whenever CTS is not received because the relay node is not present in sender range which eventually increases energy consumption and network overhead.

Directional Flooding Based Routing (DFR)

DFR, introduced in [30], is a receiver-based routing protocol assuming each sensor node identifying its position along with one-hop neighbor and sink, measuring the quality of the link with the neighbor and describes the method to avoid the difficulty of traversing the void region by allowing minimum one sensor node in forwarding of the packet. The routing process requires the limited number of nodes and flooding zone is created in the form of scoped flooding. This helps limit the flooding of the packet to the whole network. In this protocol, the angle between FS and FD decide the flooding zone where S is the source node, D is the destination node, and F is the intermediate node that receives the packet.The key advantage of the DFR protocol is that it addresses the void problem by letting minimum one node to participate in a packet forwarding. To improve the reliability, the DFR mainly relies on the technique of packet flooding. The main disadvantage of DFR protocol includes high energy consumption caused by directional flooding.

2.3.2 Localization-Free Routing Protocols

This section considers localization-free routing schemes and highlights the advantages and drawbacks. Localization by means of GPS signal is also not effective because the electromagnetic signal does not propagate efficiently through the underwater environment. Acquiring full dimension location information of underwater sensor node is a challenging task. Node resources get wasted to attain location information due to extensive control packets exchange. Hence, the localization-free routing algorithms are preferred as these protocols require merely the information of the depth of sensor nodes for data routing.

Depth Based Routing (DBR)

DBR, proposed in [31], is a localization-free receiver-based routing protocol, where the sensor nodes calculate the depth using a depth sensor instead of attaining complete location dimensions. Multiple sinks are positioned on the water surface for data collection. The routing decisions rely on depth value of sensor nodes. Higher depth sensor nodes transfer data packets to lower depth sensor nodes. During the packet transmission, the current depth value is inserted in the header field. When the data packets are received by neighboring nodes, they compare the depth field in packet header with their own depth through packet inspection. The data packet will be forwarded only if the current depth is smaller as compared to the depth in the received packet header. The concept of holding time is used to avoid redundant transmission. The packet is forwarded in this manner toward the sink. If the packet is received on any sink, then it is considered successfully delivered at the final destination. There are certain drawbacks of this protocol. First, in sparse networks, it does not perform well. The problem of the void region can occur due to greedy manner routing. Second, the failures of sensor nodes close to the sink occur earlier due to convergence behavior.

Energy Efficient Depth-Based Routing (EEDBR)

EEDBR, proposed in [32], is the extension of the DBR protocol, where Residual Energy (RE) parameter alongside depth is considered for selecting the optimal forwarding node.The protocol is based on two phases: knowledge acquisition phase and data forwarding phase. The information is shared with neighbors using Hello packet. The packet contains three main fields which are sensor ID, depth, and RE. The depth value information is stored by sensor node only if the value is smaller than its own depth value. The data forwarding phase is dependent on the depth and RE. The forwarder nodes are at all times nearer to the sink than the transmitting nodes. Nodes having lesser depth values can contribute to data forwarding mechanism, however, the forwarder selection also depends on RE. The priority list is maintained to determine the RE, holding time, sensor ID, and depth parameters. Packet forwarding is done by taking into account the priority list. In this protocol, each node has information regarding depth and RE of all the neighbors in its transmission range. A sensor node first checks the receiver nodes' depth with itself and then checks the receiver node RE. The node of least depth value in the neighboring nodes and the maximum RE becomes the next hop destination. No proper strategy is defined for the selection of efficient, reliable and shortest routing path. The data is transferred over the one noisy channel in a multi-hop manner. This protocol suffers from a high BER due to noise and multi-path fading. In addition, the energy balancing mechanism is not properly defined. Proper convergence at the node near the sink is also another issue.

Hop-by-Hop Dynamic Address-based Routing Protocol (H2-DAB)

H2-DAB, developed in [33], is a localization-free receiver based routing protocol that applies a dynamic addressing scheme to all network nodes. Multiple sink architecture is employed and at various levels of depth, the sensor nodes are deployed in the network topology. Surface sinks use Hello packet for the generation of dynamic addresses and these addresses are used by the sensor nodes to send the information toward the sink. The sensor nodes greedily forward the data packet towards the upper level. In this scheme, there are two types of addresses for a sensor node, i.e., NodeID and HopID. NodeID is the physical addresses of the node, while HopID is the hop count. The HopID of a node nearest to sink will have a value 1 and HopID value is incremented as the depth of nodes increases. HopID is assigned in the network setup phase and destination ID is set to zero for all nodes. The main drawback of this routing protocol is that hop count mechanism is not defined properly. Because of convergence behavior, the nodes nearer to sink are frequently used and become dead, creating a void region. The network performance is also degraded by the node mobility.

Directional Depth Based Routing (D-DBR)

D-DBR, proposed in [34], is a localization-free receiver based routing protocol. It is also an extension of DBR, where packet forwarding is done using diagonal distance approach. The network topology consists of a single sink and periodic control messages are not exchanged in this routing protocol. The data is forwarded through the optimal path towards the sink. The algorithm uses the Time-of-Arrival (ToA) ranging techniques in data forwarding mechanism whereas holding time function with angle holding time is used for route directives. The main drawback of this protocol is that it does not describe the detailed method of how to recover from the void region which results in degradation of throughput. There is no method defined how high delivery data ratio is achieved in a sparse network.

