AN EFFICIENT MAC PROTOCOL FOR HANDLING TRIPLE HIDDEN TERMINAL PROBLEMS OF MULTICHANNEL UNDERWATER SENSOR NETWORKS

By

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Dedication

THIS THESIS IS DEDICATED

TO

MY PARENTS & MY HUSBAND

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List of Abbreviations

WSN	Wireless Sensor Network
UWSN	Underwater Sensor Network
MAC	Medium Access Control
RF	Radio Frequency
CUMAC	Cooperative Underwater Multichannel MAC
CAM	Channel Allocation Matrix
AUV	Autonomous Underwater Vehicle
UW-ASN	Underwater Acoustic Sensor Network
ISI	Inter Symbol Interference
EM	Electromagnetic Medium
GPS	Global Positioning System
FDMA	Frequency Division Multiple Access
TDMA	Time Division Multiple Access
CDMA	Code Division Multiple Access
UW-OFDMAC	Underwater Orthogonal Frequency Division Multiple Access
MACA-U	Multiple Access Collision Avoidance for Underwater
DOTS	Delay-aware Opportunistic Transmission Scheduling
COPE-MAC	Contention based Parallel rEservation MAC
CUMAC	Cooperative Underwater Multichannel MAC
UMMAC	Underwater Multichannel MAC
H-MAC	Hybrid MAC
P-MAC	Preamble-MAC
PDR	Packet Delivery Ratio
PLR	Packet Loss Ratio

List of symbols

R	Transmission range
v	Propagation speed of the acoustic signal
T	Maximum propagation time
E_{avg}	Average energy consumption per byte
$E_{consumption}$	Total energy consumption
$\in$	Belongs to
λ	Packet arrival rate
P_{Col}	Probability of Collision
$S_{SuccessRate}$	Number of packet successfully received by
	number of generated packets in total simulation time
x_i	Throughput of node i
n	Number of nodes
N	Number of packets
S_n	Time at which nth packet is sent
R_n	Time at which nth packet is received

Acknowledgment

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Abstract

As multi-channel communication is becoming more and more common in Radio Frequency (RF) arena, acoustic communication protocols have also started to adopt the same concept to utilize multiple channels in Underwater Sensor Networks (UWSN). Although the deployment of multi-channel increases throughput significantly, it also opens up the possibility of collision occurrence due to the hidden terminal problem. In particular, Triple Hidden Terminal (THT) problem, a phenomenon characterized by collision occurrence due to multi-hop, multi-channel communication with long propagation delay, persists more dominantly in UWSN. Existing MAC protocols try to mitigate the adverse effect of Triple THT without utilizing the information of propagation delay that may be exploited to improve the performance of UWSN significantly. Hence, this research work proposes a Cooperative Underwater Multi-Channel MAC protocol with delay mapping and channel allocation assessment. A new Channel Allocation Matrix (CAM) has been introduced for estimating propagation delay ensuring enhanced channel utilization. In this scheme, each node maintains a delay mapping database, based on which senders and receivers perform a scheduling algorithm before initiating any transmission. This mapping helps a node to predict whether it's upcoming packet transmission will collide with other nodes' transmission or not. In brief, the objective is to ensure successful transmission by mitigating problems in multichannel underwater sensor networks as well as to enhance the channel utilization with the benefit of delay mapping and channel allocation assessment. Simulation results, carried out for performance analysis, show that the proposed MAC protocol is more efficient in terms of network throughput, energy consumption, end to end delay, packet delivery ratio, packet loss ratio, collision probability and fairness index compared to the contemporary cooperative underwater multichannel MAC (CUMAC) protocol and RTS/CTS based multichannel MAC protocol.

Chapter 1

Introduction

1.1 Motivation

In recent times, there has been a great interest on the subject of Underwater Sensor Networks (UWSN) and multiple ocean applications of UWSN such as: oceanographic data collection, seismic waves monitoring, sea water pollution measurement, assessment of water quality, supporting unmanned underwater robotic missions and biological monitoring. Moreover, the extension of WSNs to the UWSNs have opened up new opportunities as these networks are supporting smart, reconfigurable and fault tolerant sensor nodes deployment. However, UWSNs are susceptible to various issues as water is the worst communication medium compared to the air. Therefore, UWSN communications are characterized by large propagation delays, limited link capacity, limited bandwidth, noise and high bit error rates. A range of studies have been conducted on MAC protocols in underwater network [1, 2]. Most of the studies focused on single-channel networks in underwater. As multi-channel communication is becoming more and more common in RF arena, acoustic communication protocols have started to adopt the same concepts to utilize multiple channels in underwater sensor networks.

Researchers came up with a Cooperative Underwater Multi-Channel MAC (CUMAC) protocol, focusing on Triple Hidden Terminal (THT) problems in underwater sensor networks [3–8]. THT problems include three kinds of hidden terminals in underwater sensor networks and these are: a) multi-hop hidden terminal problem which is the traditional hidden terminal problem in multi-hop networks; b) multi-channel hidden terminal which is a new kind of hidden terminal problem in multi-channel networks; c) long-delay hidden terminal - the long propagation delays of underwater acoustic channel introduce this kind of hidden terminal problem. As UWSNs involve multi-hop, multi-channel and long propagation delay therefore it will suffer from THT problems. An illustration of THT is given in Figure 1.1.

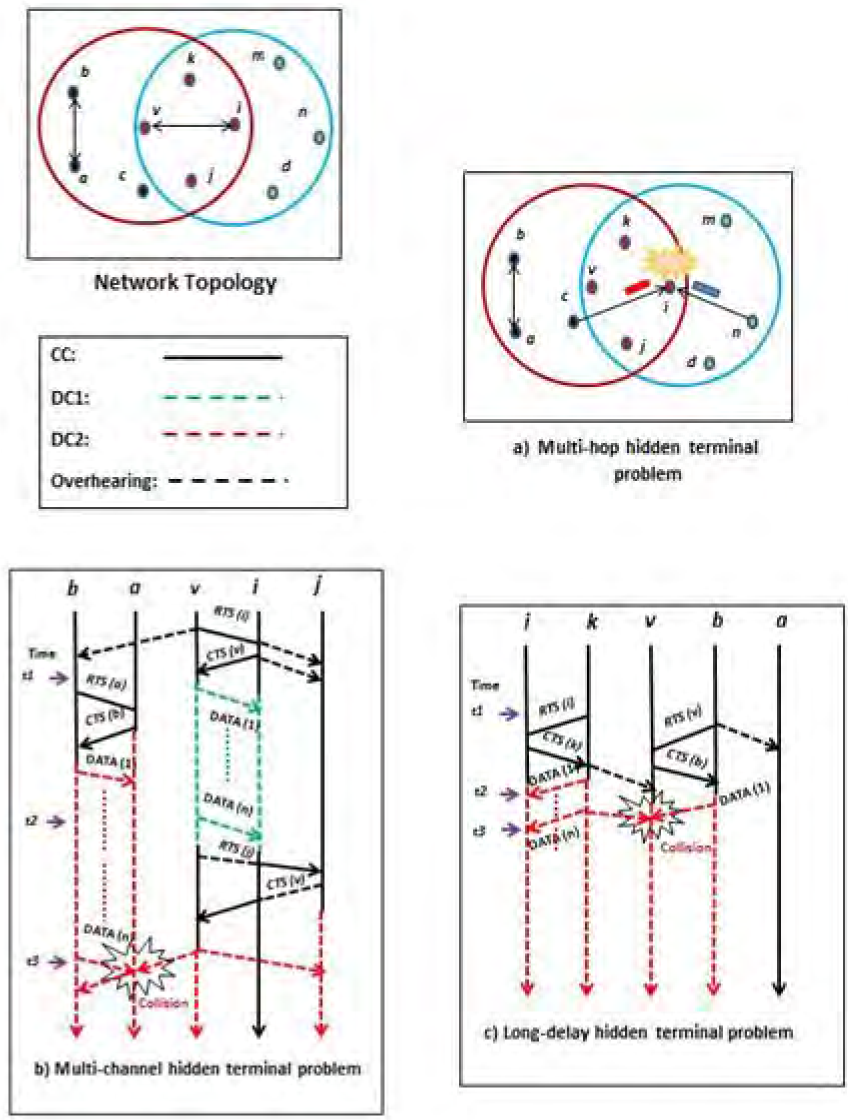

Figure 1.1: The Illustration of Triple Hidden Terminal (THT) problems

A sample network topology is presented here which involves number of sensor nodes (a, b, c, d, v, k, i, j, m, n), one control channel (CC) and two data channels (DCs). The effect of traditional multi-hop hidden terminal problem is depicted in the Figure 1.1(a). Then, from the Figure 1.1(b) it is observed that, when node v has a data for i then it puts the possible data channels and reservation information to RTS and send to i on the CC. After RTS/CTS handshaking, both nodes switch to the selected data channel (DC1) around the time t1 and carry out the data transmission.

During the period (t1, t2), *b* has a data for *a*. Next, both nodes (*b, a*) switch to another idle channel (DC2) after reservation. As *v* and *i* are not overhearing on CC over the period (t1, t2), *v* and *i* still assume that DC2 is idle. Around the time t3, one situation causes packet collisions at a or b. When *v* finishes sending data to *i* and *v* has data for *j*. Now, if *v* also selects DC2 channel, that node *a* and *b* are still occupying, then a collision happens and this collision causes due to the effect of multi-channel hidden terminal problem. Similarly, long-delay hidden terminal problem is depicted in Figure 1.1(c). As shown in the Figure, node *k* starts handshaking process with node *i* and then selects channel DC2 for communication. Later, node *b* and *v* also negotiate on the CC for their transmission. Let assume that, CTS message of node k arrives at node v after is selects its own data channel (DC2) and send CTS message back to *b*. In this case node *v* does not know that the same channel that is DC2 is already occupied by node *k* and thus create a collision. Therefore, this delay related hidden terminal problem is referred as "long-delay hidden terminal problem". CUMAC and previous studies on underwater network has paid attention on overcoming the challenges of the acoustic channel. However, very few works exploit the characteristics of large propagation delay as a means to increase throughput. This research work focus on the enhancement of earlier work on CUMAC with incorporation of propagation delay mapping and channel allocation assessment. A Channel Allocation Matrix (CAM) is introduced with an aim to enhance channel utilization. Moreover, propagation delay map database and CAM will be aligned to ensure successful transmission by mitigating triple hidden terminal problems in underwater sensor networks. In brief, the key concept of proposed scheme is the prediction of upcoming transmission, in such a way that facilitates data transmission with free of collisions.

1.2 Related Work

UWSNs are projected to be implemented in numerous applications such as, environmental monitoring, underwater explorations, disaster prevention, assisted navigations and tactical surveillance [9, 10]. Therefore, UWSN came up to researchers as an interesting research area for the last few years due to the fact of ocean exploration improvement and fulfillment of numbers of underwater applications. Unlike electromagnetic wave, underwater acoustic channels are characterized with long propagation delay, low data rate and limited bandwidth [11, 12]. Furthermore, in underwater acoustic communication, transmission is almost 100 times more expensive compared to reception in terms of energy consumption [1, 13]. Therefore, primary goal of designing a MAC protocol for UWSN focuses on minimizing number of collisions, even at the cost of high duty cycling of sensor nodes.To minimize the impact of long propagation delay and limited bandwidth, a Delay-aware Opportunistic Transmission Scheduling (DOTS) MAC protocol [14] is proposed for underwater sensor networks. DOTS exploits propagation delay and provides an efficient mechanism to support the concurrent transmission over a single channel with preventing the possibility of collisions. Multi-channel MAC protocols for UWSNs analyzed two generalized multi-channel MAC protocols: multi-channel access with ALOHA and multi-channel access with RTS/CTS on a dedicated control channel [15], similar to the protocol in [16]. Moreover, multichannel transmission in UWSNs also compensates the adverse effect of long propagation delay and low data rate. However, utilizing multichannel in underwater sensor networks, which suffers long propagation delay introduce hidden terminal problem more dominantly [17]. To mitigate the triple hidden terminal problems, CUMAC is proposed in [8] where collision detection scheme is employed with a simple tone device by utilizing the cooperation of neighbor nodes. Another multichannel MAC protocol, named as UMMAC, based on slot reservation is proposed in [18] where fixed length of slot duration makes it impossible to avoid collision. UMMAC combines channel reservation and negotiation to reduce the overhead of time and energy as well as utilize multiple channels to improve the network performance.

1.3 Objectives and Scope of the Thesis

The goal of this research work is to enhance network performance , to ensure successful transmission as well as to increase concurrent transmission while preventing the likelihood of collisions. The main objectives and scope of this research work are:

- To develop a propagation delay aware cooperative multi-channel MAC protocol in UWSNs.

- To mitigate triple hidden terminal problems of multichannel underwater sensor networks.
- To enhance channel utilization with the benefit of delay map.
- To devise an algorithm for transmission scheduling based on channel assessment, collision detection and delay mapping.

1.4 Outline of Methodology

The methodology consists of following stages:

- An efficient collision detection and channel selection process will be developed for multi-channel MAC protocol in long-delay underwater sensor networks.
- Channel allocation matrix and propagation delay map database will be maintained by each node to support the desired channel selection.
- An update mechanism of channel allocation will be introduced after completion of each on-going transmission to address the triple hidden terminal problems of multichannel long-delay underwater sensor networks.
- An algorithm will be devised for transmission scheduling based on channel assessment, collision detection and delay mapping.
- A simulation model of the new proposed protocol will be developed in Aqua-Sim, an extension of NS2 simulator for simulating UWSN protocols.
- Finally, the performance of the proposed protocol in terms of 'average network throughput', 'average energy consumption', 'end to end delay', 'packet delivery ratio', 'packet loss ratio', 'collision probability' and 'fairness index' will be investigated and compared with the existing state of the art protocols.

1.5 Organization of Thesis

The thesis consists of six chapters. The chapters are described as follows:

Chapter 1 introduces brief prospect of underwater sensor networks, the key motivation that drives to do research work in the area of underwater sensor networks.

Related research regarding underwater sensor networks, objectives and methodology also presented in this chapter.

Chapter 2 gives an overview of underwater sensor networks, practical issues, research challenges and communication architectures of underwater sensor network.

Chapter 3 reviews the tremendous amount of research work on design and implementation of underwater sensor networks, design challenges and classification of MAC protocol for underwater sensor networks.

Chapter 4 introduces the proposed protocol which focused on the enhancement of earlier research work on Cooperative Underwater Multichannel MAC protocol in underwater sensor networks. The details scheme of handling THT problems in underwater sensor networks also has been presented in this chapter.

Chapter 5 presents the performance analysis between the proposed scheme and existing protocols on which enhancement has been investigated. The performance is evaluated in terms of performance metrics such as, energy consumption, network throughput, end to end delay, packet delivery and loss ratio, collision probability and fairness index.

Chapter 6 concludes the thesis and also presents the recommendations for the future work.

1.6 Summary

This chapter introduces a brief discussion on underwater sensor networks and its range of application. Key motivation, research objectives and detail analysis of research works related to underwater sensor networks are explained here. Finally, the methodologies of the research also stated in this chapter. The aim is to get an overview of the proposed efficient mechanism to improve network performance and handle THT problems in underwater sensor networks.

Chapter 2

Underwater Sensor Networks: A Detail Overview

2.1 Introduction

Underwater Wireless Sensor Networks (UWSN) has drawn a great attention to the research group for the last few years. The reason behind is, UWSN can advance ocean exploration and meet the needs of number of underwater applications [1, 3, 4]. It has developed to explore and observe the ocean environment. UWSN comprises of various number of sensors and vehicles which are deployed to execute monitoring task in a collaborative manner within a given area. To meet this goal, sensors and vehicles self-organize in an autonomous network to embrace the characteristics of the ocean environment. Figure 2.1 depicts an overview of underwater acoustic sensor networks.

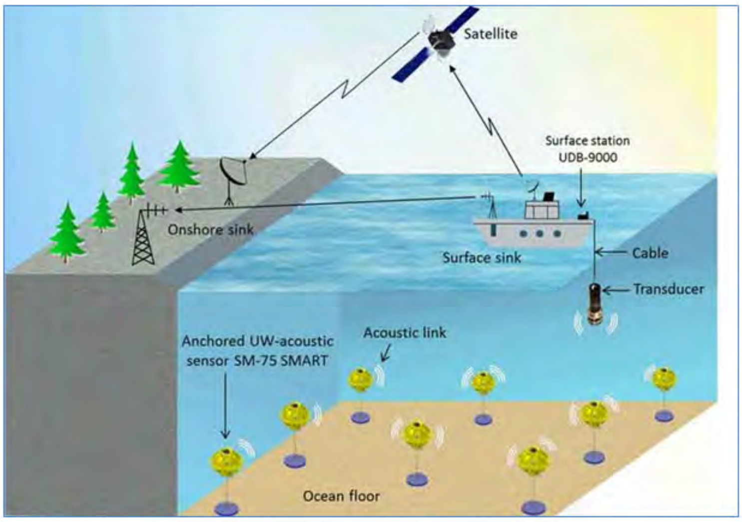

Figure 2.1: Underwater Acoustic Sensor Network Deployment [19]

2.1.1 Applications of Underwater Sensor Networks

Applications of underwater sensor networks are as follows [9]:

- **Environmental monitoring:** UW-ASNs can be implemented for pollution monitoring (chemical, biological and nuclear). For example, it may be promising to monitor streams, rivers, lakes and ocean bays by measuring chemical slurry of antibiotics, estrogen-type hormones and insecticides and water quality [12, 20]. Besides these, other possible applications are observing ocean currents and winds, improved weather forecast, perceiving climate change, predicting the effect of human activities on marine ecosystems, biological monitoring. To notice extreme temperature pitches, the design and construction of a simple underwater sensor network is described in [21], that are considered as a breeding ground for certain marine micro-organisms.

- **Ocean sampling networks:** Networks of sensors and AUVs accomplish the cooperative adaptive sampling of the 3D coastal ocean environment such as the Monterey Bay field experiment. It illustrates the benefits of bringing together new robotic vehicles with advanced ocean models. The objective is to improve the capacity of observation and prediction of the oceanic environment characteristics.

- **Undersea explorations:** Underwater sensor networks can help identifying underwater oilfields, determine routes for placing undersea cables, and assist in exploration for valuable minerals.

- **Disaster prevention:** Sensor networks provides tsunami warnings and analyze the effects of submarine earthquakes by exploring seismic activity from remote locations.

- **Assisted navigation:** Sensors in the networks help to identify as well as locate threats on the seabed and dangerous rocks in shallow water.

- **Distributed tactical surveillance:** AUVs and fixed underwater sensor networks are designed for monitoring areas for surveillance, reconnaissance and intrusion detection system in a collective fashion. A 3D underwater sensor networks are intended for tactical surveillance system, which can detect and categorize submarines, small delivery vehicles and divers based on the sensed data collected from acoustic sensors [22]. Underwater sensor networks can provide a higher accuracy in comparison of traditional systems.

- **Mine reconnaissance:** Several AUVs with acoustic and optical sensors can be implemented simultaneously to execute environmental assessment and discover mine-like objects.

2.1.2 Differences with Terrestrial Sensor Networks

The major differences between terrestrial and underwater sensor networks are [23]:

- **Cost:** Underwater sensor networks are expensive devices compared to terrestrial sensor nodes. As more complex underwater transceivers and hardware protection is required in the extreme underwater environment therefore the acoustic sensors for underwater sensor networks are costly. The low economy of scale because of limited number of suppliers leads to high cost underwater sensors.

- **Deployment:** The sensors in the terrestrial networks are densely deployed whereas the underwater sensors are sparsely deployed in the underwater environment.

- **Power:** The power required for underwater communication is higher than terrestrial communications. The reason is the higher distances and the different physical layer technology. Moreover, more complex signal processing techniques are implemented at the receivers to recompense the channel impairments in the underwater environment.

- **Memory:** The underwater sensor nodes have more storage capacity than terrestrial sensor nodes. The storage capacity of terrestrial sensor nodes is very limited. But underwater sensors require more storage capacity as sensors may need to do data caching due to characteristics of underwater environment.

- **Spatial Correlation:** The readings derive from terrestrial sensors are often related. In case of underwater networks this is more unlikely to happen because of the greater distance among the sensors in the underwater networks.

2.1.3 Characteristics of the Underwater Acoustic Environment

Characteristics of the Underwater Acoustic Environment can be outlined as follows [10]:

- **High and Variable Propagation Delay:** The propagation delay is five orders of scale higher than radio frequency terrestrial channels. The propagation speed of sound in underwater is around 1500m/s. As because the propagation delay in underwater extremely varies corresponding to temperature, salinity and depth of water. Propagation delay is a big challenge for underwater communications whereas propagation delay is negligible for short range RF. Therefore, there is a significant implication in designing of MAC protocols for underwater sensor networks.

- **Limited Bandwidth and Low Data Rate:** The bandwidth in underwater sensor networks depends on the distance. It suffers from high environmental noise at low medium frequencies. The available acoustic bandwidth can be lower than 1 kHz at low medium frequencies. At high frequencies, it can be greater than 50 kHz [3]. Few kHz bandwidth is available at 10 kms and around 10 kHz may be available at few kms. Generally, acoustic modems perform at the range of frequencies between few kHz to 10 kHz. Therefore, the data rate for underwater sensors can be maximum up to 100 kbps. RF radios offer several hundred MHz. On the other hand, a very limited bandwidth of acoustic channels needs to design carefully for coding schemes and MAC protocols used in underwater sensor networks.

- **Noise:** There are various types of noise present in underwater environment, such as man-made noise and ambient noise. The principal sources of man-made noise are machinery noise, motor vehicles and industrial sources. On the other hand, natural noises include seismic and biological phenomena causes ambient noise.

- **Energy Consumption:** The transmission power in underwater sensor is much higher than terrestrial devices as there is higher ratio of transmit to receive power. Therefore, the acoustic transceivers have transmission powers in the order of higher magnitude compared to terrestrial devices and it becomes an important factor at the time of designing MAC protocols in underwater sensor networks.

- **High Bit Error Rates:** Due to multi-path and fading, the underwater channel is adversely effected by impairments. As multi-path propagation degrades the acoustic communication signals and acoustic communication signals generate Inter Symbol Interference (ISI). Higher value of ISI leads to higher bit error rates and causes shadow zones and temporary connectivity losses.

2.2 The Underwater Wireless Sensor Networks

The internal architecture of an underwater sensor is shown in Figure 2.2. The acoustic sensor comprises of main controller, oceanographic device/ sensor over a sensor interface circuitry. The major task of controller is to receive data from the sensor then it stores the data in the on-board memory. After that, it starts data processing and send data to other devices in the network with the control of acoustic modem. Underwater sensors measure the quality of water as well as analyze the characteristics of underwater environment like chemicals, acidity, temperature, dissolved methane gas and turbidity [12].

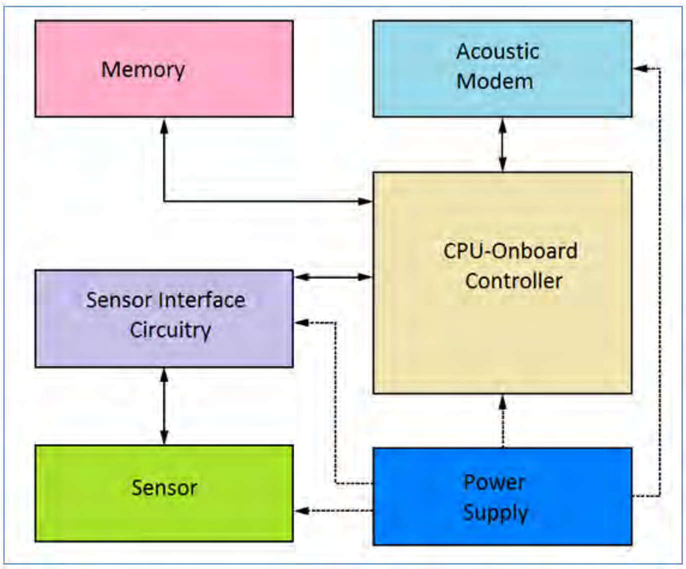

Figure 2.2: Internal Organization of an Underwater Sensor Node [12]

The sensor nodes in the underwater network deployed at the sea surface and in the underwater with a goal of performing a task collaboratively within a given area. In order to serve this purpose, the collected information should be exchanged and shared among the sensor nodes and sensor nodes to the base station. At the same time, sensor nodes should self-organize the features of the communication channel because of the nodes have to embrace to the need of current applications. The applications in the underwater sensor networks can be categorized into three types and these are: monitoring applications, tracking applications and finally actuating applications.

There are three types of transmission medium: Acoustic Communication, Radio Wave and Optical Communication [24]. The advantages and drawbacks of each medium should be emphasized before selecting one. The details of each medium are given below:

- **Acoustic Medium** The ideal physical layer technology in underwater networks is acoustic communication. Acoustic channels can propagate smoothly over conductive sea water in long distances at low frequencies. Many applications in underwater sensor networks use sonic transducers [25]. However, the speed of the sound in water depends on temperature, salinity and pressure.

- **Electromagnetic Medium** The main characteristic of the Electro Magnetic (EM) communication is the use of higher carrier frequencies. It drives to larger bandwidth at low range cost. In addition, electromagnetic waves are exempt to acoustic noise or other human activity [26]. However, the prediction is the submarine electromagnetic propagation will face very high attenuation because of the conductive sea water. Last of all, there will be high Electro Magnetic Interference (EMI) with the use of EM.

- **Light Medium** As light absorption increases and light intensity reduces exponentially related to the depth of water therefore, the exploitation of optical waves in underwater sensor networks are very limited [26]. Hence, due to the nature of light, the strong alignment among nodes is necessary and operation must be processed in clear water. With respect to EM waves, underwater communication through optical medium performs better in higher bandwidth but there is a limitation of turbidity. In general, it performs good in short ranges.

2.3 A Protocol Stack for Underwater Acoustic Sensor Networks

In this section, the design of a protocol stack for underwater acoustic sensor networks is briefly described. Therefore, details discussions are presented on physical, data link, network, transport and application layer issues in underwater sensor networks [11].

2.3.1 Physical Layer

The development of underwater modem was constructed on non-coherent frequency shift keying (FSK) modulations before the beginning of the last decade. Even though the high power efficiency is one of the features of non-coherent modulation schemes but low bandwidth efficiency makes this scheme incompatible for high data rate multiuser networks. Therefore, coherent modulation schemes have been advanced to support long range and high throughput systems. In the last few years, Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM), which are the types of fully coherent modulation scheme, become popular because of the robust digital processing [2]. The primary constraint in underwater channel is the time-variability which impacts the performance of contemporary receivers. Moreover, multi-path cause two problems and these are delay spread and phase shift of the signal envelope. Therefore, time varying multi-path and Doppler spread significantly effect the coherent communications. In consequence, high speed phase coherent communications become quite difficult for underwater sensor networks.

2.3.2 Data Link Layer

The objective of the development of multiple access technique is to allow devices to access a common medium by sharing available bandwidth in an efficient approach. Due to the characteristics of underwater channel, channel access control mechanism in underwater sensor networks experiences additional challenges such as limited bandwidth and high and variable delay. There are three main categories for multiple access techniques [10] i) contention free - for example: FDMA, TDMA and CDMA ii) contention based, based on random access (ALOHA, slotted-ALOHA/ carrier sense access CSMA) or on collision avoidance with handshaking access (DOTS, MACA-U, CUMAC) and iii) hybrid (combine the advantages of contention-free and contention-based MAC). A detail description of the existing MAC protocols is presented in the chapter 3.

2.3.3 Network Layer

The network layer determines, how the packets are delivered from source to destination within a network. As nature of the underwater environment is quite different so several numbers of limitations are identified for Underwater Acoustic Networks with respect to the compatibility of existing solutions in underwater environment. Existing routing protocols are usually divided into three categories, namely proactive, reactive and geographical routing protocols [27]:

- *Proactive Protocols*

  Proactive protocols maintain updated routing information to mitigate the message latency introduced by route discovery. The up-to-date routing information is acquired by broadcasting control packets which contain the routing information. Therefore, these protocols aggravate overhead for large signaling to set up routes at the network initialization period. Each time the network topology is updated for the reason of node mobility or failures and in this process each node becomes able to establish a route to other nodes in the network.

- *Reactive Protocols* A node process the route discovery operation when there is a need for route findings to a destination. As soon as the route has been setup, the process for route maintenance is maintained whenever the route discovery is required. Reactive protocol is more appropriate for dynamic environments. However, it suffers from higher latency and also need source originated control packets flooding to set up a route. As a result, reactive protocols are not suitable for underwater acoustic sensor networks due to higher latency. Moreover, it may also be amplified for the long delay of the acoustic signals in the underwater environment.

- *Geographical Routing Protocols* The mechanism of these protocols is to establish a route from source to destination by gathering localization information. The next hop is selected by a node based on the position of neighbor and destination node. Therefore, a routing scheme need to be developed to minimize the signal overhead and latency. Virtual circuit switching techniques could be considered as one of the geographical routing protocols for underwater acoustic sensor networks. In this technique, a route is established before each source and sink then each packet follows the same path. Additionally, routing schemes need to be developed for 3D underwater environment. As direction of currents and intensity depend on the depth of the sensor node therefore the effects of current should be taken into consideration. In this manner, underwater current modifies the relative position of sensor devices and causes the connectivity holes.

2.3.4 Transport Layer

In the sensor networks, reliable event is triggered based on the information, which has been collectively detected by number of nodes in the network. If there is a limitation of reliable transport mechanism then event detection may be impaired significantly due to the underwater challenges.

A transport layer is required to provide reliable transport for the event detection, to perform flow control and congestion control. The goal is to improve network efficiency. A reliable transport protocol ensures the accurate identification of events which has been collected and measured by the sensor nodes. Congestion control is required to prevent the network from the congestion of excessive data in terms of network capacity. On the other hand, flow control is required to avoid the devices in the network which are occupied by overflowing data transmissions.

2.3.5 Application Layer

An application layer specifies the protocols and interface methods that are implemented by hosts in a communications network. The purpose of an application layer is:

(i) To provide a network management protocol that facilitates hardware and

software details of the lower layers transparent to management applications.
(ii) To provide a language to get information of the sensor network.
(iii) To allocate tasks as well as to promote any events and data.
Depth knowledge of the application areas and the communication challenges in underwater sensor networks is essential to structure some design principles. Therefore, outlining the design principle for underwater sensor is meant for defining the procedure to extend the existing application layer protocols available for terrestrial sensor networks. The recent developments may be analyzed and revised to offer an effective application layer for underwater sensor networks.

2.4 Communication Architecture

The architecture of UWSNs can be classified in the following three types [12]:

- *Static two-dimensional UW-ASNs* This architecture is suitable for the ocean bottom monitoring for the sensor nodes that are anchored to the lowermost of the ocean, as discussed in Section 2.4.1. The applications may be environmental monitoring as explained in[9].

- *Static three-dimensional UW-ASNs* It includes networks of sensors whose depth can be controlled by means of techniques as discussed in Section 2.4.2, and may be used for surveillance applications or monitoring of ocean phenomena.

- *Three-dimensional networks of autonomous underwater vehicles (AUVs)* This type of network includes fixed portions comprised of anchored sensors and mobile portions instituted by autonomous vehicles, as detailed in Section 2.4.3.

2.4.1 Static Two-dimensional underwater sensor networks

Figure 2.3 depicts the reference architecture of two-dimensional underwater sensor networks.

A set of sensor nodes are anchored at the bottom layer of the ocean. The surface station is composed of acoustic transceiver which can handle concurrent communications with the deployed underwater sinks. It is also possessed with satellite transmitter to communicate with the onshore sink and/or to a surface sink. Sensors can be connected to underwater sinks through direct links or through multi-hop

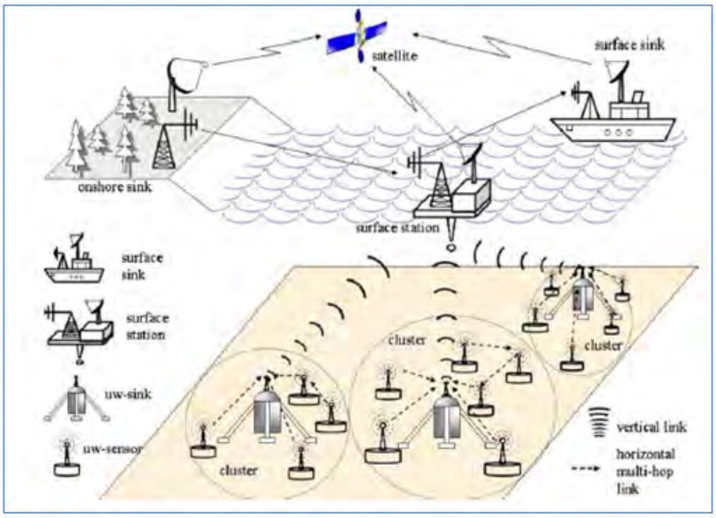

Figure 2.3: Architecture for 2D underwater sensor networks [12]

paths. In the prior case, the collected data by each sensor is sent directly to the underwater sink. However, the transmission power degrade with the distance and the sink in the underwater networks may be far from the sensor node.

Although, the direct link connection is the easiest way to the sensor network but it does not provide the energy efficient solution. Moreover, there is a probability of reduction of network throughput for the direct link communication. In case of multi-hop paths like terrestrial sensor networks, the data is transmitted by a source node is relayed by the intermediate nodes until it reaches to the destination node. Consequently, it saves energy and increase the network capacity. However, the complexity of routing functionality is increased. As a whole, every device in the network participate in a collaborative process to share the topology information so that each intermediate node can take efficient routing decisions which results to improve the network performance.

2.4.2 Static Three-dimensional underwater sensor networks

To perform cooperative data collection of the 3D underwater environment, three dimensional underwater networks are implemented which is quite difficult to observe by the ocean bottom sensor nodes. In case of three-dimensional underwater networks, sensor nodes move at different depths to observe and sense the ocean environment. The possible solution may be to attach each underwater sensor node to a surface buoy [22] but multiple moving buoys may hinder ships to navigate on the surface. In addition, floating buoys are affected to weather condition. As illustrated in Figure 2.4, each sensor is placed to the ocean bottom and equipped with a floating buoy. The buoy drives the sensor in the direction of ocean surface. In such architecture, the challenge is to address the effect of ocean currents for the adjustment of the depth of the sensors.

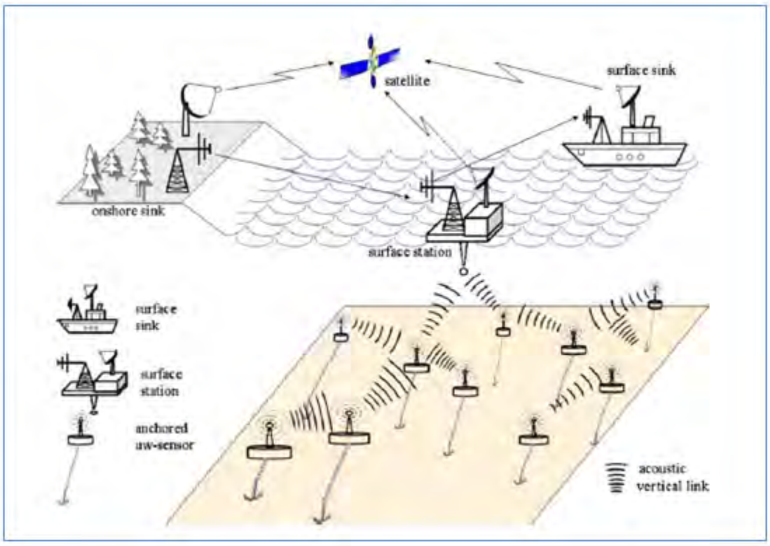

Figure 2.4: Architecture for 3D underwater sensor networks [12]

The major challenges which are required to solve to enable 3D monitoring include:

- *Sensing coverage:* With the purpose of achieving 3D coverage of the ocean environment as per sensing ranges, sensors should regulate their depth in a collaborative approach. Therefore, it would be possible to accomplish sampling of the expected phenomenon at all depth of the ocean environment.

- *Communication coverage:* In the 3D underwater networks, sensor nodes have to relay information to the surface station through multi-hop paths therefore depth of the devices should be synchronized very carefully. Therefore, the sensor nodes in the network topology are always connected.

  In [28], sensing and communication coverage in a 3D environment are rigorously investigated.

2.4.3 Three-dimensional networks of autonomous underwater vehicles (AUV)

AUV has numbers of applications in environmental monitoring, oceanography and research study in the area of underwater as these devices can perform without cables or remote control. Prior research work described on autonomous underwater vehicles submarines which is relatively inexpensive and can traverse to any depth in the ocean. Therefore, it can be implemented to increase the capabilities of underwater sensor networks in various ways. Furthermore, the research area could be extended to the integration and the enhancement of fixed sensor networks with AUV, which is yet to explore and requires some novel network algorithm for coordination. For example:

- *Adaptive sampling:* This focuses on control strategies to control the mobile devices to the desired places where from useful data could be collected for the event detection. This mechanism is also referred as adaptive sampling which has been offered to pioneer monitoring mission.
- *Self-configuration:* With an aim to automatically detect connectivity hole, this approach proposes control procedures and request for AUV intervention. Additionally, AUV can also be implemented for sensor network infrastructure installation and maintenance. It can also perform as a temporary relay node to reestablish connectivity.

Generally, control procedures for AUV is required for autonomous coordination, obstacle avoidance and navigation strategies. Different types of AUV exists for underwater experiments. Few AUVS are small-scale submarines and others are simpler devices. Simpler devices do not employ for sophisticated capabilities such as, drifters and gliders. Drifters and gliders are implemented for underwater explorations which is briefly explained in [29, 30].

2.5 Summary

This chapter gives an overview of underwater sensor networks. A broad range of applications of UWSNs as well as differences between UWSNs and terrestrial networks are also described here. In addition, the major discussion area focused on the challenges of underwater acoustic environment, internal architecture of underwater sensor, different types of transmission medium and communication architecture of UWSNs.

Chapter 3

Medium Access Control protocols for UWSNs

3.1 Introduction

There are numbers of research works on UWSNs design and Implementation [3,29,30] and these research works not only focused on MAC protocol but also analyze the various traits of UWSNs. For example network, transport, localization and synchronization protocols. Moreover, few surveys on UWSNs MAC protocols represent the variants of designs and implementations. Several early MAC protocols have been reviewed in [5,31]. These reviews concentrate on the medium access strategies and the issues inherited from physical layer. Hence, these issues should be taken into consideration at the time of designing protocol.

3.2 Challenges to the design of MAC protocols for UWSNs

The key challenges [10] in case of designing a MAC protocol and for the deployment of UWSN are explained as follows

- Network Topology and Deployment in UWSNs: The deployment of the underwater sensor nodes could affect the performance of the MAC protocols as the performance of the MAC protocols is dependent on the underwater nodes deployment. It could be sparse or dense. Event detection of sparsely deployed nodes is highly uncorrelated because of sensor nodes monitor and communicate at long distance as a result of the availability of long range acoustic modems.
- Hidden Node and Exposed Node Problem: In contention based collision avoidance MAC protocols, the hidden and exposed nodes problem generates significantly. Hidden node occurs in a situation where a node cannot sense other

nodes which may interfere with its transmission. On the other hand, expose node occurs when a node delays its transmission assuming that its transmission could collide with other nodes ongoing transmission. In consequence, collision will happen for the hidden node problems and the nodes have to keep making effort for a successful transmission.

- High Delay Associated in Handshaking: Hidden terminal and exposed terminal problem can be resolved with the contemporary handshaking schemes. But handshaking schemes require time and energy for sharing control information, which is time consuming. The propagation delay for exchanging control packets also becomes high due to the characteristics of underwater acoustic environment. Consequently, it causes a big challenge issue in case of designing efficient protocols.

- Power Wastage due to Collision: The power consumption of transmission is very high compared to reception and transmitting power is about 100 times more compared to receiving power [1]. In addition, this ratio may be significantly impacted for the frequent collision occurrence. Therefore, an appropriate collision avoidance mechanism is necessary as a requirement of efficient MAC protocol for providing a collision free transmission.

- Near-Far Effect: The near-far effect happens when a receiver experiences that a signal received from a nearer sender is stronger than the signals received from the farther sender. Thus, the transmission power should be carefully selected in such a way that the signals transmitted from the transmitter to the targeted receiver satisfy the desired SNR that is neither lower nor higher to the required SNR.

3.3 Classification of MAC protocols for UWSNs

The classification of MAC protocols for UWSNs is shown in the Figure 3.1 and explained in details in [10]. The contention-free MAC protocols are classified according to the different multiple access techniques, such as frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). Contention-based MAC protocols are categorized with random access

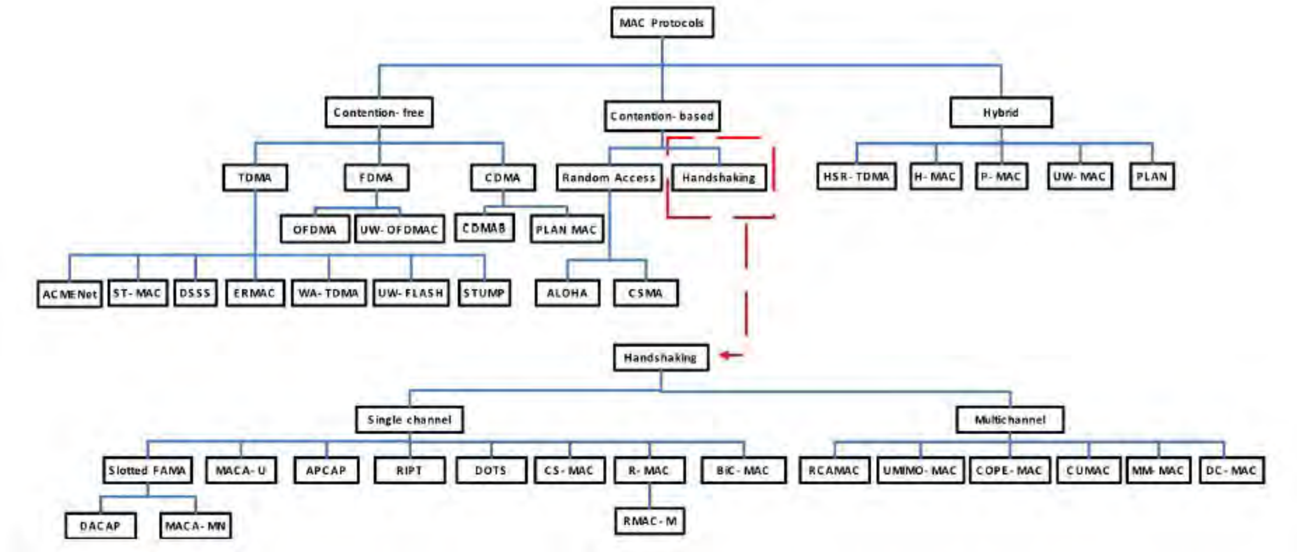

Figure 3.1: The Classification of MAC protocols for UWSNs [10]

and random MAC protocols and it has been focused on by investing most of the effort during the design of MAC protocols for underwater sensor networks. Last of all, hybrid MAC protocols are presented, which combine the benefits of the contention-free and contention-based MAC protocols.