2.3.3 Cooperative Routing (CR) Protocols

This Section give the brief overview of the CR protocols that have been proposed for UWSN. CR protocols exploit multicast mode to transmit a packet to a certain group of nodes, which can create a virtual antenna array by cooperation among multiple sensor nodes. Multiple-input and multiple-output (MIMO) antennas are not required by a node as it takes advantage of the neighbor antenna. It is widely known that multiple antennas can increase the reliability of UWSNs by building virtual multiple-input-multiple-output (MIMO) links. However, it is difficult to employ the co-located (or real) multiple antennas in UWSN sensors, because of inherent hardware limitations of sensor nodes such as physical size, energy, transmit power, and computational complexity. CR also ensures that the packet is delivered reliably from the bottom to the surface sink. CR is gaining considerable interest in the development of energy-efficient and reliable routing protocols by taking advantage of the wireless channel broadcast nature.

Cooperative Energy-Efficient Protocol for Underwater WSNs (Co-UWSN)

In Co-UWSN protocol, introduced in [35], has three phases: initialization phase, cooperation phase, and relay selection and routing phase. In the initialization phase, it performs three tasks: i) all possible routes toward the sink are evaluated, ii) location of sink is determined, and iii) the node identifies its neighbors. In the cooperation phase, i) the source node will forward its information towards destination and relay and ii) received information at relay node is transmitted towards the destination. The destination uses a Fixed Ratio Combining (FRC) mechanism to combine the two signals. In the relay selection and routing phase, relay nodes receive information from source nodes based on the instantaneous channel condition which depends on weight factor.

Cooperative Depth-based Routing (CoDBR)

CoDBR protocol, presented in [36], is an extension of DBR which consists of two phases: path setup and data transmission phase. In the path setup phase, two relays and next-hop destination are selected based on depth value by the source node in transmission range. If source node lies in sink's vicinity, then it will select sink as the destination node. In the data transmission phase, the data will be transmitted along the pre-established path. The packet, which is being broadcasted by source node will be heard by both relays and destination. Relays receive the packet, amplify, and forward the packet. The destination receives multiple copies of data packet, two from relays and one from the source node directly. Maximal Ratio Combining (MRC) technique is used on received data at destination. BER is calculated at the destination, and receive data is checked against the threshold, that is the maximum allowable error in data. The packet is accepted if BER is equal to or less than the threshold, otherwise, it is dropped.

Cooperative Partner Nodes Selection Criteria (PNS-DRE and PNS-DRE-SNR)

A. Umar et al. [37] proposed two different approaches to select partner nodes: Partner node selection based on depth and residual energy (PNS-DRE) and partner node selection based on depth, residual energy and SNR (PNS-DRE-SNR). Reliability and integrity of data is monitored based on cooperative techniques. Depth, RE and SNR routing parameters are considered and implemented on the Network layer. These propose approaches assume that nodes are perfectly synchronized with each other and the system model includes mobiles sinks. Depth threshold is defined to avoid flooding which is calculated at regular intervals based on alive nodes in neighbors.

Energy-Efficient Cooperative Opportunistic Routing (EECOR)

In [38], the authors proposed EECOR protocol, which enhances the PDR, increases lifetime and reduces end-to-end delay in packet forwarding by employing energy-efficient routing protocol. At the receiver, Received Signal Strength (RSS) can be utilized to measure the relative distance amid the two nodes. By using the wireless node's broadcast nature, the source node selects forwarding relay set based on depth and link quality information. They assume a single sink node, but via increasing the number of sinks, reception of the packets can be enhanced. The sink broadcasts a beacon towards source nodes that embed the depth and RE. The source node determines the forwarding relay set and after that fuzzy logic is applied to select the best relay.

Cooperative Energy-Efficient Optimal Relay Selection Protocol (Co-EEORS)

Co-EEORS, which was presented in [39], is described using four phases: network description, network initialization, destination selection, relay nodes and cooperative routing. In the network description phase, the network topology is described alongside which media is used for communication between different sensor node, sink and sensor nodes, and sink and onshore data center.The destination also acknowledges the source node as to whether the data packet is successfully received or retransmission is required. Furthermore, end-to-end delay increases due to the involvement of relay node processing, cooperation, and ACK of the status of the received packet by source node.

Chapter 3

Underwater Acoustic Channel

The chapter is organized as follows. In Section 3.1, we present the Underwater Acoustic Channel parameters that critically effect the delivery of packet having low bit error rate. Section **??** problem formulation is addressed, Section 3.3 delivers objective of design the cooperative based routing protocol, Section 3.3 focuses on proposed approach. Finally, Section 4.2 presents the results and their discussions.