3.3.1 Contention-Free MAC protocols

In the prior research studies, contention-free MAC protocols have been considered for UWSNs. In this section, variations of contention-free MAC protocols, perform based on the multiple access techniques, have been reviewed and explained as follows:

- Frequency Division Multiple Access (FDMA) :

  In FDMA scheme, the frequency band is divided into sub bands and each sub band is allocated to an individual user. The channel is occupied until it is released by the user. The most recent FDMA based MAC protocol in underwater sensor networks is the UW-OFDMAC [32], which is based on the OFDMA technique. However, FDMA multiple access technique is not appropriate for UWSNs because of the limited bandwidth of underwater acoustic channels and also for fading and multipath challenges issues.

- Time Division Multiple Access (TDMA):

  TDMA divides a time interval, called a frame, into time slots. Each time slot is allotted to an individual user. The guard time is added to avoid packet collisions from adjacent time slots. Hence, TDMA is considered as a better multiple access technique for UWSNs because of its simplicity and flexibility. The guard time is required to separate different channels as well as to mitigate the data transmission collision probability which happens for the large propagation delay and delay variance over the acoustic channels. Moreover, precise synchronization, a requirement of TDMA, becomes difficult due to delay variance.

Acoustic Communication network for Monitoring of Environment (ACMENet), a TDMA-based MAC protocol has been proposed in [33] for UWSNs, that employs the acoustic propagation delay to avoid collisions. In [34], a transmission scheduling for TDMA-based MAC protocol has been offered, that utilize the benefits of the long propagation delay of acoustic signals to facilitate concurrent transmissions and receptions. Then, PR-MAC (Priority Reservation MAC) is proposed in [35], which is energy efficient and minimize the conflicts and energy loss. In [36], a Spatial-Temporal MAC Scheduling protocol (ST-MAC) has been projected to overcome the spatial-temporal uncertainty in the TDMA-based MAC scheduling. In [37], a protocol, named as Dynamic Slot Scheduling Strategy (DSSS) MAC, has been presented which offers channel utilization and collision prevention by exploring strategies such as: grouping, ordering decision, scheduling, and shifting.To achieve higher energy efficiency, Efficiency Reservation MAC (ERMAC) protocol offers to make only one sensor node in the transmission mode and the other nodes in the sleep mode [38]. In this scheme sensor nodes are classified into groups and accordingly transmit their packets in a collision-free way. The staggered TDMA Underwater MAC Protocol (STUMP) [39] allow nodes to implement simple and more energy efficient scheme for synchronization. However, four possible conflicts and propagation delay made the scheduling to be constrained. Furthermore, based on the schedule constraints, a number of time slots may be scheduled for transmissions as proposed in SF-MAC [40] with an objective of collision prevention.

- Code Division Multiple Access (CDMA):

  In CDMA scheme, multiple users can operate concurrently over the entire frequency band. The signals are differentiate with the help of pseudo-noise

(PN) codes which are used for broadcasting the user message. The receiver can get the correct signal by filtering nose with spreading code. CDMA-B, a CDMA based MAC protocol has been proposed in [41], which offers a periodic sleeping mode and supports to save energy.

3.3.2 Contention-Based MAC protocols

The nodes contend for a shared channel with the contention based MAC protocol. The contention-based protocols can be categorized into random access based and handshaking protocols.

A. *Random Access Based :*

ALOHA and Carrier Sense Multiple Access (CSMA) are the two approaches of contention-based MAC protocols. In random access method, when a sender node has a data ready for delivery, it just starts its transmission. At the receiver end, a receiver can successfully receive the packet, if it is not receiving any other packets in that period. Moreover, without any control mechanism multiple nodes can randomly share their transmission with this random access method.

1. **ALOHA protocols:**

   ALOHA is one of the simple approaches of random access MAC protocol and can be easily implemented. In this protocol, a node will send data to the intended receiver, if the data is ready to send. Collision occurs when two nodes transmit packet simultaneously and reaches to the receiver at the same time. Hence, retransmission is required to handle this case. Variations of ALOHA scheme can be found in [42] which represents the detail variants of ALOHA schemes.

2. **CSMA protocols:**

   In CSMA protocol, all nodes sense the channel for a certain period of time before accessing the channel. The variations of CSMA scheme have been presented in details in [43]. A novel CSMA-based protocol with collision avoidance has been proposed in [44]. To avoid collisions this protocol use the differences of propagation delay between the incident nodes pairs. UWAN-MAC, a protocol for underwater acoustic networks has been proposed in [45]. With the intention of resolving the problem of space-time uncertainty, Tone-Lohi**(T-Lohi)**, a

CSMA-based MAC protocol has been proposed in [13]. In this approach, nodes compete for reserving the channel for sending data. Each frame comprises of reservation period (RP) trailed by a data transfer. T-Lohi employs short tones and low power receiver, therefore its reservation process is rapid and energy efficient. On the other hand, the limitation of T-Lohi is the low channel utilization. The reason is, in each contention round a node remains idle and listen to the channel during contending for the channel. The listening period includes the maximum single-trip propagation time and the contention tone detection time. Hence, it results low channel utilization.

B. *Handshaking Based:*

Another important type of the contention-based MAC protocol is the handshaking protocol, which is essentially a group of the reservation-based protocols. The basic idea of the handshaking or the reservation-based schemes is that a transmitter has to capture the channel before sending any data. The handshaking MAC protocols are classified into two categories as the MAC protocol with single channel and the MAC protocol with multiple channels.

1. **MAC protocols with single channel:**
   In case of MAC protocols with single channel, only one channel is employed for data communication. Before any data transmission, the handshaking message will be exchanged to capture the channel. Handshaking MAC protocols that use only one channel can be classified into two groups. The aim of the first group of handshaking MAC protocol is to attain energy efficiency. In [46], Slotted Floor Acquisition Multiple Access **(Slotted FAMA)** has been proposed. Similarly, the Distance-Aware Collision Avoidance Protocol **(DACAP)** associates carrier sensing and RTS/CTS control packet exchange prior to data transmission. However, it does not need the corresponding nodes to be harmonized into common time slots. The goal of the second group is to minimize the long propagation delay impact. A modified four-way handshaking scheme has been proposed in [47], named Multiple Access Collision Avoidance for Underwater **(MACA-U)**, where collision probability could be high. A Delay-aware Opportunistic Transmission Scheduling **(DOTS)** protocol [14] makes use of passively overhearing information to improve the concurrent transmissions

while reducing the likelihood of collisions. The impact of long propagation delay and limited bandwidth can be minimized with this scheme. In short, DOTS provides an efficient technique of facilitating multiple transmissions over a single channel and significantly advances the overall network performance.

2. **MAC protocols with multiple channels:**
   MAC protocols with multiple channels exploit more than one channel for communication [15]. In this scheme, one common control channel and multiple data channels are available. If a node has a packet to send then it will send a RTS control packet over the control channel. The RTS frame comprises of sender/receiver identifier, available channel set and the packet length. After receiving the RTS, the receiver sends back to sender a CTS including the selected data channel.Then after successful RTS/CTS handshaking both the sender and receiver switch to the selected data channel for transmission.This scheme is like the protocol in [16] that is proposed for terrestrial sensor networks and later designed and analyzed in [15] for UWSNs. Brief descriptions of some MAC protocols with multiple channels are given below:

   A Reservation Channel Acoustic Media Access Protocol **(RCAMAC)** on basis of RTS/CTS handshaking has been proposed in [48]. The total bandwidth is distributed into two channels in this scheme. Between two, one is for control channel which occupied less bandwidth and other is the data channel employed more bandwidth. Another new Contention based Parallel reservation MAC **COPE-MAC** has been proposed in [49] that concentrate on parallel transmission . It also adopts the contention-based reservation approach in order to avoid collisions. Consequently, it improves the system throughput and energy efficiency.
   Moreover, in multichannel long delay underwater sensor networks, multichannel and long delay hidden terminal have been exposed besides the traditional multi-hop hidden terminal problem, which is termed as triple hidden terminal problem. To handle these problems, Cooperative Underwater Multichannel MAC Protocol **(CUMAC)** has been proposed in [8].

In case of CUMAC, when a node has a packet to send, it initiates a channel

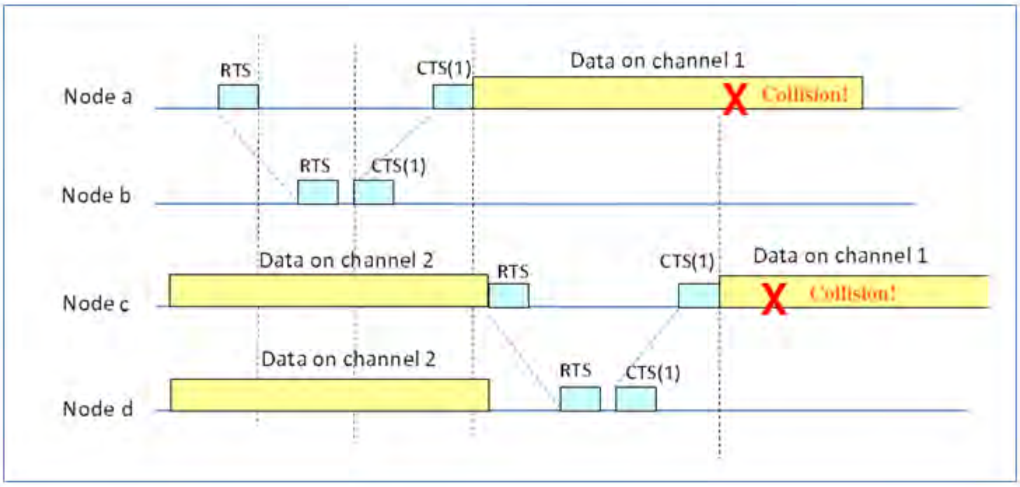

Figure 3.2: Multichannel hidden terminal problem [8]

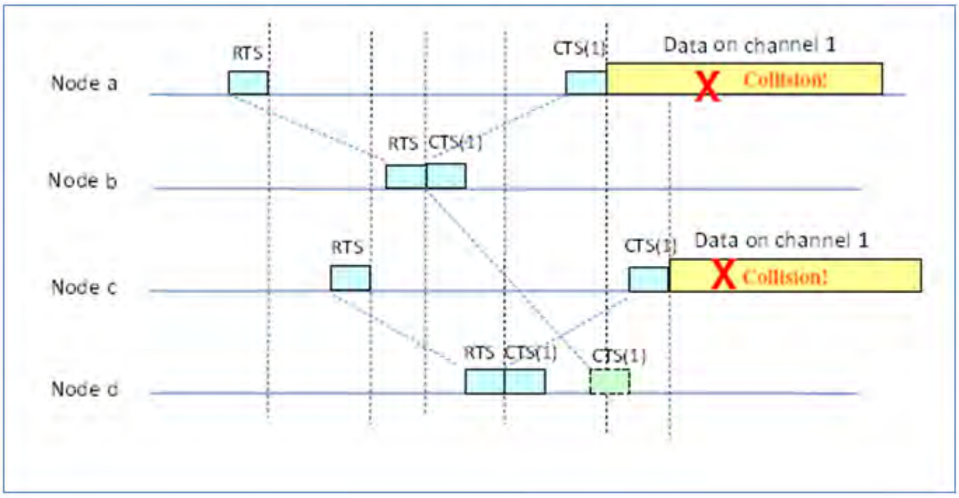

Figure 3.3: Long delay hidden terminal problem [8]

negotiation process which consists of RTS/Beacon/CTS control messages [12]. The receiving node cooperates with its neighbor nodes for channel selection and collision detection before sending CTS response back to the sender node, Multichannel hidden terminal problem in underwater sensor network has shown in the Figure 3.2. When node a and b continuing channel negotiation over the control channel then node c and node d are communicating on data channel 2. So node c and node d do not know about channel allocation of data channel 1 by node a and b. Afterward, when node c wants to transmit a data packet to node d, it continues again handshaking on the control channel. As node d does not know about data channel 1 allocation by others node, it may select the same channel and collision occurs.

The limitation of CUMAC is the sender node does not consider its neighbor nodes on-going transmission and collision detection. Collision may also happen in sender end but CUMAC does not consider the sender side multichannel hidden terminal problems for collision detection. Moreover, Long propagation delay hidden terminal problem has been addressed in CUMAC, which is depicted in Figure. 3.3. But it does not take advantages of propagation delay information to continue node communication and enhance channel utilization without any collision. In addition, every node maintains a channel usage table to keep records of data channel usage but this channel usage table does not help receiver nodes to get the channel status for channel selection. So, the cooperative collision detection scheme asks for help from neighbor nodes. If a neighbor node sends tone pulse sequence to receiver node to notify on collision detection, then receiver node selects another channel and it repeats the whole process of channel selection trials until it gets a right channel. Another multichannel MAC protocol, referred as Underwater Multichannel MAC protocol **(UMMAC)**, based on slot reservation is proposed in [18].UMMAC, which utilizes multiple channels to improve good put for UANs. It combines channel reservation and negotiation in one phase to reduce the overhead on time and energy. UMMAC requires a single transceiver at each node, which lowers the hardware cost and dimension.

3.3.3 Hybrid MAC protocols

Finally, the hybrid MAC protocols incorporate different types of MAC protocols and medium access techniques to attain better performance. In recent years, hybrid MAC protocols have become an interesting research area in underwater sensor networks. HSR-TDMA, H-MAC, P-MAC, UW-MAC, PLAN are the examples of hybrid MAC protocols [50, 51]

3.4 Summary

A comprehensive detail of MAC protocols in underwater sensor networks has been presented in this chapter. Large numbers of mechanisms and protocols are described which reflects the importance of the research activities on MAC protocol. Amongst all the protocols this research work focused on CUMAC. As in CUMAC and previous studies on underwater network has paid attention on overcoming the challenges of the acoustic channel. However, very few works exploit the characteristics of large propagation delay as a means to increase throughput. Therefore, the goal of this research is the enhancement of earlier work on CUMAC which will be introduced in the following chapter.

Chapter 4

Proposed MAC Protocol for Handling Triple Hidden Terminal Problems of Multichannel UWSNs

4.1 Introduction

This research work focuses on the enhancement of earlier work on Cooperative Underwater Multichannel MAC protocol (CUMAC) with incorporation of propagation delay mapping and channel allocation assessment. A Channel Allocation Matrix (CAM) is introduced with an aim to enhance channel utilization. Moreover, propagation delay map database and CAM will be aligned to ensure successful transmission by mitigating triple hidden terminal problems (THT) in underwater sensor networks. In brief, the key concept of proposed scheme is the prediction of upcoming transmission, in such a way that facilitates data transmission with free of collisions.

4.2 System Model

- For simplicity, the underwater network considered here static underwater sensor network that is nodes in the network are static and uniformly distributed within a fixed area.
- Multi-hop topology of static nodes is considered and depicted in Figure 4.1 .The intermediary nodes of the network can communicate with each other in single hop distance in both directions.
- For each node, circular transmission range is considered as R and two nodes will not interfere with each other if their distance is larger than transmission range, R.

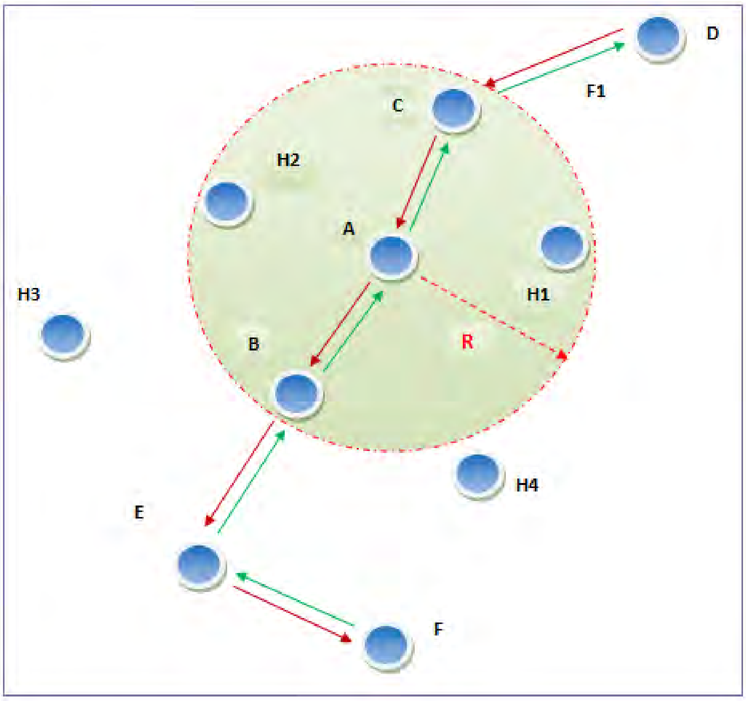

Figure 4.1: Network Topology

- The propagation speed of the acoustic signal is v and maximum propagation time T for acoustic signal from node to reach its transmission range is R/v.
- It is assumed that, while the network is initialized, the distance between nodes are calculated with the help of control packets by measuring round trip time or by sharing information between neighbor nodes [52].
- In keeping with assumption of CUMAC, there are multiple channels with equal bandwidth. There is one control channel and multiple data channels. Control channel is used for exchanging control messages and data channels for data transmission. When there is no data to send or receive then every node listens to the common control channel.
- Every node has only one acoustic transceiver and thus node can dynamically switch to different channels whenever required. A node can work either on control channel or data channel but not on both at a time.
- The enhancement of the proposed scheme demands that, every node in the network will maintain a CAM and delay map database, which will be briefly explained in the section 4.3.1.

- A node will keep updating channel information and propagation delay in its CAM and delay map database respectively by passively overhearing RTS/CTS handshaking over the control channel.

- Packets arrives at nodes following a poisson process with arrival rate of λ packets per second over a small interval. Therefore, the packet generation of every node is poisson distributed.

- Furthermore, It is assumed that, every node knows its own position information by some localization algorithms which is required for coordination among sensor nodes such as [53].

4.3 Protocol Description

The key methods: "Channel Allocation Matrix(CAM) and Propagation Delay Map Database", "Cooperative Update on Channel Allocation" and "Transmission Scheduling with Collision Detection and Channel Assessment" of the proposed scheme are presented in this section followed by a discussion how the proposed scheme resolves the THT problems of multichannel underwater sensor networks.

4.3.1 Channel Allocation Matrix (CAM) and Propagation Delay Map Database

As stated earlier, all nodes maintain **CAM** and **delay map** information. CAM is used to keep the details of data channel allocation, which must contain the information of occupied channel, source and intended receiver for which the channel is observed as reserved, timestamp – the time at which the MAC frame is sent and finally, the transmission time duration for the MAC frame.

On the other hand, each node can maintain delay map by passively overhearing neighbor nodes transmissions. The delay map database consists of source and destination information of the observed MAC frame and the estimated propagation delay between the source and the destination. In this context, the proposed protocol makes the assumption of time synchronization among all nodes in the network as DOTS protocol [14], in order to precisely estimate the transmission delay between nodes with measurement of propagation delay.

For an example, one control channel and two data channels (F1, F2) are available in the proposed network model. As shown in Figure 4.2, a transmission is going on over the data channel F2 from source node A to node B. In the meanwhile, node D and node C is handshaking on the control channel to reserve the data channel F1 and continues their transmission on the desired data channel after successful negotiation. The other remaining nodes keep listening to the control channel and update their CAM accordingly. Afterwards, these records of CAM along with delay map will be employed for their future transmission.

As each node maintains CAM and delay map database therefore, each node will occupy additional memory for the maintenance of CAM and delay map in the proposed scheme. Memory will be allotted by each node according to update of their CAM and delay map information. The memory allocation with respect to nodes is represented in Figure 4.3.

4.3.2 Cooperative Update on Channel Allocation

Cooperative Update on Channel Allocation scheme is introduced to address the multi-channel hidden problem in underwater sensor network. Figure 4.2 depicts that, node A and node B missed out the RTS/CTS handshaking between nodes D and C due to multi-channel hidden terminal problem. As this set of nodes was in on-going transmission on the data channel F2, they are not aware of handshaking and upcoming transmission information. Neighbor node of node A and node B has the handshaking information. In addition, neighbor nodes also know that when the on-going transmission between node A and node B is going to complete. Accordingly, after completion of each on-going transmission, neighbor nodes act as a helper node by cooperating communication pairs with UPDATE control packets as depicted in Figure 4.4. The objective is to provide updated information on channel allocation status to alleviate the multi-channel hidden terminal problem in underwater sensor networks.

The packet format of UPDATE packet is shown in Figure 4.5. At the end of

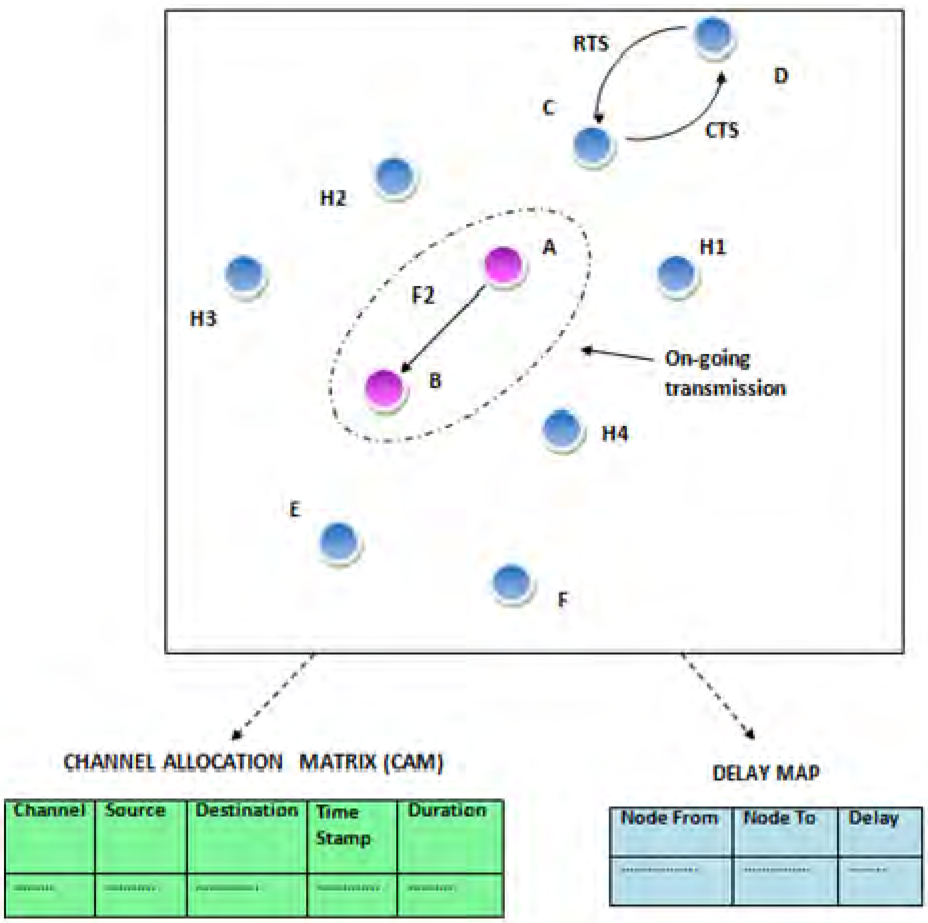

Figure 4.2: Nodes are maintaining CAM and delay map database by overhearing neighbor nodes transmission

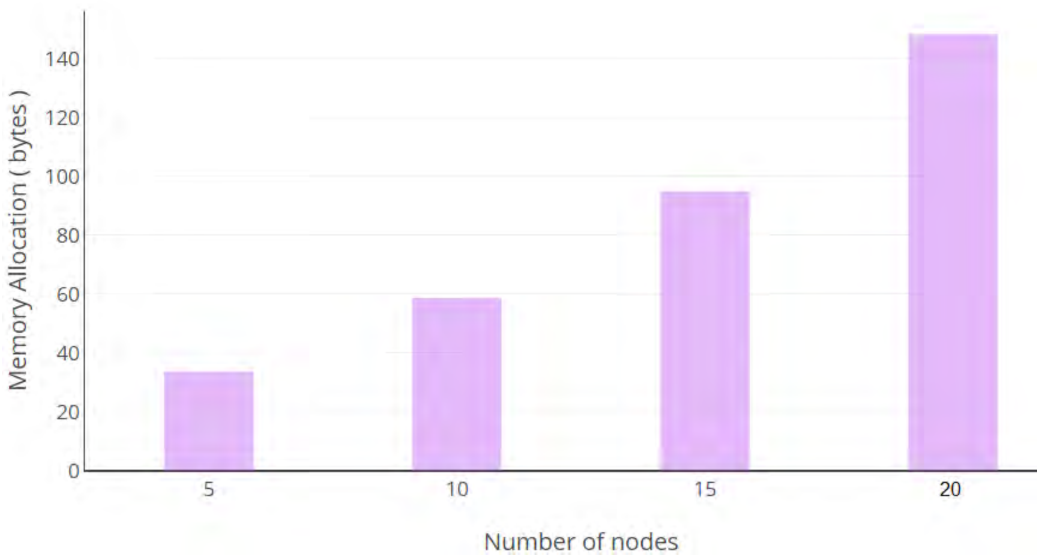

Figure 4.3: Memory allocation for CAM and delay map with respect to no. of nodes

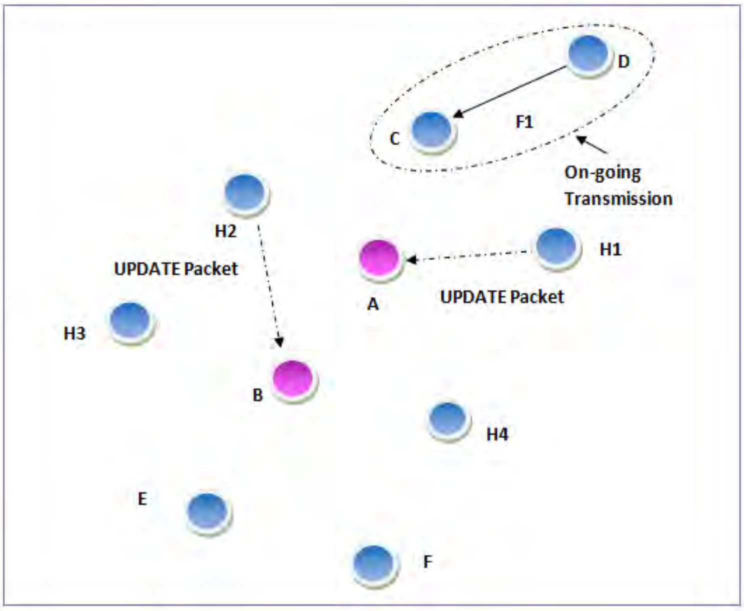

Figure 4.4: UPDATE packets sent by neighbor nodes

Packet Type	Packet Length	Sender ID	Sender Location	Receiver ID	Receiver Location	Selected Data Channel	Data Packet Length	Remaining Duration

Figure 4.5: UPDATE packet

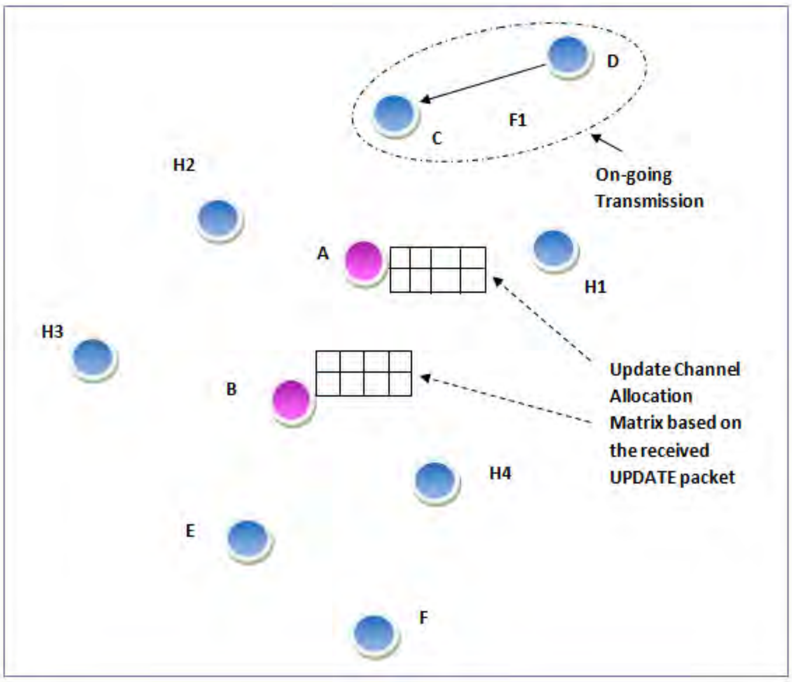

Figure 4.6: CAM update based on the received UPDATE packet

prior transmission and before initiating future transmission, the communication pairs wait up to maximum propagation delay for getting the UPDATE packets from their respective neighbor nodes. After receiving the UPDATE packets, node A and node B will update their CAM and estimate the remaining duration by considering the propagation delay between their respective neighbor nodes.

In order to mitigate UPDATE packet collision in the event of cooperative update on channel allocation, neighbor nodes send UPDATE packets through random back-off algorithm. Thus, node A and B update their respective CAM from their cooperative nodes, as represented in Figure 4.6. Furthermore, work flow of cooperative update on channel allocation is portrayed in Figure 4.7.

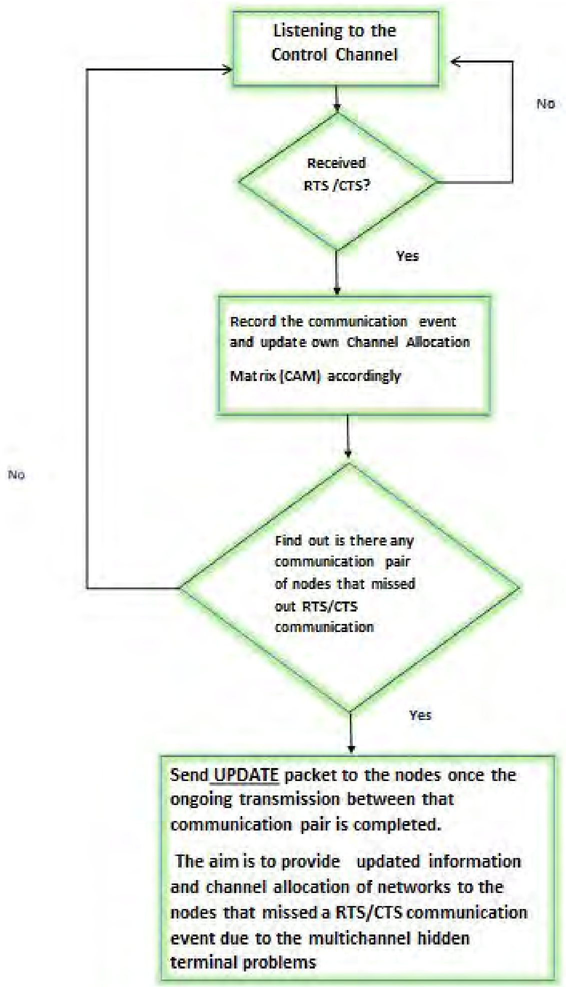

Figure 4.7: The work flow of cooperative update on channel allocation

4.3.3 Transmission Scheduling with Collision Detection and Channel Assessment

Whenever a node has a frame to send, at first it checks its CAM to select a data channel. If any data channel is found free after checking the channel allocation in CAM, then this phase is straightforward. That is, sender node directly moves for RTS/CTS handshaking over the control channel.To avoid collision on control channel that is if a sender or receiver node found that control channel is not available for control packets then they goes to backoff and tries again after a random period of time. An example of RTS/CTS collision scenario is shown in Figure 4.8. It represents that,information of RTS which is sent from node b to node v, reaches to node k after experiencing a long propagation delay. At that time node k was receiving the CTS from node i. As a result, control packet collision occurs at node k at time t3.

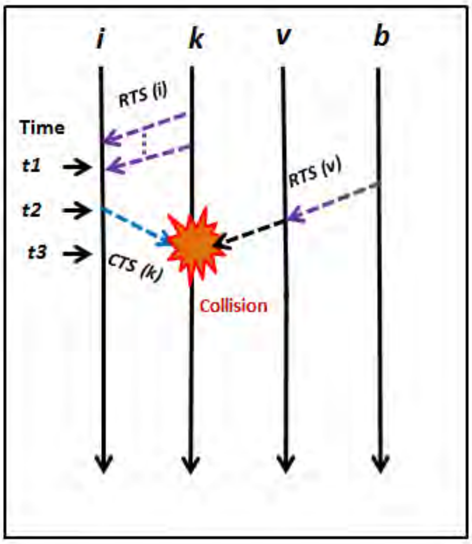

Figure 4.8: RTS/CTS packet collision

On the other hand, if data channels are found occupied then nodes have to run the transmission scheduling algorithm based on the delay map database to make data transmission decision over the data channel as [14]. In the proposed scheme, sender and receiver both nodes run the transmission scheduling algorithm to initiate an upcoming data transmission. The aim is to prevent the likelihood of collisions by taking a decision whether a node can transmit/receive without interference of neighbor node's on-going transmission or not.

In the light of this research work, for any upcoming transmission a channel negotiation process is done by the set of communication pair willing for the transmission. After a successful RTS/CTS handshaking and channel negotiation, both the sender and receiver switch to the desired data channel from the control channel. Later, both nodes shift back to the control channel after successful data transmission.

Now this section presents the details scheme of free channel assessment, sender and receiver end collision detection along with the implementation of transmission scheduling algorithm (Algorithm 1).

Algorithm 1 TRANSMISSION SCHEDULING ALGORITHM BASED ON DELAY MAP

/*Transmission scheduling with sender end collision detection*/

1: for all nodes ∈ delay map do

2: **if** frame type is DATA **then**

3: DATA arrival time at neighbor node <- timestamp + trans.time+(2*prop.ctrl.delay)+prop

4: **if** DATA **transmission time** at **sender node** ∈ DATA **arrival time** at **neighbor node then**

5: **return** collision detected

6: **end if**

7: **end if**

8: **end for**

/*Transmission scheduling with receiver end collision detection*/

1: For all nodes ∈ delay map do

2: **if** frame type is DATA **then**

3: DATA arrival time at receiver node <- timestamp + trans.time+(2*prop.ctrl.delay)+prop.data.delay

4: **if** DATA **arrival time** at **receiver node** ∈ DATA **transmission time** at **neighbor node then**

5: **return** collision detected

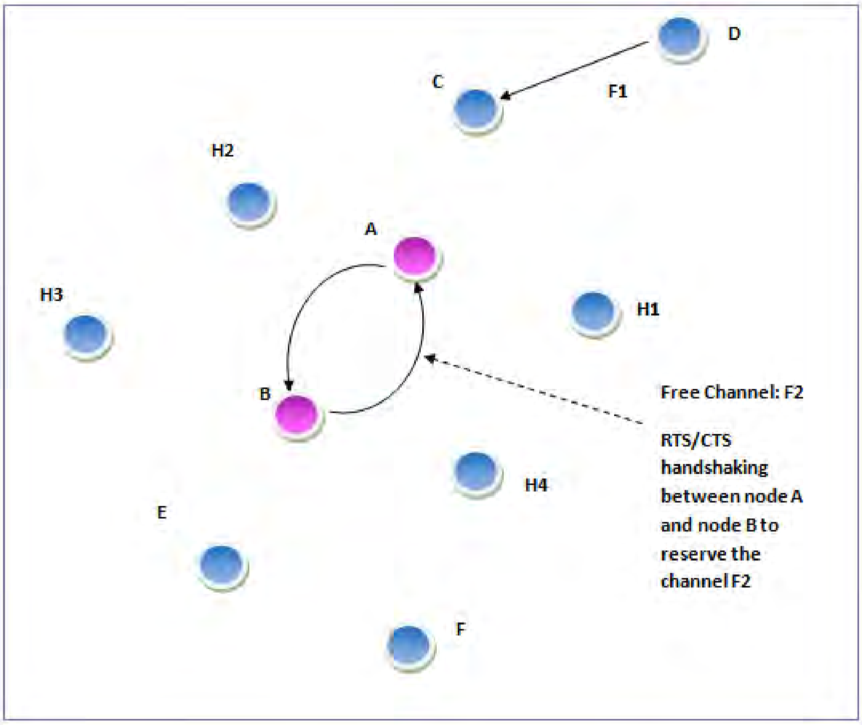

Figure 4.9: RTS/CTS handshaking to reserve the channel F2 for the upcoming transmission

6: **end if**

7: **end if**

8: **end for**

4.3.3.1 Free Channel Assessment

If any data channel is found free by verifying the CAM that is not occupied by any other nodes, then the sender node will initiate the RTS/CTS handshaking process over the control channel to communicate with the intended receiver, as illustrated in Figure 4.9. The goal is to take initiative of upcoming packet transmission over that free data channel. Thus the free channel assessment ease the process of getting data channel status and select a data channel by node itself with the help of CAM. The work flow of free channel assessment is illustrated in Figure 4.10.

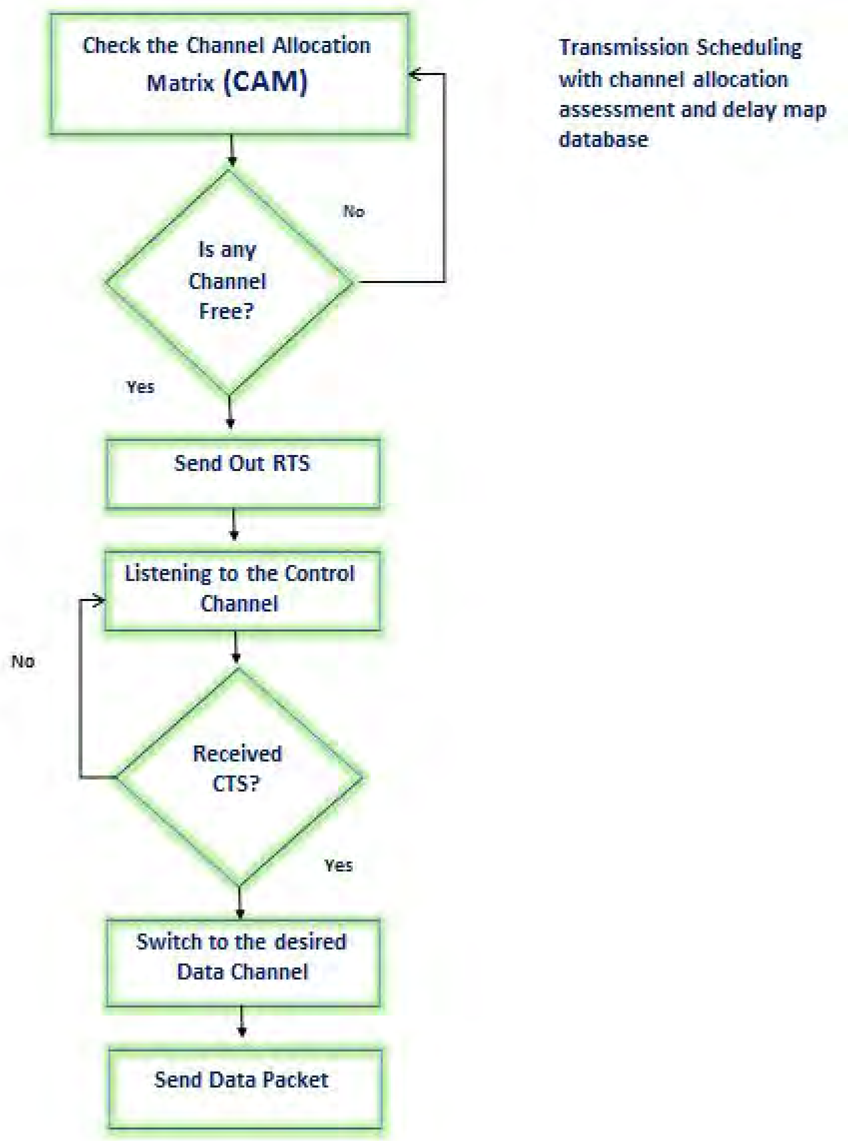

Figure 4.10: The work flow of Free Channel Assessment

4.3.3.2 Sender End Collision Detection

In case of unavailable free data channel, at first sender node checks the occupied channels information from CAM. Then it will run the transmission scheduling algorithm aligning with delay map database. It will guide the sender node to take a decision to move forward for upcoming packet transmission without hampering its one hop neighbor node's packet reception over the desired channel, which is occupied by that one hop neighbor node.