3.1 Channel Model

3.1.1 Path Loss Model

For the communication of sensor node with their neighbour node either it is sensor node or sink, this path-loss model is considered. Path loss of acoustic signal in acoustic underwater channel, which occurs due to spreading and absorption losses. It is the function of signal frequency and distance, which is given by

$$A(l,f) = l^k a(f)^l,$$

where l is the distance between transmitter and receiver in km, $a(f)$ is the absorption coefficient, f is the acoustic signal operational frequency in kHz, and k is a spreading factor. To be specific, k = 1 for cylindrical spreading, k = 1.5 for practical spreading and k=2 for spherical spreading. As a result, the path loss in dB is determined by

$$10 \log A(l,f) = 10k \cdot \log l + 10l \cdot \log a(f).$$

The Thorp's formula is employed to represent the absorption coefficient as shown in Fig. 3.1, where $a(f)$ for f in kHz is in dB/km [1] and is given as

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

Generally (3.1.1) is true for frequencies greater than several hundred Hz. The absorption coefficient for lower frequencies follows the following formula

$$10 \log a(f) = 0.002 + 0.11 \frac{f^2}{1+f^2} + 0.011 f^2. \tag{3.1}$$

The main sources of noise include the current of water, turbulence, thermal noise, waves created by wind on the water surface, shipping activities, rainfall, sound waves from marine animals, and seismic events. These kinds of noise must

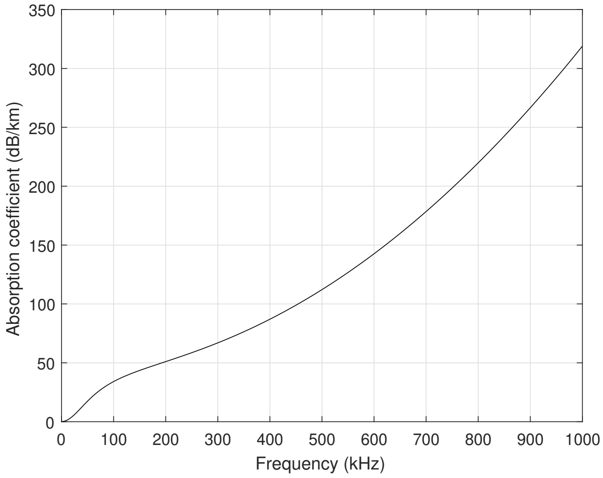

Figure 3.1: Absorption coefficient, $10\log(a(f))$ in dB/km [1].

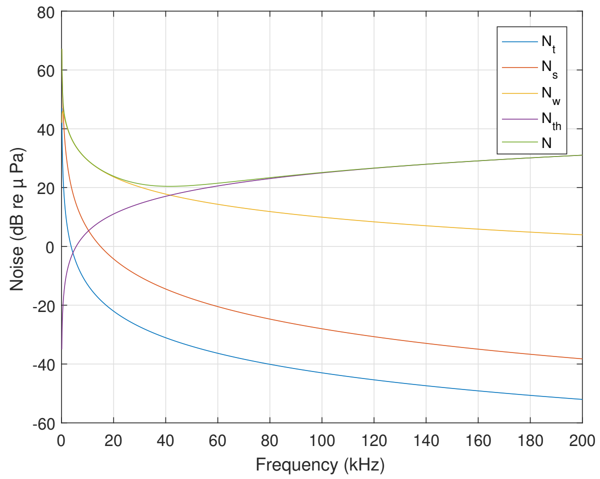

Figure 3.2: Ambient noise categories in underwater environment.

be considered when designing routing protocol because noise is higher in UWSNs than in TWSNs. Ambient noise is modeled by four constituent noise sources that include turbulence noise (N_t), shipping activity noise (N_s), waves noise (N_w), and thermal noise (N_{th}). The power spectral density of the four constituent noises is given by

$$10\log N_t(f) = 17 - 30\log f, \tag{3.2}$$

$$10\log N_s(f) = 40 + 20(S - 0.5) + 26\log f - 60\log(f + 0.03), \tag{3.3}$$

$$10\log N_w(f) = 50 + 7.5\sqrt{w} + 20\log f - 40\log(f + 0.4), \tag{3.4}$$

$$10\log N_{th}(f) = -15 + 20\log f, \tag{3.5}$$

where S in (3.3) represents shipping activity factor that ranges between 0 and 1, and w is the wind speed in m/s.

Fig. 3.2 shows how the four different noises change as the frequency varies. In different portions of the frequency spectrum, the most dominant one among the four types of the constituent noise sources is varying. For example, N_t influences very low frequency region where 1Hz $< f <$ 10 Hz. N_s is dominant between 300 Hz $< f <$ 100 kHz, whereas N_w plays a major role from 100Hz to 100 kHz. Lastly, N_{th} effect starts from frequency above 100 kHz [1]. It can be seen that N_{th} increases with the increase in operating frequency. Consequently, the power spectral density of the total ambient noise in the acoustic underwater channel is the sum of the four power spectral density functions in (3.2), (3.3), (3.4), and (3.5) as

$$N(f) = N_s(f) + N_t(f) + N_w(f) + N_{th}(f). \tag{3.6}$$

3.2 System Model

Consider an underwater environment as shown in Fig. 3.3 where the Sinks are shown in black blocks and the sensor nodes are show in circle. We simulated the