Suppose, a transmission is going on over a data channel F1 and the channel is

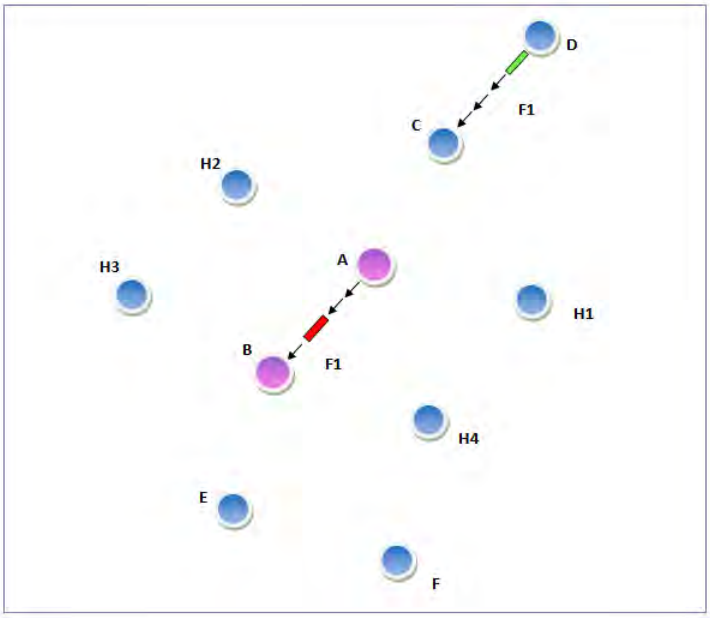

Figure 4.11: Sender End Collision Detection- Node A transmits a packet to node B over the channel F1 before its one hop neighbor node C receives a packet from node D over the same channel

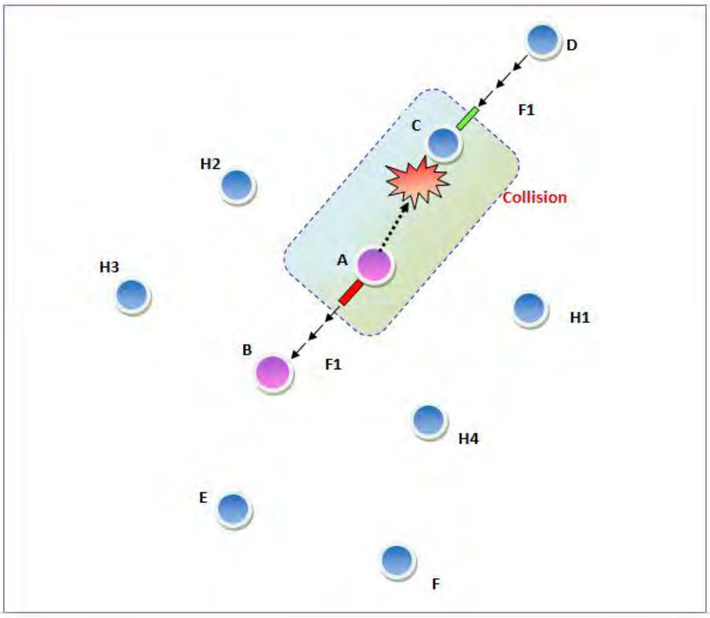

Figure 4.12: Sender End Collision Detection - Collision occurs if node A transmit a packet to node B over the channel F1 without considering collision at one-hop neighbor node C's packet reception on the same channel

occupied by a communication pair node D (sender) and node C (receiver). Node C is one-hop neighbor node of node A. In this scenario, if node A wants to transmit a packet to node B then at first, node A checks the CAM and found that all the data channel are occupied. Afterwards, node A runs the transmission scheduling algorithm based on the propagation delay map to verify whether its upcoming data transmission over the desired data channel will collide with one hop neighbor nodes packet reception or not. For the given example, node A will move forward for data transmission over the data channel F1 as shown in Figure 4.11, if it get assurance from transmission scheduling that, node A must be able to transmit data packet before its one hop neighbor node C receives the transmitted packet from node D otherwise collision will occur as depicted in Figure 4.12. In short, a node will move forward for data transmission over any occupied channel if it estimates that its upcoming transmission will not hamper or collide with one-hop neighbor node's packet reception. To give a picture of the work flow of transmission scheduling with delay map at sender end, a pictorial representation is given in Figure 4.13.

4.3.3.3 Receiver End Collision Detection

After getting the RTS, receiver will also check the CAM and runs transmission scheduling algorithm based on the delay map. Taking the Figure 4.14 as an example, where a transmission is continuing over the data channel F1 between the communication pair node E (sender) and node F (receiver). E (sender) is a one-hop neighbor node of node B. In this scenario, say, node B receives a RTS packet from node A for the upcoming transmission over the same channel F1. As per the proposed scheme node B also estimates whether it's packet reception from node A will be interfered with one hop neighbor node E's ongoing packet transmission or not. Node B will reply with CTS if and only if it predicts by running transmission scheduling algorithm that it will receive the incoming packet from node A after its one hop neighbor node E completes transmitting packets to the intended receiver, node F. Otherwise, collision will occur as shown in Figure 4.15. In addition, before replying CTS, node B will wait up to maximum propagation delay according to its delay map database. The purpose is to alleviate collisions, occurred for long delay hidden terminal problem in underwater sensor networks.

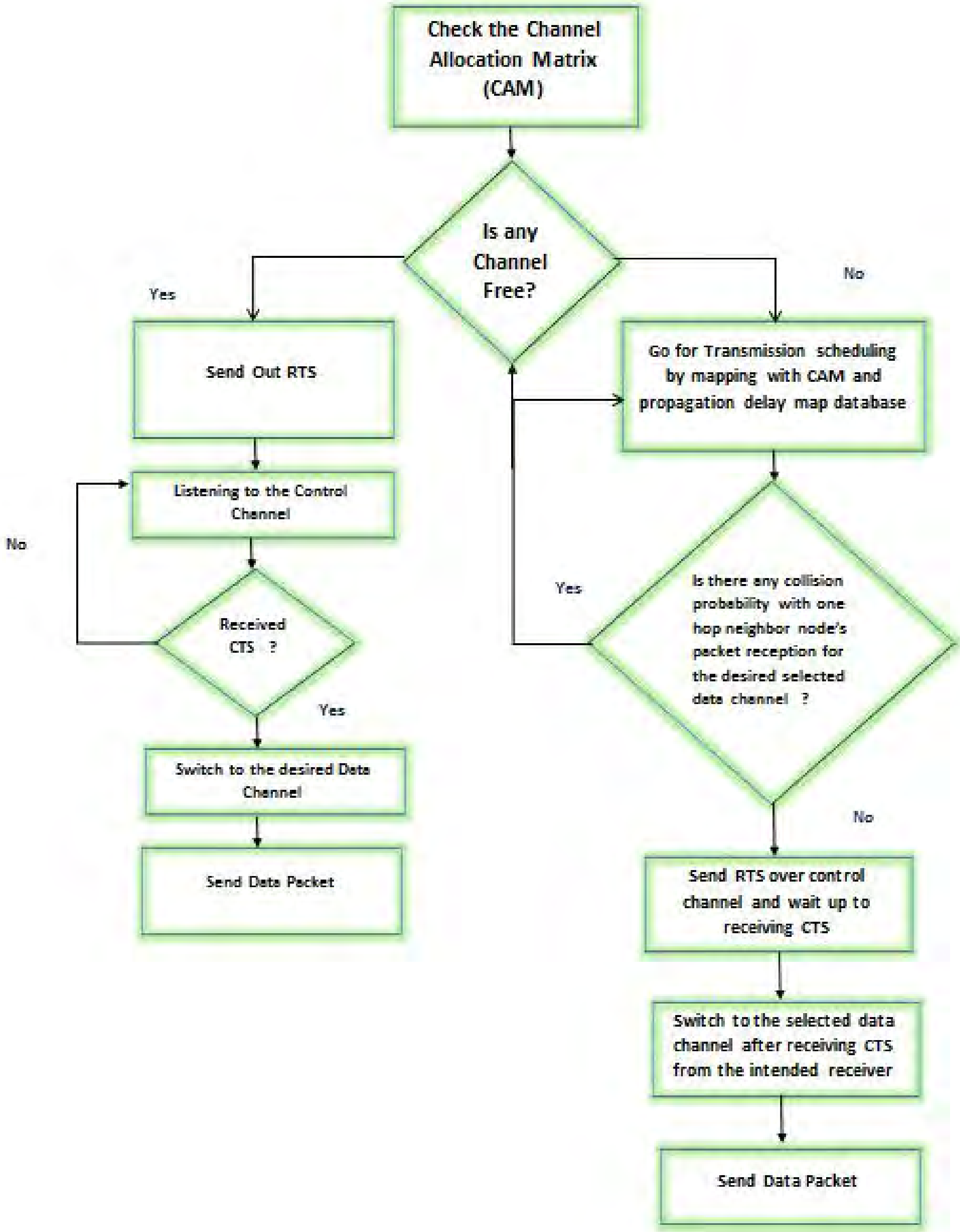

Figure 4.13: The work flow of Sender end Transmission Scheduling with delay map

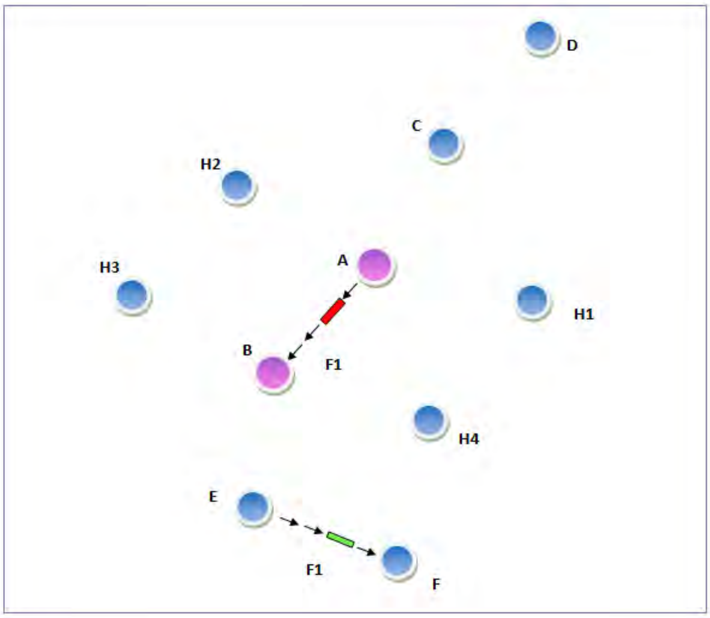

Figure 4.14: Receiver End Collision Detection- Node B will receive packet from node A on F1 channel after node B's one hop neighbor node E transmits a packet to its intended receiver - node F over the same channel

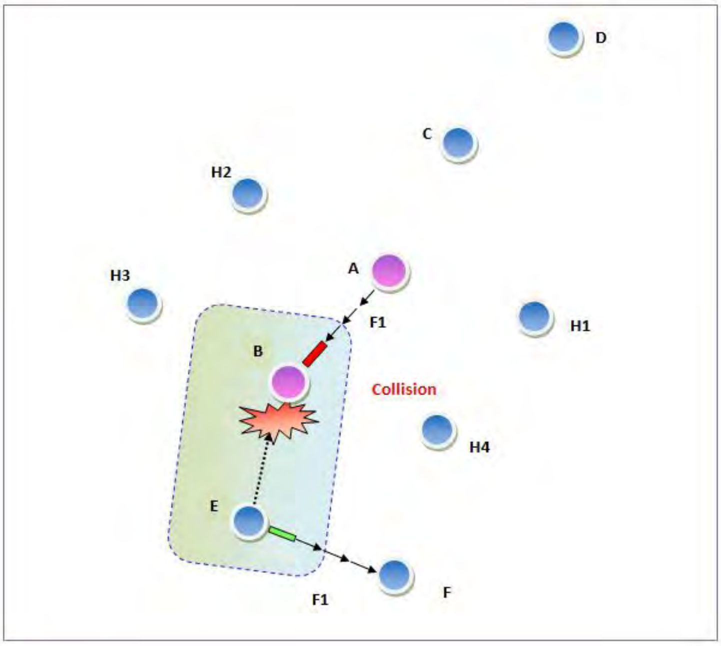

Figure 4.15: Receiver End Collision Detection- Collision occurs if node B receives a packet over the channel F1 while its one hop neighbor node transmitting a packet to node F over the same channel

As a whole, the procedure of receiver end transmission scheduling with delay map is depicted in Figure 4.16.

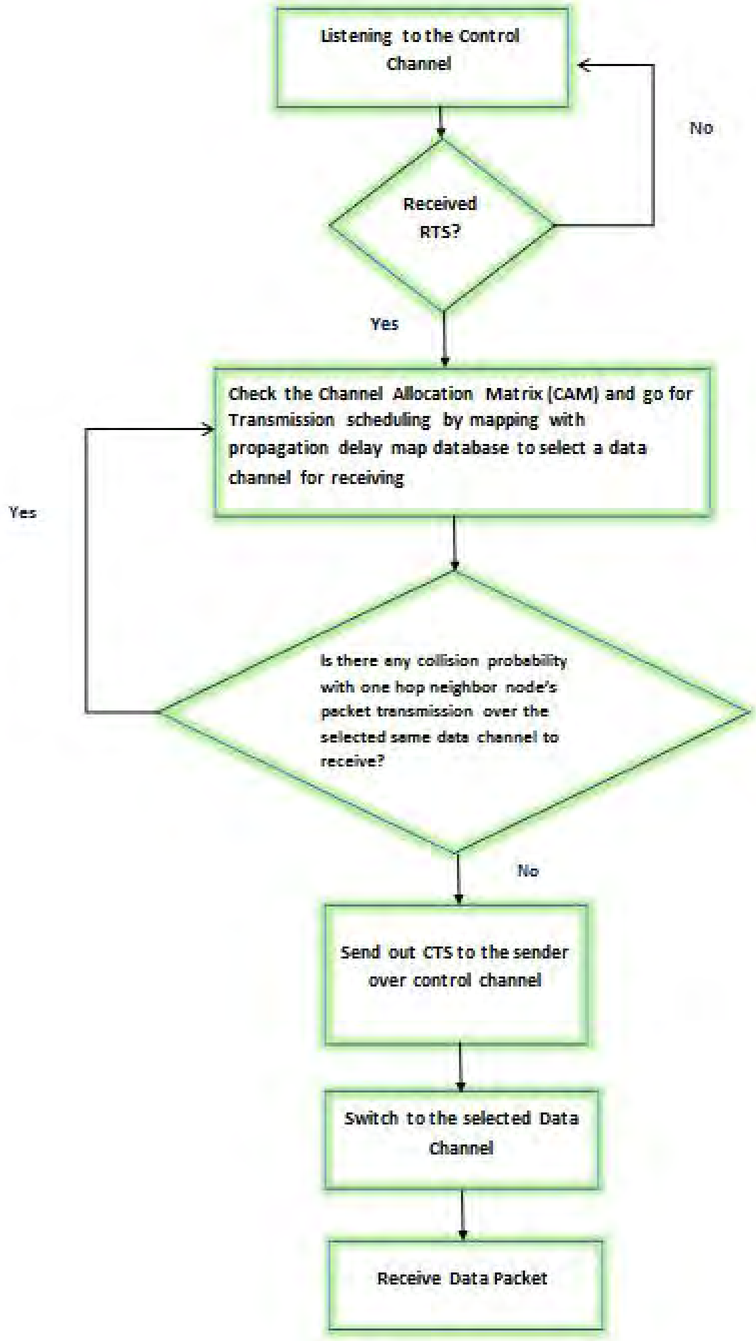

Figure 4.16: The work flow of Receiver end Transmission Scheduling with delay map

Thus channel assessment and transmission scheduling algorithm of the proposed scheme facilitates for collision detection as well as enhance the concurrent transmission with the benefit of delay map.

Subsequently, when receiver node replies with its control message CTS to the sender, both nodes switch to the desired data channel. The receiver node starts a timer and keeps waiting for the incoming packet. If it does not receive any packet before the time out it switch back to the control channel, updates it's CAM accordingly and broadcast a CANCEL control message to cancel the channel reservation. On the other hand, if sender node does not receive any CTS after sending its RTS packet then after random back-off period sender node retransmit the RTS packet to initiate the transmission by following the proposed scheme.

4.3.4 Discussion

The enhancement on CUMAC with the introduction of CAM, channel assessment, cooperative update on channel allocation and transmission scheduling with delay map effectively mitigate the THT problems in underwater sensor networks. As per reference of CUMAC and research work in literature, the traditional multi-hop hidden terminal problem can be easily alleviated by RTS/CTS handshaking process. Therefore, the major challenge is to handle multi-channel and long delay hidden terminal problems in underwater sensor networks.

In the proposed scheme, CAM has been introduced and each node maintains CAM and delay map by passively overhearing the ongoing transmission of neighbor nodes. Cooperative update on channel allocation scheme effectively addresses the multichannel hidden terminal problem in underwater sensor networks. As this scheme helps the communication pair (which was busy on their ongoing transmission on data channel and missed out the recent channel negotiation through RTS/CTS handshaking over the control channel) to get the update channel allocation information.

Moreover, each node evaluates the channel and run transmission scheduling algorithm mapping with delay map to have collision free transmission at both sender and receiver end. Additionally, receiver node waits up to maximum propagation delay before replying CTS to its respective sender to proceed for data transmission on the selected data channel. Therefore, the receiver node may have a chance to get the channel status before the waiting time out from the long delayed neighbor nodes for which the same data channel is already occupied. Thus the proposed protocol efficiently mitigates the THT problems in underwater sensor networks.

4.4 Summary

In this chapter, an efficient MAC protocol is proposed to handle THT problems in multi-channel underwater sensor networks. With the benefit of CAM and propagation delay, the proposed scheme focuses on increasing the chances of concurrent transmission while preventing the likelihood of collisions.

Chapter 5

Results and Performance Evaluation

5.1 Introduction

With the purpose of analyzing performance using simulator, proposed protocol implemented in Aqua-Sim, one of the most popular network simulators for underwater sensor networks. Aqua-Sim is an extension of NS2 simulator for simulating underwater sensor network protocols [54]. Aqua-Sim can be used by researchers and developers who want to implement different algorithms and protocols in underwater sensor networks.

Aqua-Sim follows object-oriented style and all network objects are implemented as classes. At present, Aqua-Sim is organized into four folders, uw-common, uw-mac, uw-routing and uw-tcl. The codes that simulate underwater sensor nodes are grouped in folder uw-common, the codes that simulate acoustic channels and MAC protocols are organized in the folder of uw-mac and lastly uw-routing folder contains all the routing protocols.The folder uw-tcl contains all tcl scripts which defines the network simulations for different scenarios. Furthermore, a simulation can be executed with the command 'ns <tclscript>', where <tclscript> refers to the name of a Tcl script file. After execution, the script creates some output, writes a trace file or starts NAM animator to visualize the simulation. Figure 5.1 depicts the sample simulation network in Aqua-Sim where sensor nodes are randomly deployed in the network.

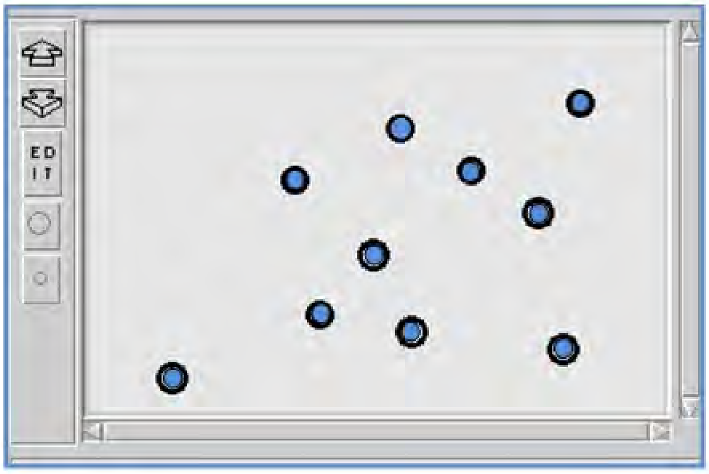

Figure 5.1: Sample Simulated Network in Aqua-Sim

5.2 Simulation Settings

In this section, the performance of proposed protocol analyzed through simulation and compared with two multi-channel MAC protocols : CUMAC and RTS/CTS based multi-channel MAC protocol. The performance is evaluated in terms of the following metrics:
i) Average network throughput ii) Average energy consumption iii) End to end delay iv) Packet delivery ratio v) Packet loss ratio vi) Collision probability vii) Fairness Index

In this set of simulations, random network is examined. The proposed protocol is implemented in a random network where maximum 20 static nodes are uniformly distributed in 500m X 500m area. Unless otherwise specified the number of hops of the simulation is 2, number of channels is 2, data packet length is 200 bytes and input traffic is set to 0.02 packets per second for all the results.