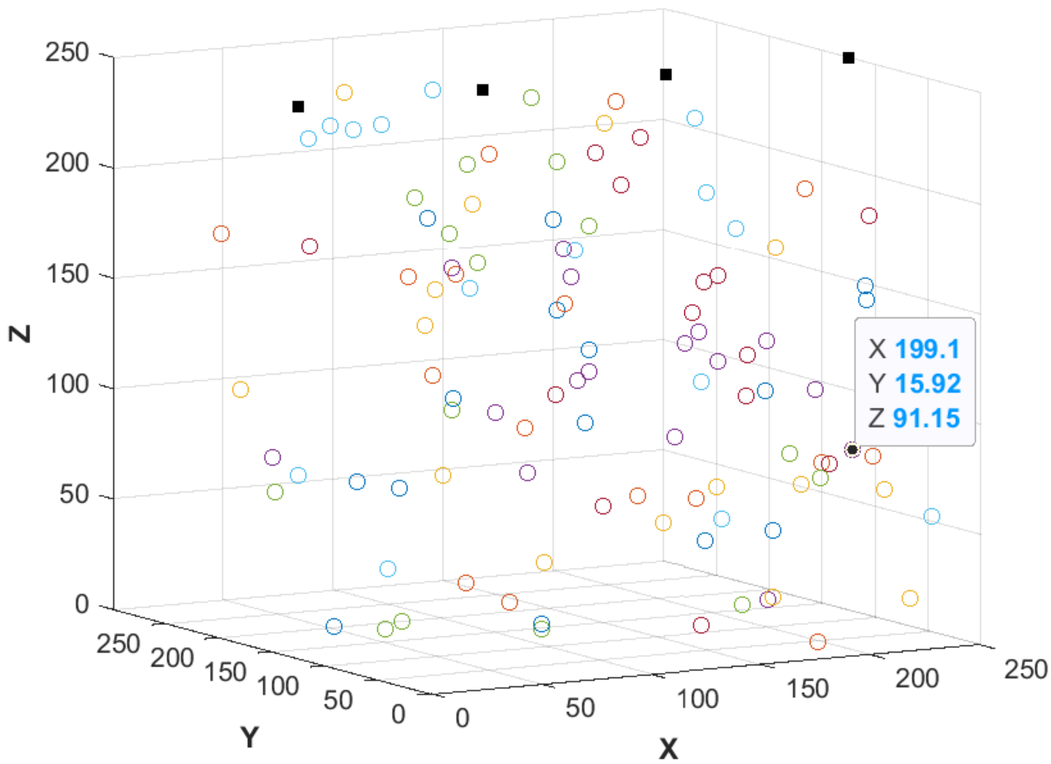

Figure 3.3: Pictorial View of Nodes Deployment Model.

designed three dimensional environment where Sensor nodes have same energy and transmission range. The model consists of source, destination and maximum of two relays. It is assumed that each link has AWGN and rayleigh fading. Sensor node modulates the signal using BPSK modulation and cooperative diversity amplify and forward (AF) technique is used by relay nodes. On the destination maximum of three signal are received. The mathematical representation of the signal received at destination ad relays is represented as;

$$y_{sd}(t) = x(t)(\sqrt{P})h_{sd} + n_i(t) \tag{3.7}$$

$$y_{sr_i}(t) = x(t)(\sqrt{P})h_{sr_i} + n_j(t) \tag{3.8}$$

$$y_{r_id}(t) = x_s(t)(\sqrt{P})h_{r_id} + n_k(t) \tag{3.9}$$

$$x_s(t) = Gy_{sr_i}(t) \tag{3.10}$$

$$y_d = y_{r_id} + y_{sd} \tag{3.11}$$

The signal transmitted by the node is $x(t)$ with power P. Channel coefficient is represented by h whereas n is the channel noise. MRC at the destination will be performed which is given in equation 3.11. i value of the number of relay nodes that will participate in cooperative transmission and the maximum value is two.

3.3 Objective

The main objective is to decrease end-to-end delay while considering the packet delivery ratio and reliability. The data packet must be broadcasted by the source node to the selected relay. Due to the underwater wireless channel broadcast nature, relay nodes overhear the packets that are in the source node transmission range. When the packet is received on selected relay having high residual energy and lower depth value, it will be forwarded to the next-hop destination. The Residual energy and BER are the two important parameters that were addressed. Efforts were made to increase the network lifetime while considering E2ED. We compared the different parameters of our protocol in Section 4.3. The following section 3.4 explain the proposed approach we consider to achieve our objectives.

3.4 Proposed Approach

The Flow chart of the proposed approach is given in Figure. 3.4. Section 3.2 discusses the system model parameters that have been used for the deployment of sensor nodes and the sink nodes. In the initialization phase, Hello packets are exchanged that will contain the depth and residual energy of the node which is broadcasting the Hello packet. Every node will be built the neighbour table based on the information that is received via Hello packets. Three dimensions are taken into account while calculating the distance between two nodes. If the distance is greater than the transmission range or the depth value is higher than the node that is receiving the packet then entry of that nodes will not make it into the neighbour table. If the network is sparse and there is no entry in the neighbour table the broadcast packet will be discarded due to this void region. In order to mitigate the effect of the void region, the Broadcast Initiator (BI) is chosen randomly from nodes having high depth values. BI will look into its neighbour table and if nodes entries in the neighbour table are greater then always two relays will be chosen, else if there are two nodes one will be chosen as this hop destination node. When the entries in the neighbour table are greater than one, MRC will be used to combine the signal else if there is only one node it will be used as the destination node. In algorithm section 4.2 we will explain which parameters are used to decide whether the destination node will become the next hop BI and the number of relays that are chosen for achieving high PDR.

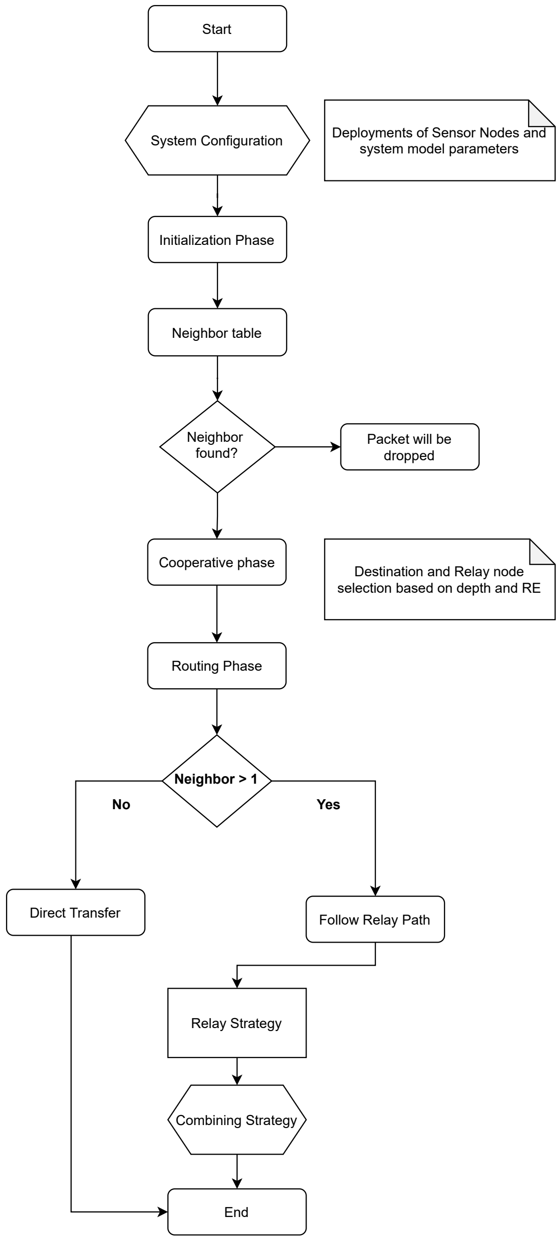

Figure 3.4: Flow Chart of our proposed approach.

Chapter 4

PRUCR in UWSNs

The term cooperate originates from Latin words *co* and *operari* which means working together. The primary objective of the cooperation is that entities collaborate by sharing their resources to attain a mutual goal. Cooperative diversity is a spatial diversity technique that uses the resources of other sensor nodes benefiting from the broadcast nature of wireless channel [40]. Traditional multi-hopping techniques in UWSN transfer the packet through multiple hops between source and sink. However, the CR takes benefit of the underwater wireless channel broadcast nature to transmit the packet through relay nodes in each hop.

Van der Meulen first proposed a CR concept in [41], in which CR is defined as a routing algorithm that benefits from cooperative transmission at the physical layer. Energy constraint nodes having single antenna exploit the resources of neighboring nodes in cooperative transmission to achieve high link reliability, throughput, energy efficiency and network performance. In cooperative transmission, besides the direct link between transmitter node and receiver node, one or more relay nodes will transmit the signal to the receiver node, as shown in Fig.

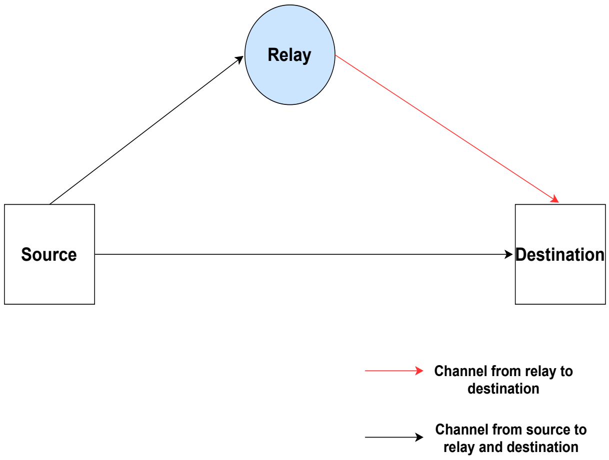

Figure 4.1: The mechanism of cooperative transmission

4.1.

CR is a cross-layer design approach to mitigate adverse channel effect which combines the physical layer with the network layer for packet transmission through a cooperative link. On every hop along the route path, multiple relay nodes in transmission range coordinate together for packet transmission towards the destination. In each hop, the destination node selects or combines the best of direct or relayed signals to generate a better signal. During the last decade, researchers are working on the cross-layer design of the routing protocol. Relay nodes that participate in cooperation exploit the underwater wireless channel broadcast nature by helping transmitter-receiver with information transmission. Relay nodes selection plays a crucial role in CR performance. Intuitively, using more relay nodes will result in higher performance and increased diversity gain, but more resources will be wasted along with increased interference at the receiver. The field of interference is proportional to the number of relay nodes engaged in cooperative transmission. Thus, optimal relay nodes selection plays a significant role in network throughput. As UWSN is an ad-hoc network without a central controller, hence overhead on the node for coordination will increase, thereby, network energy efficiency is degraded.