The simulation parameters are given explicitly in the below table:

Table 5.1: **System Parameters**

Parameters	Value
Transmission range of every node	100 m
Maximum number of channels	8
Acoustic propagation speed	1500m/s
Simulation time	300 s
Maximum data packet length	600 bytes
Control packet length	32 bytes
Data rate	1 kbps
Transmitting power	0.6 Watt
Receiving power	0.2 Watt
Number of simulation run	100

5.3 Simulation Results

5.3.1 Average Network Throughput

Average network throughput can be defined as average number of successfully transmitted data bytes per second.

$$Average\ Network\ Throughput = \frac{\text{Average of total transmitted data}}{\text{Network operation time}} \tag{5.1}$$

The performance of CUMAC, RTS/CTS scheme and the proposed protocol has been evaluated in terms of input traffic, number of channels, data packet length, delay variance and number of hops and the details comparison is given in the following section.

a) Impact of input traffic :

As depicted in Figure 5.2, throughput upturns with the input traffic for the proposed and the other two protocols – CUMAC and RTS/CTS scheme. In this set

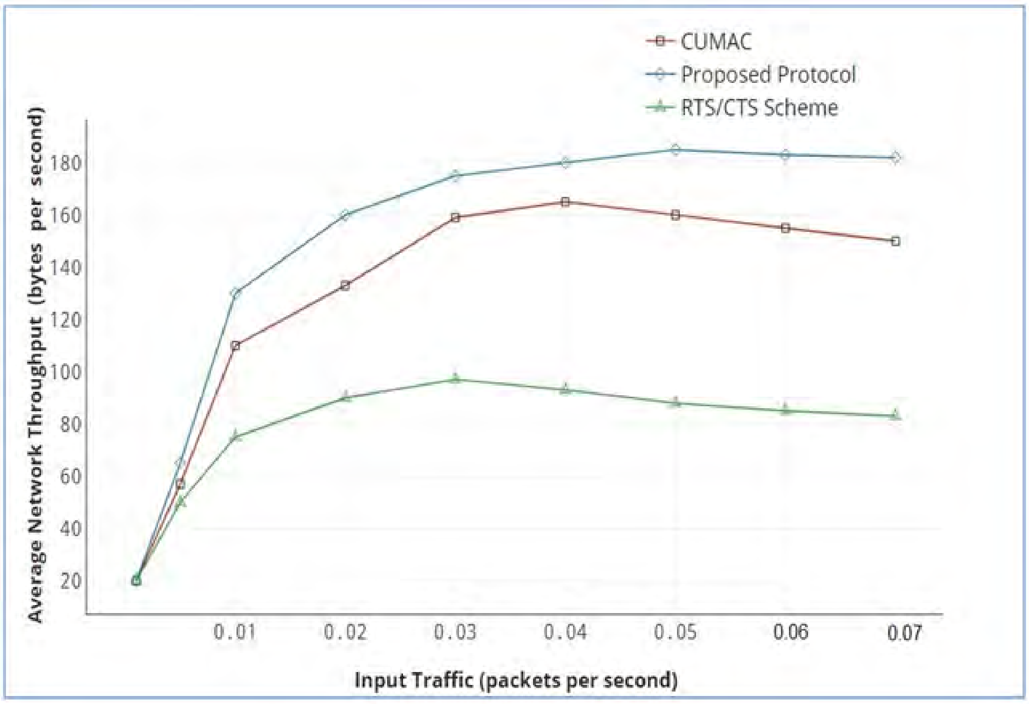

Figure 5.2: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of Input Traffic on Average Network Throughput

of simulations it is noticeable that, proposed protocol can achieve higher throughput compared to CUMAC and RTS/CTS scheme. The throughput of proposed protocol is about 175 bytes per second whereas CUMAC can achieve its maximal throughput around 165 bytes per second when input traffic is 0.04 packets per second. On the other hand, proposed protocol achieves around 170 bytes per second when RTS/CTS scheme achieve its maximal throughput 95 bytes per second at 0.03 packets per second input traffic. From the graph it is observed that, throughput gradually decreases with the input traffic for the all three cases. As collision probability increases with the input traffic therefore it impacts the throughput to decrease accordingly. In case of proposed protocol as Figure 5.2 represents, throughput reaches to the highest peak 180 bytes per second when input traffic is 0.05 packets per second. But after that, its throughput decreases slowly but provides quite steady performance than the other two protocols. The reason behind is, proposed protocol implements channel allocation assessment with channel allocation matrix and transmission scheduling algorithm to avoid the collision. As probability of network collision decreases, proposed protocol provides much better performance compared to CUMAC and RTS/CTS scheme.

b) Impact of number of channels:

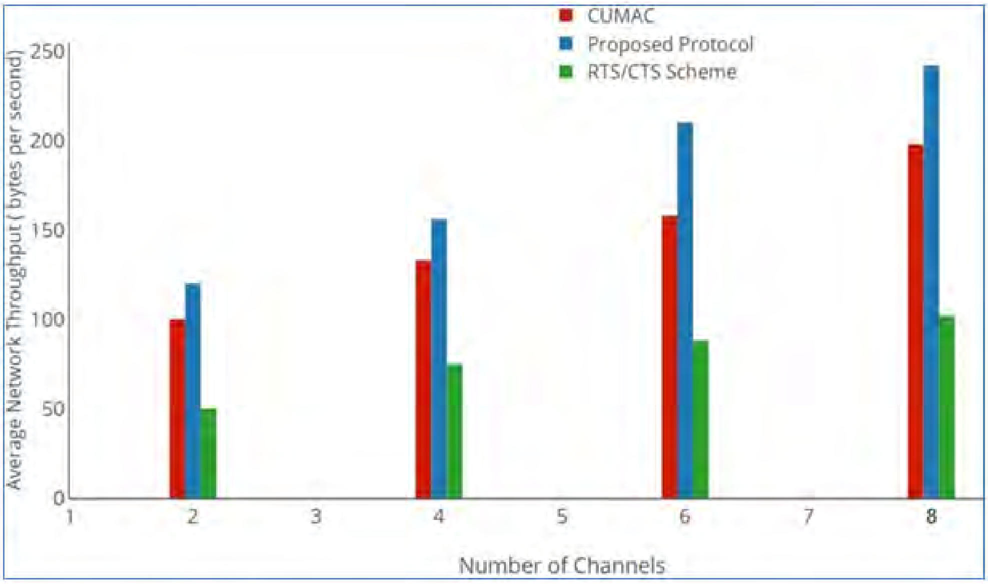

Figure 5.3: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of No. of Channels on Average Network Throughput

In this set of simulations, the performance of proposed protocol and other two protocols has been evaluated with varying number of data channels. Number of data channels is varied from 2 to 8 channels. Figure 5.3 represents that, for the all three protocols network throughput improves with the number of channels. The reason is the implementation of number of data channels in the network. If there are number of data channels in the network then the net input traffic to every data channel will be decreased. Hence, there will be less collision probability and higher throughput. Moreover, Figure 5.3 reflects that, proposed protocol is more efficient compared to CUMAC and RTS/CTS scheme. This is because, channel allocation assessment, channel utilization, collision detection along with transmission scheduling algorithm scheme of proposed protocol results less collision probability, efficient channel allocation and finally provides higher throughput.

c) Impact of data packet length:

For the performance comparison in terms of varying packet length, data packet length is changed from 200 to 600 bytes. Figure 5.4 shows that, network throughput improves with the packet length for the proposed and the other two protocols. In case of longer data packet, one data packet transmission contributes more throughputs. Thus, network throughput increases with longer data packet length. In this simulation

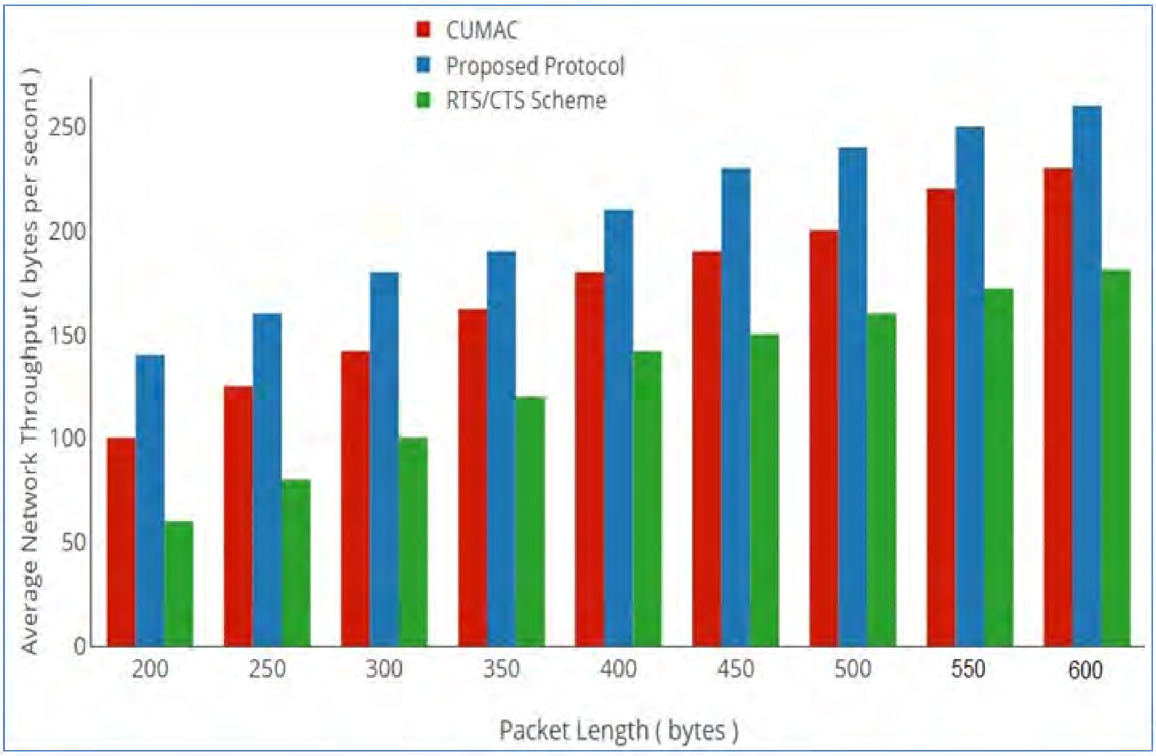

Figure 5.4: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of Packet length on Average Network Throughput

settings, proposed protocol also achieve higher throughput compared to CUMAC and RTS/CTS scheme. The throughput of proposed protocol reaches to 260 bytes per second when the maximum data packet length is 600 bytes. However, the throughput of CUMAC and RTS/CTS scheme stands for 220 and 175 bytes per second respectively with this data packet size. The reason behind of this significance is, less collision probability in the proposed protocol. As longer data packet may incur high collision probability and proposed protocol offers less collision than the other two. Therefore, proposed scheme provides moderately better performance compared to CUMAC and RTS/CTS scheme.

d) Impact of delay variance:

For the performance comparison in terms of delay variance, propagation delay varies from 0.1 to 0.7 seconds. In this set of simulations, the average distance of nodes varies from 50 m to 100 m. Propagation delay can be calculated from the distance between nodes by dividing the propagation velocity of acoustic wave (1500 m/s). Figure 5.5 plots that, network throughput decreases noticeably with the increase of

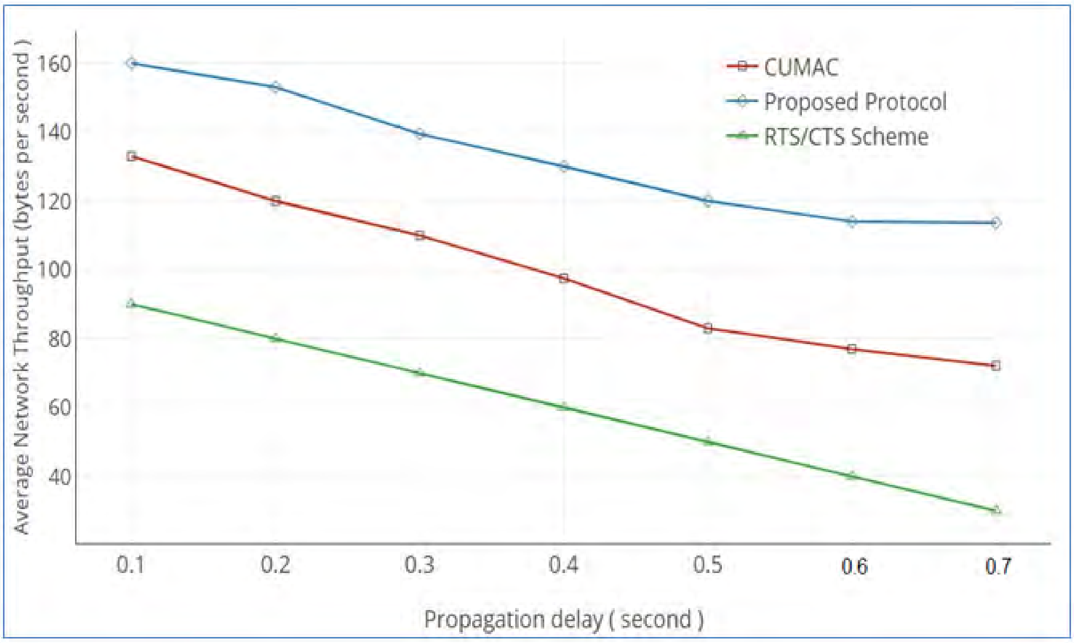

Figure 5.5: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of Propagation Delay on Average Network Throughput

propagation delay. Furthermore, it is observed that, proposed protocol outperforms the other two protocols with delay variance. Proposed protocol implements delay map and channel allocation matrix as well as run transmission scheduling to ensure collision free parallel transmission. On the other hand, CUMAC does not consider the propagation delay for continuing parallel transmission and RTS/CTS scheme does not focus on long delay hidden terminal problem. Therefore, proposed protocol still provides better performance, with varying propagation delay, compared to CUMAC and RTS/CTS scheme.

e) Impact of number of hops:

In this set of simulations, the performance of proposed protocol and other two protocols has been evaluated with different number of hops. Figure 5.6 represents, for the all three protocols network throughput decreases with the number of hops. The reason is the implementation of number of hops in the network. As the chances of collisions increased rapidly with the number of hops. Therefore, it degrades the network performance. Figure 5.6 illustrates that, proposed protocol provides much better results compared to other two protocols in case of varying number of hops. As proposed protocol implements the mechanism of channel allocation assessment,

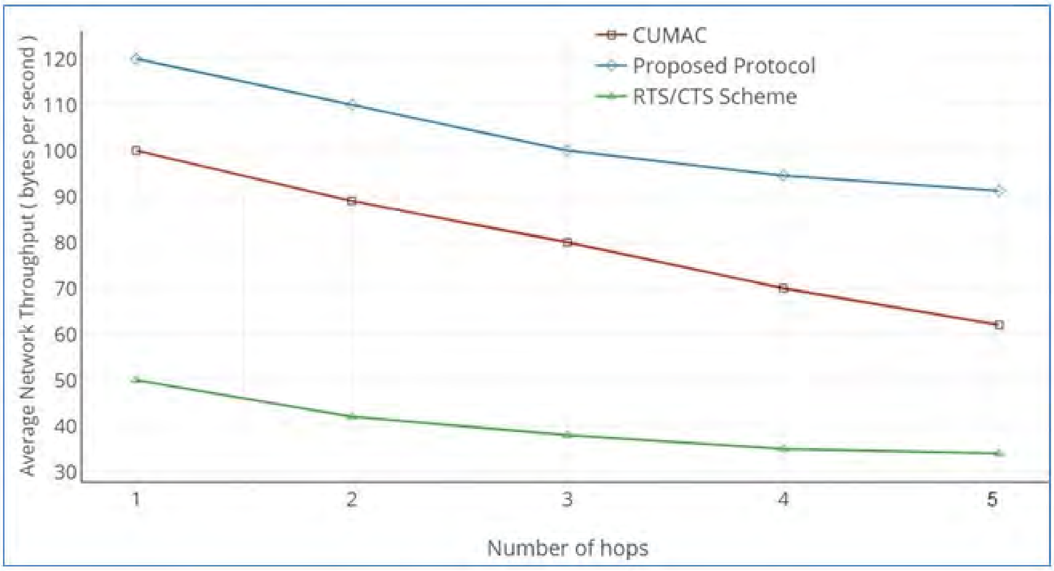

Figure 5.6: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of Number of hops on Average Network Throughput

transmission scheduling with collision detection at sender and receiver end, which helps to alleviate collision and provides better output than CUMAC and RTS/CTS scheme.

5.3.2 Average Energy Consumption

Average energy consumption is obtained by dividing the overall energy consumption in the network by the successful transmitted data bytes. It is measured by milli-joule per byte.

$$E_{avg} = \frac{E_{consumption}}{\text{Total transmitted data}} \tag{5.2}$$

Here, E_{avg} is the average energy consumption per byte and $E_{consumption}$ is the total energy consumption in the network.

a) Impact of input traffic :

Figure 5.7 plots that, average energy consumption per byte decreases with the increase of input traffic for the proposed and CUMAC protocol. But it is noticed that, energy consumption increases with the input traffic for RTS/CTS scheme. In case of CUMAC and proposed protocol, less energy will be expended for idle listening with the increase of input traffic and energy consumption decreases accordingly. As it is seen from the performance evaluation of Figure 5.7, proposed protocol achieves higher energy efficiency than the other two. This is because, CUMAC

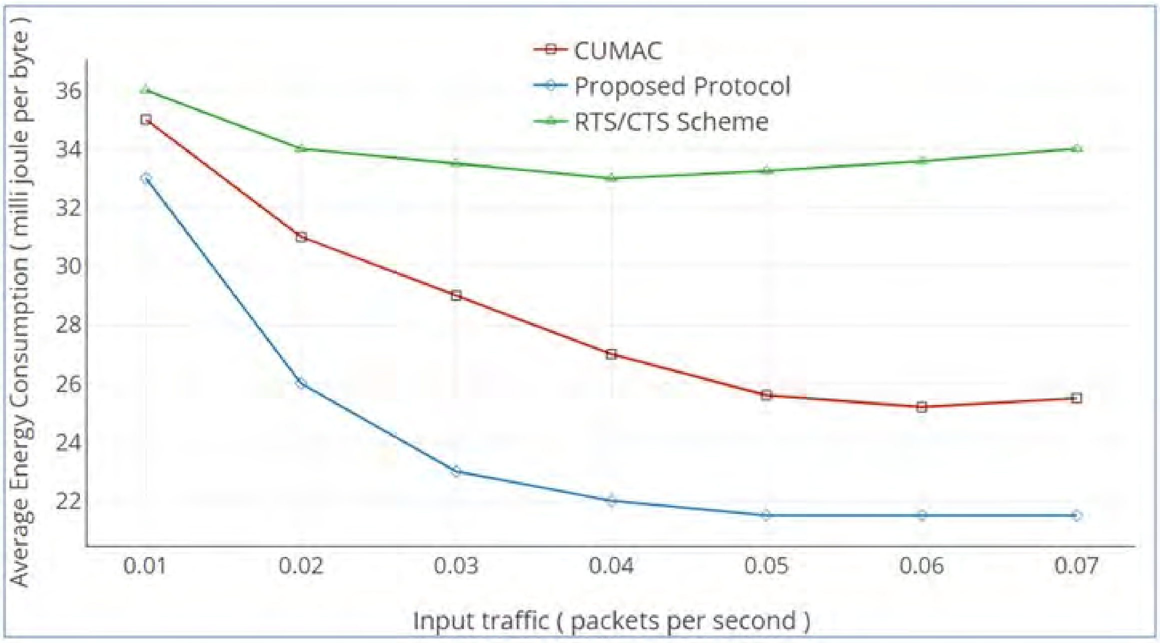

Figure 5.7: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of Input Traffic on Average Energy Consumption

implements cooperative collision detection and tone pulse sequence to suppress the triple hidden terminal problems of underwater sensor networks. On the other hand, RTS/CTS scheme does not consider the hidden terminal problems which occurred for multichannel and long propagation delay. Consequently, collision increases with the increase of input traffic and it impacts in case of energy consumption. Finally, channel allocation matrix along with propagation delay map database and transmission scheduling with collision detection mechanism of proposed scheme defeats the triple hidden problems more efficiently. As a consequence, proposed protocol provides better results compared to CUMAC and RTS/CTS scheme.

b) Impact of number of channels: Impact of data channels has also been taken under consideration to analyze the energy efficiency improvement with the number of channels. As more the data channels, less the collision probability on the data channels.