4.1 Cooperative Routing Protocol Design

The prominent feature in the research field of UWSNs is the routing protocol design, which provides a reliable and effective data delivery between the source node and destination node. UWSNs differ from traditional wired and TWSNs. It is difficult and in some cases impossible to implement the ideas developed for TWSNs straight to UWSNs. TWSNs use radio waves for communication, which are not a very appropriate choice due to their impairments that limit remote transmissions for the vast underwater areas monitoring. In underwater applications, wired connection using optical fibre link between sensors and surface sink could be used for real-time underwater communication. In many instances, however, their operating costs and safety become complex. Because of the above-mentioned parameters, acoustic waves are considered a preferable choice for underwater communication beyond tens of meters. Sensor nodes in general are energy constraint and are deployed randomly without proper planning. Moreover, interoperability between the standards is not required because the network is deployed by a single organization using one standard. The network's main purpose is to perform a single task at a time. Routing becomes unreliable because of the movement of nodes by water currents and transmission error probability increases due to severe underwater conditions. The routing protocols must rebuild promptly for reliable delivery in scenarios where routing fails meanwhile data communication.

4.2 Proposed Algorithm

Algorithm 4.1 Packet Reliability Using Cooperative Routing (PRUCR) Protocol Algorithm!!!!

```
Input: n
Output: A
// n number of nodes deployed in 3D environment
// Sensor node having higher depth value choosen as Broadcast Initiater
   (BI)
Initialize: Packet.Sent = 0
Initialize: P.Rx.Sink = 0
for = 1 to x do
    // BI will send x number of packets
    if BI Energy > 0 then
        Packet.Sent=Packet.Sent + 1
    end
    while Packet not reached at sink=true || All nodes dead =true do
        if BI Energy > 0 then
            BI.RE = BI.RE + ETX  ETotal = ETotal + ETX  for 1 to k do
                // where k is number of neighbours
                Nn_R E = Nn.RE − ERX
                 ETotal = ETotal + ERX
            end
        end
        if BI in transmission range of Sink then
            P.RX.Sink = P.RX.Sink + 1; // Packet Received at Sink
            Total.P.RX.Sink ++1 // Total Packets at Sink
            else if BI.RE>0  Neigh.table.empty then
                // Two nodes at max will act as relay nodes
                // Maximal Ratio Combining (MRC) is used to combine relay
                   nodes
                // BER will be calculated by comparing the original signal
                   with the received signal after MRC
            end
        end
        if BER < 0.5 then
            BI will be next hop destination  else
                Packet.drop=Packet.drop+1
            end
        end
    end
end
```

The 3D environment of 100x100x100 m^3 and 300x300x300 m^3 for the deployment of sensor nodes has been simulated. The proposed algorithm shown as Algorithm 4.1 above was used to increase the packet reliability. The algorithm explains that every node will send the Hello packets that are used to calculate the neighbour table. The nodes in the neighbour table will determine how many relay nodes will participate in the transmission of the packet. In this environment, BI will be selected from the nodes having a depth greater than 100 and 200 meters for the above mentioned deployment. BI will forward the packet to nodes having less depth value by using the neighbour table. The BI will check its neighbour table to determine the destination node and relay nodes in its transmission range. BPSK modulation is used to transfer the data. BI will broadcast the packet and all the nodes in the neighbour table will listen to the packet. BI will select the destination node and a maximum of two relay nodes using the depth value of nodes in the neighbour table. In PRUCR-1R as the name suggest one relay at maximum will be chosen while in PRUCR-2R two relays at maximum will be chosen. The algorithm (4.1) explain PRUCR-2R. The destination node calculates the BER, if the value is less than 0.5 the destination node will become the next hop BI otherwise, the packet gets dropped. The node having the lowest depth value in the neighbour table will always be selected as the next hop BI. The destination node will receive the signal from BI and relay nodes. The Maximal Ratio Combining (MRC) technique is used for combining the signal at the destination node.

4.3 Simulation Results

Section 4.3 explain briefly explains the PRUCR-2R protocol multiple parameters results that we obtain during the simulation and their comparison with DBR, PRUCR-1R and PRUCR-2R. Furthermore, the number of sensor nodes are increased by the factor of 50 from 50 nodes to the 200 nodes that are deployed in the 3D environment of 300x300x300 m^3.

Fig. 4.2 depicts that while increasing the number of nodes PDR of the all three compared protocols increases. PRUCR-1R is using one relay while PRUCR-2R is two relays. We can see that, for the greater number of nodes, DBR, PRUCR-1R and PRUCR-2R packet delivery ratio is following a trend. The peaks of PDR for the 200 nodes deployment is greater than 50, 100 and 150. The peak of PDR for DBR, PRUCR-1R and PRUCR-2R are 0.194, 0.209 and 0.74 respectively. for the lower number of nodes, I.e. 50, 60 and 70 is around 0.5. It can be seen that with increasing the number of nodes the PRUCR-2R PDR increases almost 70 % due to the use of a cooperative routing scheme. Our proposed method has the highest packet delivery ratio as compared to other protocols.

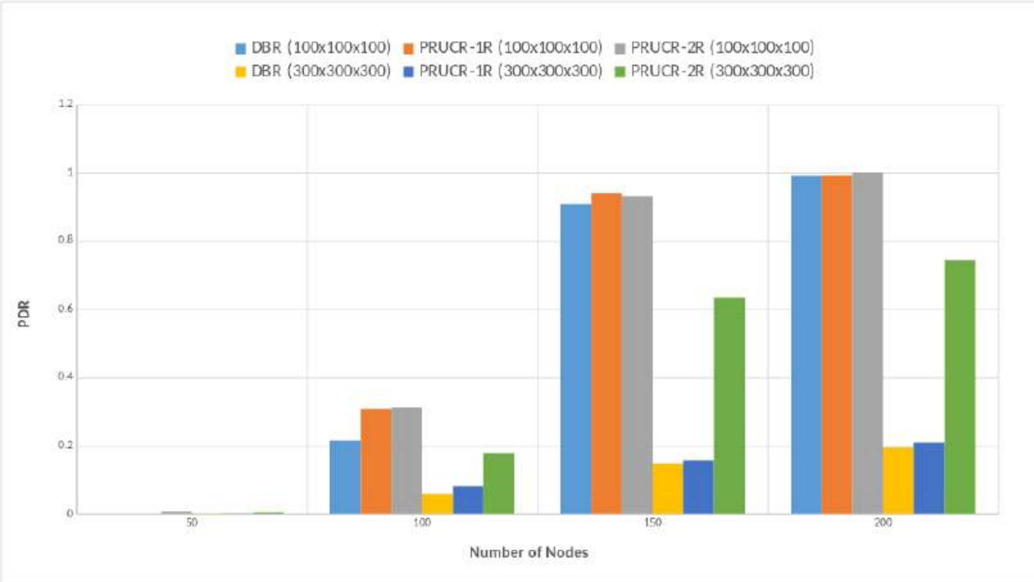

Figure 4.2: Nodes effect on PDR.

The pattern in Fig. 4.3 shows the energy consumption increase with the increase in the number of nodes hence system becomes more energy-intensive. The result shows that the energy consumption of our proposed method is relatively higher than the other methods because we in our proposed approach restricted the number of retransmission. The source node chooses the destination nodes and the relay nodes having the lowest depth in their neighbour table. As discussed earlier Hello packets are used to calculate the neighbour table where the depth threshold parameter is used which is approximately half of the transmission band. PRUCR-2R maximum energy consumption is 35.6 Joule which is almost 15 times higher than other protocols.

Figure 4.3: Comparison of RE.

Fig. 4.4 shows the effect of BER while the number of nodes is increased. The result shows that when we increase the number of the node the retransmission by the relay nodes in almost every hop will be two hence 3 packets will be received on destination node one directly and two from relay nodes. MRC will be performed at the destination node. PRUCR-2R BER is equal to 0.37 which is much lower than PRUCR-1R and the DBR when we increase the number of nodes is increased. The average BER for our proposed algorithm is minimum as compared to DBR due to cooperative communication which decreases the overall BER. Using this approach we can reduce the number of retransmissions. When we use 50 nodes BER for all the three compared protocol is approximately equalled to 0.6 because the density of the nodes is low for transmitting the packets. As discussed above PDR for 50 nodes is almost zero due to BER which is higher than 0.5.

Comparing the Fig. 4.4 and 4.4 we can conclude that while increasing the number of nodes relay nodes increase which results in high PDR and low BER.

Figure 4.4: Comparison of BER.

Delivery efficiency has been calculated by dividing the packet received at the sink with the total energy consumption of the system. Fig. 4.5 shows that for low density deployment of 50 nodes, packet delivery ratio as discussed in the above Fig 4.2 for DBR, PRUCR-1R and PRUCR-2R is zero hence Delivery efficiency is also zero. In PRUCR-2R for 200 nodes Packet reception is higher while energy consumption is only 15% higher which has a lower impact. The maximum amount of delivery efficiency is 20.86 is achieved using PRUCR-2R which is higher than DBR and PRUCR-1R.

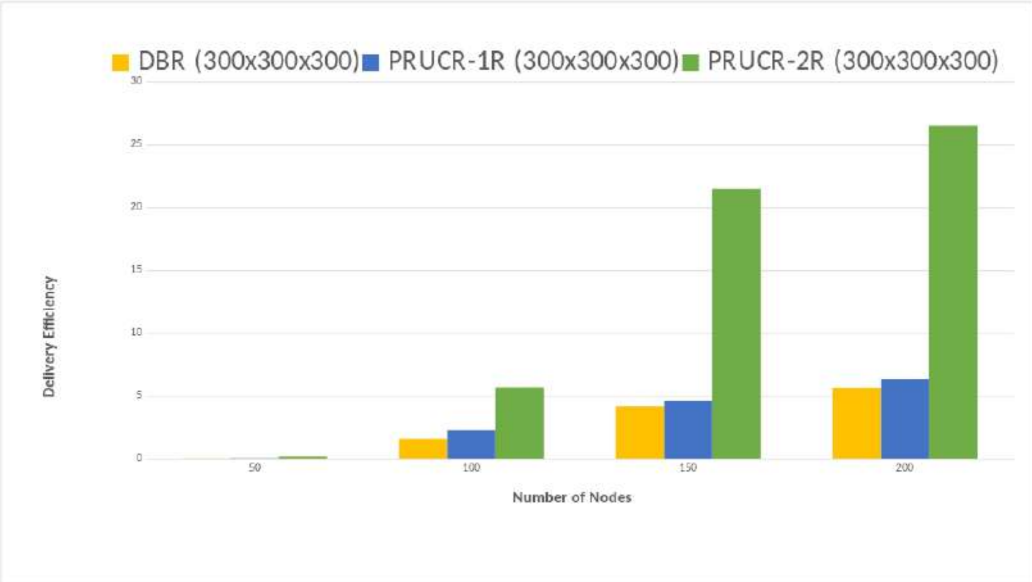

Figure 4.5: Comparison of Delivery efficiency.