In this set of simulations, number of data channels is varied and it is set to 2, 4, 6, and 8. Figure 5.8 shows that, proposed protocol can attain much higher energy efficiency than CUMAC and RTS/CTS scheme. Energy efficiency also improves according to number of channels. In view of the performance comparison, when the

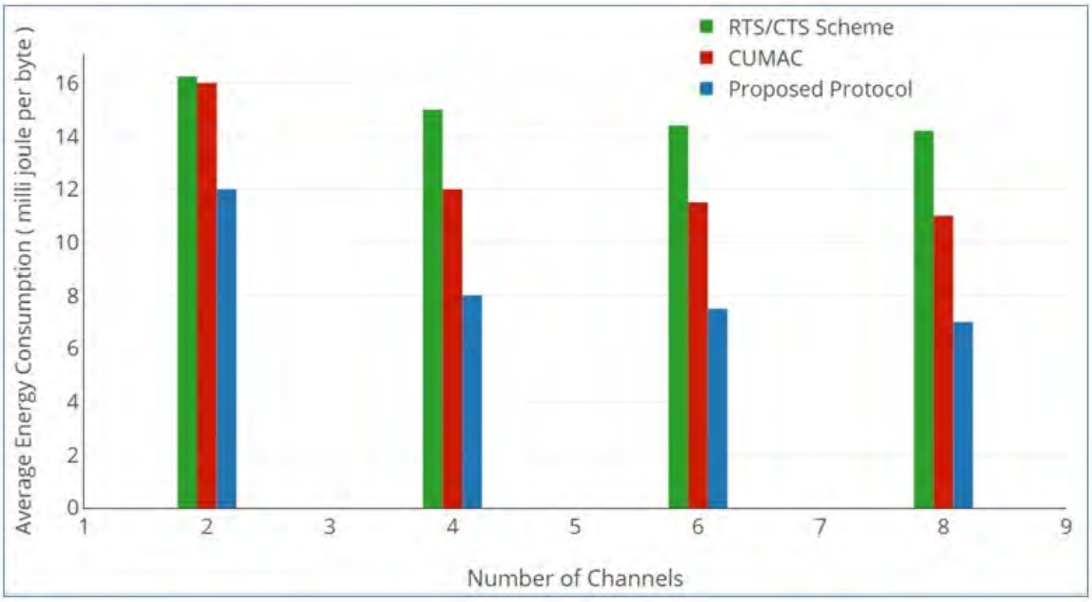

Figure 5.8: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of No. of Channels on Average Energy Consumption

number of data channels is 2, average energy consumption is about 15 milli-joules per byte for CUMAC and 16 milli-joules per byte for RTS/CTS scheme. On the other hand, average energy consumption for proposed protocol is 12 milli-joules per byte with two data channels. If there are maximum 8 data channels in the network then average energy consumption for CUMAC reduces to 11 milli-joules per byte. For the proposed one, it significantly reduces to 7 milli-joules per byte. This is because, with association of number of data channels, collision probability reduces and impact emulates in the network performance. However, average energy consumption is much higher for RTS/CTS scheme than the proposed one and CUMAC, as there is higher collision probability for multichannel hidden terminal problems.

c) Impact of data packet length:

For the performance comparison in terms of varying packet length, the length of data packet is changed from 200 to 600 bytes. The performance results are illustrated in Figure 5.9. This figure portrays, average energy consumption decreases with the packet length for the proposed and CUMAC protocols. In case of RTS/CTS scheme, with the increase of data packet length average energy consumption decreases monotonically. From the performance comparison results, it is observed that proposed protocol achieves higher energy efficiency compared to CUMAC and RTS/CTS

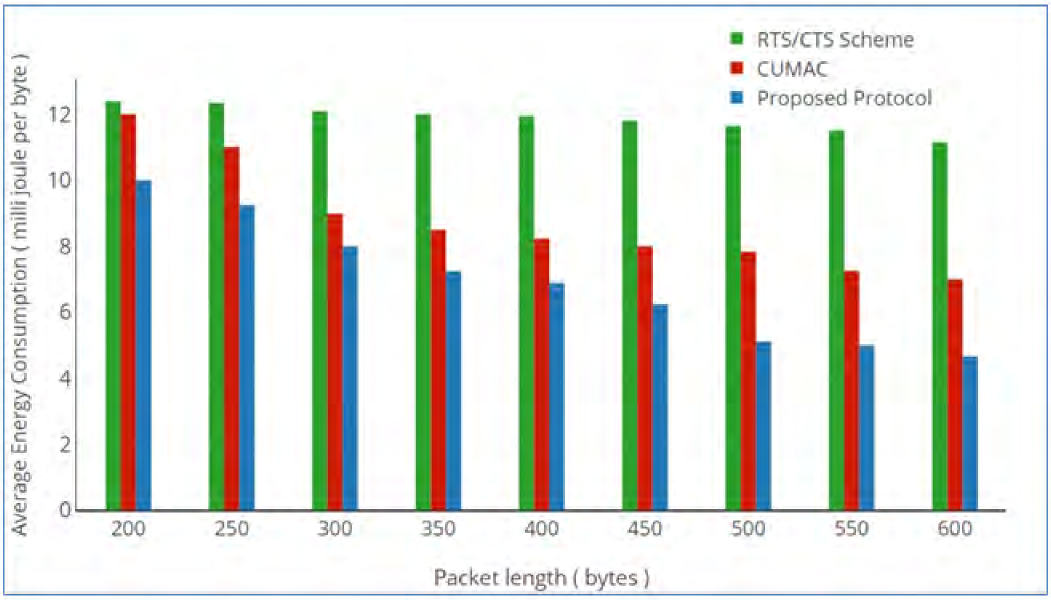

Figure 5.9: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of Packet length on Average Energy Consumption

scheme. Average energy consumption reduces to 5 milli-joules per byte and 7 milli-joules per byte in case of proposed and CUMAC protocol respectively. On the contrary, in case of RTS/CTS scheme, average energy consumption reduces to 11 milli-joules per byte when the data packet length changes to maximum length 600 bytes. The reason behind of this significance is, less collision probability in the proposed protocol. Therefore, the longer the data packet, the higher the collision probability and proposed protocol offers less collision than the other two. Therefore, proposed scheme provides better performance compared to CUMAC and RTS/CTS scheme.

d) Impact of delay variance:

Figure 5.10 shows the performance comparison of average energy consumption in terms of delay variance, propagation delay varies from 0.1 to 0.7 seconds. In this set of simulations, the average distance of nodes varies from 50 m to 100 m. As seen from the graph, average energy consumption increases with the increase of propagation delay. In addition, it is observed that, proposed protocol outperforms the other two protocols with delay variance. As proposed protocol exploits delay mapping before initiating any transmission therefore this mapping helps a node to predict whether it's upcoming packet transmission will collide with other node's transmission or not.

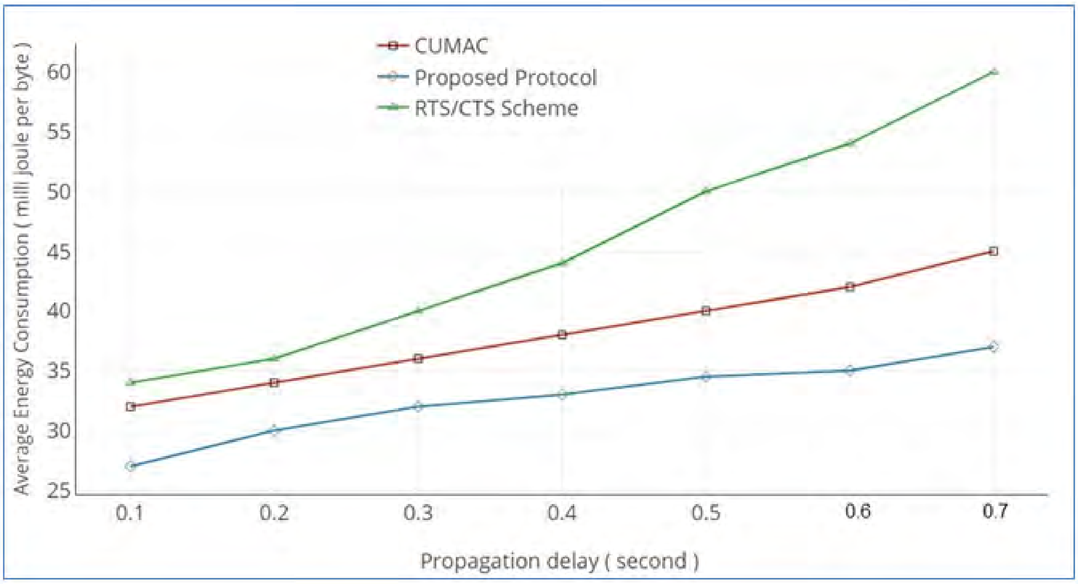

Figure 5.10: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of Propagation delay on Average Energy Consumption

On the other hand, CUMAC does not consider the propagation delay for continuing concurrent transmission and RTS/CTS scheme does not focus on long delay hidden terminal problem. Thus, proposed protocol still provides better performance, with varying propagation delay, compared to CUMAC and RTS/CTS scheme.

e) Impact of number of hops:

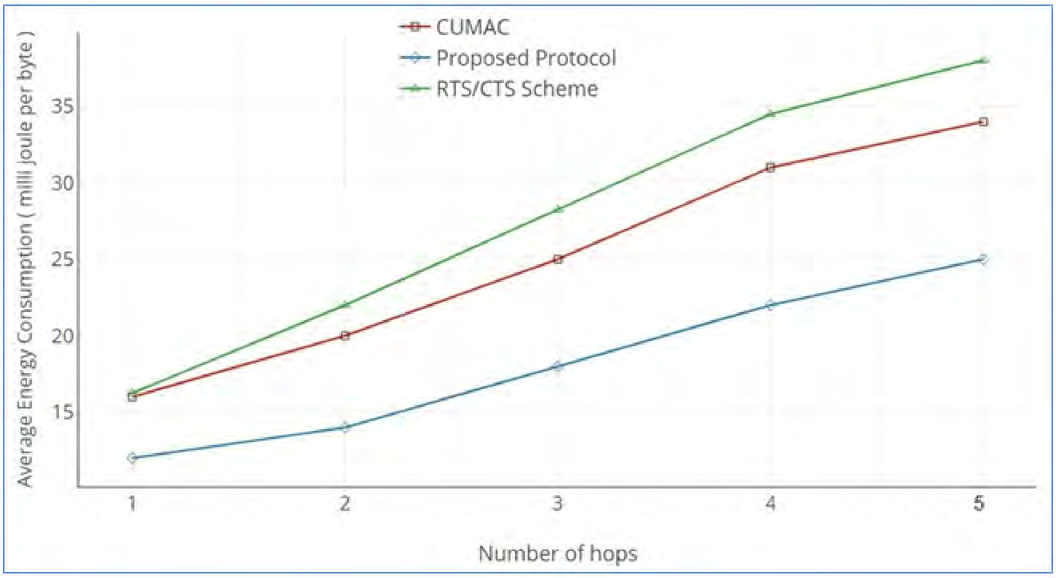

Figure 5.11: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of Number of hops on Average Energy Consumption

In this set of simulations, the performance of proposed protocol and other two protocols have been evaluated with different number of hops. Figure 5.11 represents that, for the all three protocols average energy consumption increases with the number of hops. The reason is the implementation of number of hops in the network. If there are number of hops in the network then chances of collision probability and energy consumption will be high with hop counts. As a result, energy consumption increases with the number of hops. From performance comparison it is noticeable that, proposed protocol provides much better results compared to other two protocols in case of varying number of hops. This is because proposed protocol implements transmission scheduling algorithm for collision detection at sender and receiver end. This helps to alleviate collision as well as to provide better results than CUMAC and RTS/CTS scheme.

5.3.3 End to end delay

The end-to-end delay signifies the average time taken by each packet to reach from source to destination. It comprises of all the various delays experienced during the trip from sender to receiver.

$$End\_to\_End\_Delay = \frac{\sum_{n=1}^{N} (R_n - S_n)}{\mathrm{N}} \tag{5.3}$$

Here,

S_n= Time at which nth packet is sent

R_n= Time at which nth packet is received

N=Number of packets received

a) Impact of traffic load :

Figure 5.12 represents the end-to-end delay performance among CUMAC, RTS/CTS scheme and the proposed protocol. From this graphical representation it is observed that, proposed protocol achieves a lower end-to-end delay over CUMAC protocol. As the graph shows, for the all three protocols delay upturns gradually. The reason is, at first node gets free data channel to transmit data to the intended receiver. Then data channels started to be occupied and after a certain period of time it releases again. Therefore, the curve gradually upturns with the increase of data channel access contention and traffic load. Performance results show that, proposed protocol provides much better performance than the other two. Compared with

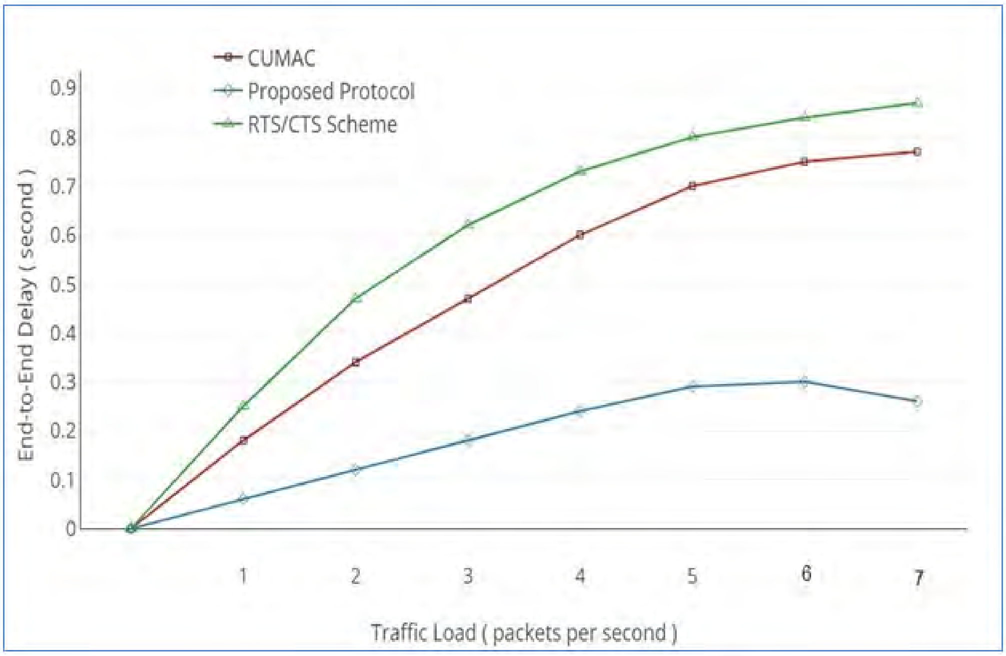

Figure 5.12: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of Traffic load on End to end delay

CUMAC and RTS/CTS scheme, this improvement comes from an aspect. That is proposed scheme allows concurrent transmission by channel allocation assessment with propagation delay map and transmission scheduling with collision detection. Thus eases the queuing delay through concurrent transmission and achieves better output for delay performance.

b) Impact of number of hops :

In this set of simulations, the performance of proposed protocol and other two protocols has been evaluated with different number of hops. Figure 5.13 represents that, for all three protocols end-to-end delay increases with the number of hops. The reason is the implementation of number of hops in the network. If there are number of hops in the network then the packet queuing delay, processing delay along with propagation delay will be incurred accordingly with the hop counts. From performance comparison it is observed that, proposed protocol provides much better output compared to the other two. This is because proposed scheme utilizes the information of propagation delay with an aim to exploit the network performance. As a result, it helps to alleviate collision and provides better output than CUMAC and RTS/CTS scheme.

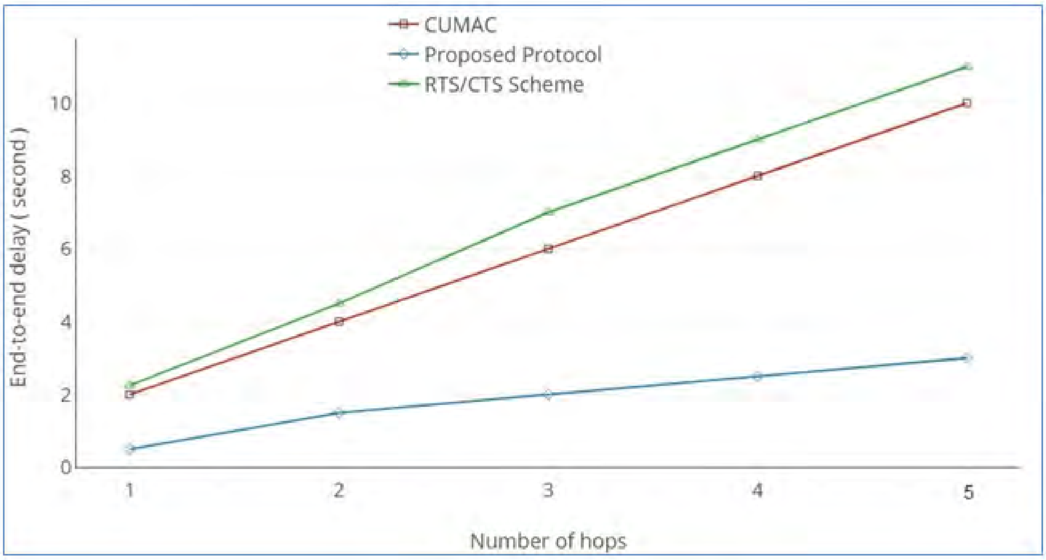

Figure 5.13: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of Number of hops on End to end delay

5.3.4 Packet Delivery Ratio (PDR)

The packet delivery ratio is the ratio of successfully delivered packets at the destination to the packets generated by the source. In short, it is the success rate of the protocol from source to destination. It can be represented as:

$$PDR = \frac{\text{Number of received packets}}{\text{Number of generated packets}} \times 100 \tag{5.4}$$

Table 5.2: **Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of Packet Delivery Ratio**

No. of Nodes	CUMAC PDR %	RTS/CTS Scheme PDR %	Proposed Protocol PDR %
5	87.5714	68.4019	91.7143
10	87.5620	67.0012	91.0014
20	86.0012	65.5578	90.0004

TABLE 5.2 shows that, packet delivery ratio degrades when number of nodes is increased. Proposed protocol also provides better performance than CUMAC and RTS/CTS scheme protocol in terms of packet delivery ratio.

5.3.5 Packet Loss Ratio (PLR)

Packet loss happens when one or more packets fail to reach their destination during data transmission across the network. Packet loss can be measured by a percentage of packets lost with respect to packets sent. Therefore,

$$PLR = \frac{\text{Number of lost packets}}{\text{Number of sent packets}} \times 100 \tag{5.5}$$

Table 5.3: **Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of Packet Loss Ratio**

No.of Nodes	CUMAC PLR %	RTS/CTS Scheme PLR %	Proposed Protocol PLR %
5	10.4286	28.5981	7.2857
10	10.4380	29.1181	8.0086
20	11.9999	30.0012	8.1281

As TABLE 5.3 represents, packet loss ratio increases with proportion to network size. With the network size, input traffic as well as collision probability in the network increases which causes packet loss. It is observed from the packet loss ratio analysis that, proposed protocol gives better performance than CUMAC and RTS/CTS scheme . This is because, channel allocation using propagation delay map along with transmission scheduling mechanism facilitates proposed protocol to manage input traffic load, channel utilization and collision detection. As a result, performance of the proposed protocol provides better output.

5.3.6 Collision Probability

The packets (control/data packets) that are transmitted within a time period are not successfully received by the intended receiver due to collision. As it is mentioned earlier, there is one control channel and multiple data channels in CUMAC, RTS/CTS scheme and proposed scheme. In case of proposed protocol, if a node detects that control channel is not available for packets then it goes to backoff and tries again after a random period of time. But collision might happen for packets due to long propagation delay.

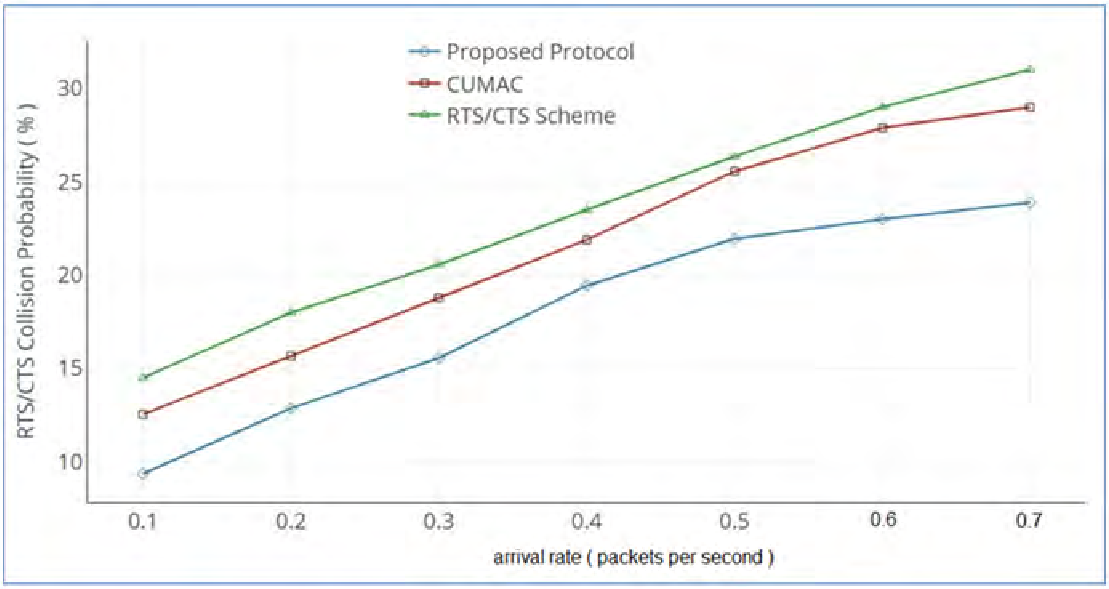

Figure 5.14: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of Arrival rate on Control Packet collision probability

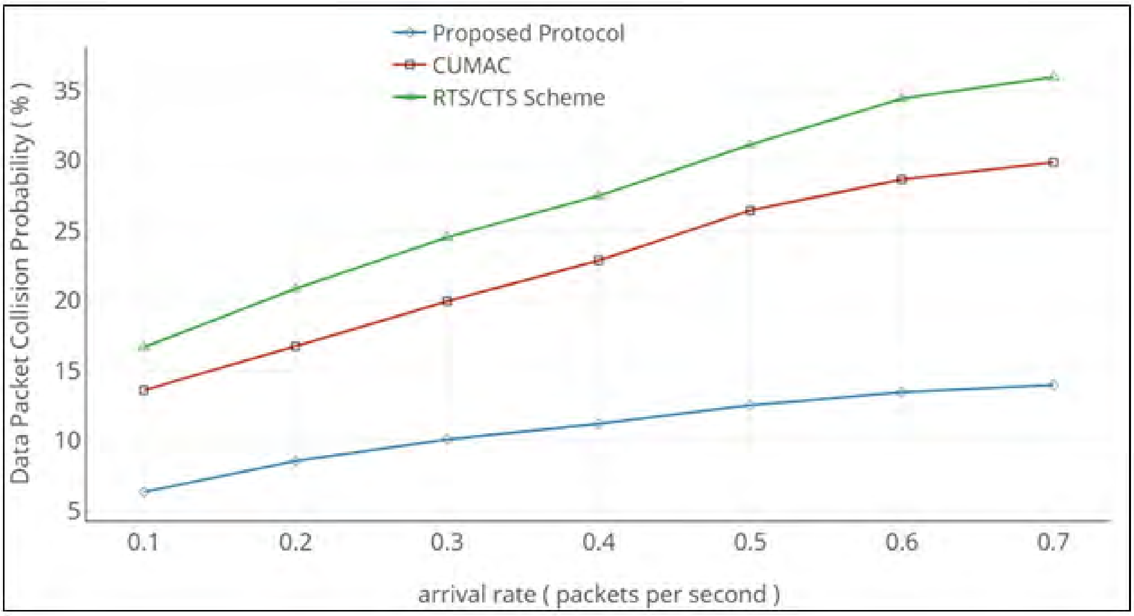

Figure 5.15: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of impact of Arrival rate on Data Packet collision probability

Although proposed scheme offers the mechanism of channel allocation assessment, transmission scheduling mapping with CAM and propagation delay to alleviate collision and support parallel transmission but collision might happen if multiple data packets are transmitted or received in the same data channel for a particular period of time. The collision probability can be calculated as:

$$P_{Col} = 1 - S_{SuccessRate} \tag{5.6}$$

Here, P_{Col} is the packet collision probability; $S_{SuccessRate}$ is obtained by dividing the number of packets successfully received by number of generated packets in the total simulation time. Figure 5.14 and Figure 5.15 show the control packet and data packet collision probability curves with respect to arrival rate and this comparison reflects that proposed protocol provides better output than the other two protocols. As proposed scheme goes for backoff algorithm for control packets transmission and implements channel allocation assessment, transmission scheduling mapping with CAM and delay mapping for data packet transmission. The aim is to avoid collisions. Therefore, results reflect that proposed protocol experiences less collision probability compared to CUMAC and RTS/CTS scheme.