Chapter 5

Conclusion

We propose PRUCR-2R and PRUCR-1R which perform better under scenarios where the movement of sensor nodes are considered and to avoid convergent behaviour Sink nodes are placed at the same offset. Cooperative routing shows convergent behaviour due to which congestion can happen on nodes near the Sink due to this packet loss retransmissions are required which consume a lot of energy which will cause energy loss and leads to high end to end delay. To encounter this congestion problem we add four sinks in our topology. Data received on one of the sinks will then communicate using radio wave to the onshore sink. This thesis compared four different parameters of DBR, PRUCR-1R and PRUCR-2R. The article addressed PRUCR-2R design and the result comparison of DBR PRUCR-1R and PRUCR-2R. The cons of this design approach are high E2ED, however, we cater for this issue by restricting the retransmission by only two relay nodes using a cooperative scheme.

The protocol discussed in this thesis aim to have a high network lifetime while improving total energy consumption, PDR, BER, Delivery Efficiency however, fairness, quality-of-service (QoS) and security are not discussed in detail and left as future work. There is a lack of standardization for these UWSN protocols because proprietary schemes are developed by manufacturers without following the standard protocols. Standardization of each layer and cross-layer protocols is therefore required. Moreover, it has been observed that there is no benchmark for measuring routing protocol efficiency, and, therefore, developing a benchmark is critical for accurate performance analysis. In particular, we focus on how many cooperative nodes we must select for the best delivery of data w.r.t Network lifetime and energy. Specifically, the result shows that by increasing the cooperative nodes PDR, throughput, and Energy consumption increases and less outage is achieved.

PRUCR-2R achieve the best delivery efficiency because has a high PDR with less energy consumption. The Cooperative routing technique used in the PRUCR-2R help us achieved the lowest BER than PRUCR-1R due to double the number of relays the cooperate. The first thing this paper addressed is to avoid the void hole region in a sparse network. Secondly, how we achieve a high delivery efficiency with a high PDR ratio and low consumption of energy by mean of co-operative routing. We can increase transmission range to avoid hole problem and also we can avoid many transmissions due to an increase in depth threshold and suppression of intermediate sensor node transmission. Due to suppression of intermediate sensor node transmission, delivery efficiency is increased.

5.1 Lessons Learned

Realistic models for node mobility and the development of channel model for simulations are fundamental problems due to unpredictable underwater environment. The sensor node battery power is limited and the harsh underwater environment makes the recharging of nodes difficult. Interoperability between the sensor nodes is not required because the equipment is mostly made by a single organization. The relation between throughput and energy is essential to understand energy consumption. Most of the routing protocols consider only one of these two metrics and consider the trade-off between them. In such protocols, the key objective is to decrease the total energy consumption by designing an energy-efficient routing protocol. Cooperative communication is an emerging technique used in UWSN to exploit diversity gain because, in UWSN, the co-located antenna array is hardly feasible in a small sensor node because of its limited hardware and capabilities. The development of new routing protocols by using limited resources is possible by understanding the harsh underwater characteristics. The high latency and signal fading constraints must be considered while designing the protocols. UWSN devices are expensive as waterproofing of hardware is required. Therefore, there is a need for making inexpensive UWSN devices for the experiment on the fields and the realization of network performance analysis. Simulation studies are not enough to evaluate routing protocol efficiency. Testbed and field experiments are needed to cross-check the performance parameter of protocols and the cost of the network. The concrete rules and protocols must be defined to preserve aquatic life in the deployment and operation of UWSN.

5.2 Future Work

The future research challenges include self-configuration of the network when the link is broken or node failure occurs. A reliable and efficient algorithm is required for obtaining the exact position of the nodes. Security is one of the critical issues that has been ignored, and it is necessary to address the security concerns. The UWSN should be secured in such a way that it should protect the information against eavesdropping. During the transmission of data, it is challenging to identify and avoid the void region. An algorithm for balancing energy in CR is required through which network lifetime can be increased. Because of high attenuation in water, more power is required for communication. Therefore, efforts must be made to develop power-efficient and cheap transmitter and receiver modems for underwater communication. The mechanism to generate energy with water current in the ocean can be developed for the sensor nodes. Different techniques must be considered for converting water current to electrical energy and how the sensor node can benefit from that energy. Propagation delay calculation is a serious issue alongside its model creation due to harsh conditions. The architecture of UWSN is three-dimensional, and the location information must be used in the testbed environment. Since location information is an important parameter for route discovery, location information acquisition is hard due to the complex and expensive algorithm. Using GPS is also not a feasible option due to electromagnetic RF waves high attenuation in the underwater environment. The reliable, energy-efficient approach for finding location information and surface sink placement also play a significant role in high PDR, which is an open research issue.

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