5.3.7 Fairness Index

In underwater sensor networks, the propagation of acoustic signal is about 1500 m/s, leading the propagation delay of UWSN being several times longer than terrestrial wireless network. Furthermore, the high propagation delay in underwater sensor networks causes space-time uncertainty. Consequently, spatial fairness becomes a challenging problem in UWSNs. The packet which is sent earlier may reach later to the intended receiver due to the location and propagation delay. Closer nodes to the receiver have the opportunities to occupy the channel quickly, leads unfairness among the nodes. To analyze the fairness, Jain's Fairness Index [14] is used and defined as:

$$Fairness\ index = \frac{(\sum x_i)^2}{n \times (\sum x_i^2)} \tag{5.7}$$

Where, x_i denotes the throughput of node i and n denotes the number of nodes in the network.

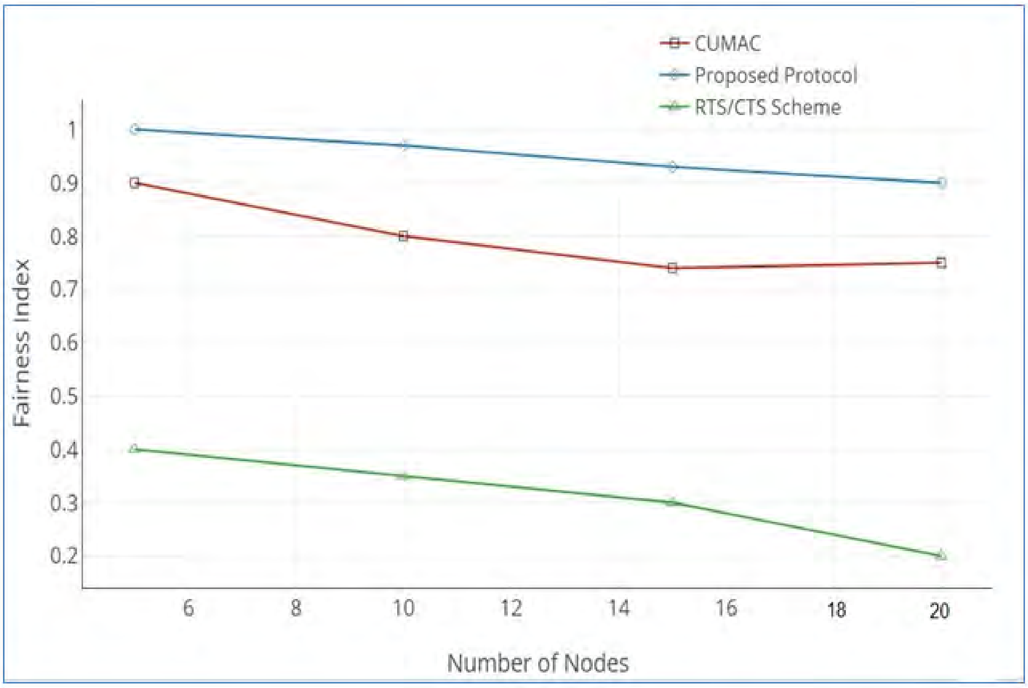

Figure 5.16: Comparison of the Proposed Protocol with CUMAC and RTS/CTS scheme in terms of Fairness Index

Figure 5.16 represents the comparison of fairness index among the three protocols. It is noticeable that, proposed protocol shows a high fairness index (0.9 and above) and remain stable with the network size. As proposed protocol use channel allocation matrix with propagation delay and timestamp information during transmission scheduling .Therefore, every sender-receiver has a fair opportunity of concurrently accessing the medium with the proposed scheme. On the other hand, CUMAC implements cooperative collision detection and tone pulse sequence. But CUMAC and RTS/CTS scheme both protocols do not consider the timestamp and propagation delay mapping during transmission. Consequently, proposed protocol achieves higher fairness compared to CUMAC and RTS/CTS scheme.

5.4 Performance Results Summary

Performance results summary of the Proposed Protocol compared to CUMAC and RTS/CTS scheme is presented in the below tables:

Table 5.4: **Results Summary : Average Network Throughput**

Metrics	**CUMAC**	**RTS/CTS Scheme**	**Proposed Protocol**
Input traffic at 0.05 packets/sec	160 bytes/sec	92 bytes/sec	180 bytes/sec
Data Channels = 8	200 bytes/sec	100 bytes/sec	250 bytes/sec
Data Packet Length 600 bytes	225 bytes/sec	180 bytes/sec	250 bytes/sec
Delay variance 0.1 sec	130 bytes/sec	90 bytes/sec	160 bytes/sec
Number of hop = 1	100 bytes/sec	50 bytes/sec	120 bytes/sec

Table 5.5: **Results Summary : Average Energy Consumption**

Metrics	**CUMAC**	**RTS/CTS Scheme**	**Proposed Protocol**
Input traffic at 0.07 packets/sec	25 milli-joule/byte	34 milli-joule/byte	22 milli-joule/byte
Data Channels = 8	11 milli-joule/byte	14 milli-joule/byte	7 milli-joule/byte
Data Packet Length 600 bytes	7 milli-joule/byte	11 milli-joule/byte	5 milli-joule/byte
Delay variance 0.1 sec	32 milli-joule/byte	34 milli-joule/byte	26 milli-joule/byte
Number of hop = 1	16 milli-joule/byte	17 milli-joule/byte	8 milli-joule/byte

Table 5.6: **Results Summary : End-to-end delay**

Metrics	**CUMAC**	**RTS/CTS Scheme**	**Proposed Protocol**
Traffic load at 7 packets/sec	0.75 sec	0.86 sec	0.25 sec
Number of hop = 1	2 sec	2.5 sec	1 sec

Table 5.7: **Results Summary : Packet Delivery Ratio**

Metrics	**CUMAC**	**RTS/CTS Scheme**	**Proposed Protocol**
Number of nodes = 5	87.5714%	68.4019%	91.7143%

Table 5.8: **Results Summary : Packet Loss Ratio**

Metrics	**CUMAC**	**RTS/CTS Scheme**	**Proposed Protocol**
Number of nodes = 5	10.4286%	28.5981%	7.2857%

Table 5.9: **Results Summary : Control Packet Collision Probability**

Metrics	**CUMAC**	**RTS/CTS Scheme**	**Proposed Protocol**
Number of nodes = 5	13%	14.5%	9%

Table 5.10: **Results Summary : Data Packet Collision Probability**

Metrics	**CUMAC**	**RTS/CTS Scheme**	**Proposed Protocol**
Number of nodes = 5	14%	16.5%	6.5%

Table 5.11: **Results Summary : Fairness Index**

Metrics	**CUMAC**	**RTS/CTS Scheme**	**Proposed Protocol**
Number of nodes = 5	0.9	0.4	1

5.5 Summary

Simulation results verify that the proposed scheme significantly improves the network performance and reliability of the system in terms of throughput, energy consumption, end-to-end delay, packet delivery ratio, packet loss ratio, collision probability and fairness index compared to CUMAC and RTS/CTS scheme protocols.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

A range of studies have been conducted on MAC protocols in underwater network. Most of the studies focused on single-channel networks in underwater. Acoustic communication protocols initiated to embrace the idea to utilize the multiple channels in underwater sensor network as RF arena. Researchers came up with a CUMAC protocol, focusing on triple (multichannel, long delay and traditional multi-hop) hidden terminal problems in underwater sensor networks. CUMAC and previous studies on underwater network has paid attention on overcoming the challenges of the acoustic channel. However, very few works exploit the characteristics of large propagation delay as a means to increase throughput. In this research work, propagation delay estimation and CAM has been addressed for enhancing channel utilization and handling multi-channel hidden terminal problem in underwater sensor networks. In addition, as stated earlier, in underwater acoustic communication, transmission is more expensive compared to reception in terms of energy consumption. To overcome all the limitations, this research work focused on the enhancement of earlier work on CUMAC and provides an efficient solution to THT problems in underwater sensor networks. A novel CAM with incorporation of propagation delay mapping and channel allocation assessment has been introduced with an aim to enhance channel utilization. With the benefit of propagation delay, proposed MAC scheme focus on increasing the chances of concurrent transmission while preventing the likelihood of collisions. Results from the performance analysis show that the proposed MAC protocol is more efficient in terms of network throughput, energy consumption, end to end delay, packet delivery ratio, packet loss ratio, collision probability and fairness index compared to both CUMAC and RTS/CTS scheme protocols. But there are some limitations also, such as each node maintains a CAM and delay map to assess channel to make a decision for collision free transmission. Therefore, an additional memory allocation is needed for the maintenance of CAM and delay map in proposed protocol. Moreover, channel allocation assessment strategy is not implemented for control packet transmission, which may lead to collisions over the control channel. Thus to provide an effective solution for avoiding control packets collision, an investigation is required to employ transmission scheduling with delay mapping strategy on control channel as implemented for data channels in the proposed scheme.

6.2 Future Work

With an aim of further improvement, the extension of this research work will be focused in three directions:

- The proposed scheme is implemented by considering the communication architecture of static sensor nodes in two dimensional underwater sensor networks. In case of three-dimensional underwater networks, sensor nodes float at different depths to detect a given phenomenon. Therefore, the future study will be focused on sensor nodes deployment by considering the architecture of static three dimensional underwater sensor networks.

- An investigation will be carried out to implement the propagation delay mapping along with channel allocation assessment scheme for the control packet transmission

- Moreover, a mathematical analysis will also be examined to validate the simulation results comparing the performance of existing and proposed protocol.

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Appendix A

APPENDIX A

Thesis simulation code

ProposedMAC.tcl [General]

```
set opt(chan) Channel/UnderwaterChannel
set opt(prop) Propagation/UnderwaterPropagation
set opt(netif) Phy/UnderwaterPhy
set opt(mac) Mac/UnderwaterMac/ProposedMAC
set opt(ifq) Queue/DropTail
set opt(energy) EnergyModel
set opt(nn) 5
set opt(x) 500
set opt(y) 500
set opt(stop) 300
Mac/UnderwaterMac/ProposedMAC
set packet size 300
set ns [new Simulator]
set topo [new Topography]
set tracefd [open $opt(tr) w] $ns_ trace-all $tracefd
set nf [open $opt(nam) w] $ns_ namtrace-all-wireless $nf $opt(x) $opt(y)
$ns_ at 0.0 "$god_ set_filename $opt(datafile)" $ns_ node-config -adhocRouting
$opt(adhocRouting)  -macType $opt(mac)
-ifqType $opt(ifq)
-ifqLen $opt(ifqlen)
-propType $opt(prop)
```

```
-phyType $opt(netif)
#-channelType $opt(chan)
-energyModel $opt(energy)
-txPower $opt(txpower)
-rxPower $opt(rxpower)
-initialEnergy $opt(initialenergy)
-idlePower $opt(idlepower)
-channel $chan_1_
-channel $chan_2_
set node_(0) [$ns_ node 0]
$node_(0) set sinkStatus_ 1
$node_(0) set passive 1
$god_ new_node $node_(0)
$node_(0) set X_ 5.0
$node_(0) set Y_ 5.0
$node_(0) set Z_ 0.0
$node_(0) set passive 1
set a_(0) [new Agent/UWSink]
$ns_ attach-agent $node_(0) $a_(0)
$a_(0) attach-vectorbasedforward $opt(width)
$a_(0) cmd set-range 100
$a_(0) cmd set-target-x -50
$a_(0) cmd set-target-y -20
$a_(0) cmd set-target-z -0
$a_(0) cmd set-filename $opt(datafile) #$ns_ at 20 "$a_(5) cbr-start"
#$ns_ at 20.0003 "$a_(2) cbr-start"
$ns_ at $opt(stop).05 "$god_ compute_energy"
proc stop
global ns tracefd namtrace
$ns flush-trace
close $tracefd
close $namtrace
```

$ns_ run

underwatersensornode.h .

```
#include "packet.h"
#include "mac.h"
#include "underwatermac.h"
#include "underwaterphy.h"
void
IncomingChannel::AddNewPacket(Packet* p){
IncomingPacket* t1;
IncomingPacket* t2;
t1=new IncomingPacket;
t1->next=NULL;
t1->packet=p;
t1->status=RECEPTION;
t2=head;
head=t1;
t1->next=t2;
num_of_active_incoming_packet++;
UpdatePacketStatus();
}
```

underwaterpropagation.h .

```
#ifndef
ns_underwaterpropagation_h
#define ns_underwaterpropagation_h
#include <topography.h>
#include <packet-stamp.h>
#include "underwaterphy.h"
class PacketStamp;
class UnderwaterPhy;
```

```
class UnderwaterPropagation : public TclObject {
public: UnderwaterPropagation() : name(NULL), topo(NULL) {}
double Attenuation(double, double, double);
virtual double Pr(PacketStamp tx, PacketStamp rx, UnderwaterPhy );
virtual int command(int argc, const charconst argv);
protected:
char name;
Topography topo;
};
```

underwaterpropagation.cc .

```
#include <stdio.h>
#include <topography.h>
#include "underwaterpropagation.h"
#include "underwaterphy.h"
static class UnderwaterPropagationClass: public TclClass {
public:
UnderwaterPropagationClass() : TclClass("Propagation/UnderwaterPropagation")
{}
TclObject create(int, const char const) {
return (new UnderwaterPropagation);
}
} class_underwaterpropagation;
double
```

proposedMAC.h .

```
#ifndef ns_proposedMAC_h
#define ns_proposedMAC_h
#include "underwatermac.h"
#define BACKOFF 0.1 // the maximum time period for backoff
#define MAXIMUMCOUNTER 4 // the maximum number of backoff
#define CALLBACK_DELAY 0.0001 // the interval between two consecutive send-
```

```
ings
#define CHANNEL_DELAY 0.0001 // the interval for switching channels
class proposedMAC;
class StatusHandler: public Handler{
public:
StatusHandler(proposedMAC);
void handle(Event);
private:
proposedMAC* mac_;
};
class CallbackHandler: public Handler{
public:
CallbackHandler(proposedMAC);
void handle(Event);
private:proposedMAC
proposedMAC mac_;
};
class BackoffHandler: public Handler{
public:
BackoffHandler(proposedMAC);
void handle(Event);
void clear();
private:
int counter;
proposedMAC mac_;
};
class proposedMAC: public UnderwaterMac {
public:
proposedMAC();
int command(int argc, const charconst argv);
int packetheader_size_;
int packet_size_;
```

```
Event backoff_event;
Event status_event;
Event callback_event;
StatusHandler status_handler;
BackoffHandler backoff_handler;
CallbackHandler callback_handler;
// to assess channel allocation and transmission scheduling
void Channelallocation(Packet );
//Node node(void) const {return node_;}
virtual void TxProcess(Packet);
virtual void RecvProcess(Packet);
void StatusProcess(Event);
void CallbackProcess(Event*); //void DropPacket(Packet*);
protected:
inline int initialized() {
return
UnderwaterMac::initialized(); }
private:
friend class StatusHandler;
friend class BackoffHandler;
};
```

proposedMAC.cc .

```
#include "packet.h"
#include "random.h"
#include "underwatersensor/uw_common/underwatersensornode.h"
#include "mac.h"
#include "proposedMAC.h"
#include "proposedMAC.h"
StatusHandler::StatusHandler(proposedMAC* p):mac_(p)
void StatusHandler::handle(Event e)
{
```

```
mac_->StatusProcess(e);
}
CallbackHandler:: CallbackHandler(proposedMAC p):mac_(p)
void CallbackHandler::handle(Event* e)
{
mac_->CallbackProcess(e);
} BackoffHandler::BackoffHandler(proposedMAC p):mac_(p)counter=0;
void BackoffHandler::handle(Event e)
{
counter++;
if(counter<MAXIMUMCOUNTER)
mac_>TxProcess((Packet)e);
else
{
clear();
mac_->CallbackProcess(e);
mac_->DropPacket((Packet) e);
}
}
void BackoffHandler::clear()
{
counter=0;
}
static class proposedMACClass :
public TclClass {
public:
proposedMACClass():TclClass("Mac/UnderwaterMac/proposedMAC") {}
TclObject create(int, const charconst) {
return (new proposedMAC());
}
}class_proposedMAC;
proposedMAC::proposedMAC() : UnderwaterMac(),status_handler(this),backoff_handler(this),callb
```

```
{
bind("packetheader_size_",&packetheader_size_);
bind("packet_size_", &packet_size_); }
proposedMAC::proposedMAC() : UnderwaterMac(),status_handler(this),backoff_handler(this),callb
{
bind("packetheader_size_",&packetheader_size_); bind("packet_size_", &packet_size_);
}
void proposedMAC::Channelallocation(Packet p)
{
hdr_new newh = hdr_new::access(p);
#ifdef new_DEBUG
printf("Time: NOW, index_, NOW, HDR_MAC(p)->macDA(), HDR_MAC(p)-
>macSA());
#endif
switch( newhh->packet_type )
case hdr_new::new_RTS: processRTS(p);
break;
case hdr_new::new_CTS: processCTS(p);
break;
case hdr_new::new_DATA: processDATA(p);
break;
case hdr_new::new_ACK:
processACK(p);
break;
default:
/*unknown packet type. error happens*/
printf("unknown packet type in proposedMAC::RecvProcess");
break;
}
Packet::free(p);
}
void
```

```
proposedMAC::RecvProcess(Packet pkt){ char mh=(char)pkt->access(hdr_mac::offset_);
hdr_cmn cmh=HDR_CMN(pkt);
assert(initialized());
int dst=this->hdr_dst(mh);
//cmh->txtime() -= getSyncHdrLen();
if (cmh->error())
{
if(drop_) drop_->recv(pkt,"Error/Collision");
else Packet::free(pkt); return;
} if(dst==(int)MAC_pkt || dst == index_ ){
if( packet_size_ ==0 ) {
cmh->size() -= packetheader_size_;
}
uptarget_->recv(pkt, this);
return;
}
Packet::free(pkt);
return;
}
void
proposedMAC::DropPacket(Packet pkt)
{
if(drop_) drop_->recv(pkt,"Stucked");
else Packet::free(pkt);
return;
}
void
proposedMAC::TxProcess(Packet pkt){
hdr_cmn cmh=HDR_CMN(pkt);
hdr_mac mach = hdr_mac::access(pkt);
mach->macDA() = (int)MAC_;
mach->macSA() = index_;
```

```
assert(initialized());
UnderwaterSensorNode n=(UnderwaterSensorNode) node_;
if( packet_size_ != 0 )
cmh->size() = packet_size_;
else
cmh->size()+=(packetheader_size_);
cmh->txtime()=getTxTime(pkt);
Scheduler& s=Scheduler::instance();
switch( n->TransmissionStatus() )
{
case SLEEP: Poweron();
case IDLE: n->SetTransmissionStatus(SEND);
cmh->direction()=hdr_cmn::DOWN;
cmh->addr_type()=NS_AF_ILINK;
//add the sync hdr sendDown(pkt);
backoff_handler.clear();
s.schedule(&status_handler,& status_event,cmh->txtime());
return;
case RECV:
{ double backoff=Random::uniform()BACKOFF;
s.schedule(&backoff_handler,(Event) pkt,backoff);
}
return;
case SEND: Packet::free(pkt);
return;
default:
return; }
}
```