A BIDIRECTIONAL MULTI-FLOW MAC PROTOCOL FOR MULTI-HOP UNDERWATER ACOUSTIC SENSOR NETWORKS

By

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MASTER OF SCIENCE

IN

INFORMATION AND COMMUNICATION TECHNOLOGY

Institute of Information and Communication Technology

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

The thesis titled "**A BIDIRECTIONAL MULTI-FLOW MAC PROTOCOL FOR MULTI-HOP UNDERWATER ACOUSTIC SENSOR NETWORKS**" submitted by Jenifar Rahman, Roll No. 0411312012 P, and Session April, 2011, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Information and Communication Technology on 25 September, 2017.

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Dedication

THIS THESIS IS DEDICATED

TO

MY PARENTS

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List of Abbreviations

AUV	Autonomous Underwater Vehicle
BiC-MAC	Bidirectional Concurrent MAC
BMF-MAC	Bidirectional Multi-flow MAC
BMF-M	Bidirectional Multi-flow
BMF-R	Bidirectional Multi-flow with reverse packet method
CDMA	Code Division Multiple Access
CMRT	Cascading Multi-hop Reservation and Transmission
CSMA	Carrier Sense Multiple Access
CTS	Clear To Send
FDMA	Frequency Division Multiple Access
HSR	Hybrid Sender- and Receiver-initiated
ISI	Inter Symbol Interference
MAC	Media Access Control
MACA	Multiple Access Collision Avoidance
MACA-U	MACA for Underwater
MFP	Multi-flow Packet
MR-MAC	Multi Receiver MAC
OS-sink	Onshore Sink
RF	Radio Frequency
RIPT	Receiver-Initiated Packet Train
ROPA	Reverse Opportunistic Packet Appending
RP	Retry Packet

RTS	Ready To Send
RTT	Round Trip Time
SDV	Small Delivery Vehicles
Slotted-FAMA	Slotted Floor Acquisition Multiple Access
SNR	Signal to Noise Ratio
S-sink	Surface Sink
STUMP	Staggered TDMA Underwater MAC Protocol
TDMA	Time Division Multiple Access
T-Lohi	Tone Lohi
UWSN	Underwater Sensor Network
UW-ASN	Underwater Acoustic Sensor Network
UW-A	Underwater Acoustic

List of symbols

f	Number of flow
$D^{f1}_{DD,S}$	Sender S delays from transmitting data for first flow f1
$d_{busy,S}$	Busy duration of node S
B_{size}	Batch size of data
$d_{WD,A}$	Waiting duration in $Wait\_Data$ state
$d^{i}_{trans,S}$	Transmitting time of data packet over i number flow for Sender S
T^{i}_{RMFP}	Receiving time of MFP for flow number i
T_w	Waiting time in $Wait\_Retry$ state
T_{RMFP}	Waiting time for receiving MFP from the next relay
$d^{i}_{WF,S}$	Waiting time in $Wait\_Flow$ state
d_{WD,R_i}	Waiting time in $Wait\_Data$ state
$d_{Reverse,R_i}$	Time to transmit data packet over reverse flow for relay node R_i
τ_{max}	Maximum propagation delay
$T\_control$	Common transmission time of control packets
d^{f1}_{data}	Batch data packets transmission time for flow one
T_{data}	Single data packet transmission time
d_{busy,R_i}	Busy duration of relay node R_i
p	Frame error probability
p_e	Bit error rate
l	Data packet size
l_{oh}	Frame overhead size
T_{CTS}	Duration of Sending a CTS Frame

Acknowledgment

All praises are for the almighty Allah for giving me the strength, without which I could not afford to attempt this research work.

I would like to express my sincere and heartiest gratitude to my honorable thesis supervisor Dr. Md. Saiful Islam, Professor, Institute of Information and Communication Technology (IICT), Bangladesh University of Engineering and Technology (BUET), Dhaka for his continuous motivation, guidance and keen encouragement which helped me throughout the time of my research work. Nothing is comparable to his keen advice and the freedom he provided for me in research. I am grateful to him for his cooperation throughout my thesis work. I would also like to express my heartfelt gratitude to my respected ex supervisors Dr. Mohammad Shah Alam, Associate Professor, IICT, BUET and Mst. Shamim Ara Shawkat, Assistant Professror, IICT, BUET for their continuous support and guidance during my Master's study and research work.

I would like to thank all the members of the board of examiners for their precious time in understanding my work and their insightful comments. I would like to thank to all of my friends and colleagues for their cooperation. At last I am grateful to my parents for their continuous supports and cooperation.

Abstract

Underwater Acoustic Sensor Network (UW-ASN) is a wireless network consisting of spatially distributed autonomous devices using sensors to monitor physical or environmental conditions under water. Due to the atypical characteristics of the physical media in underwater acoustic sensor networks (UW-ASN)–mostly because of long propagation delay, low bandwidth and high error rate–several challenges arise while designing a MAC protocol. In this research work, a Bidirectional Multi-Flow MAC protocol (BMF-MAC) for UW-ASN is proposed to handle multi-hop multi-flow data trails in such a way that multiple streams of data transmission proceed concurrently while adapting with varying traffic condition. BMF-MAC supports constitution of multi-hop flows by considering all pending packets in routing layer buffer and all flow setup requests from neighbors when setting up a flow, contrary to other underwater MAC protocols. The proposed MAC introduces a data transmission technique using the bidirectional multi-flow packet method for sending multiple data packets of the same flow in the reverse direction and thus, improve channel utilization. The protocol is aimed to schedule more data transmission over multiple multi-hop flows for rapid distribution of data and reduction of latency. In order to carry out the performance analysis of the proposed BMF-MAC protocol, a mathematical model is derived which includes the equation of energy consumption, throughput, end to end delay and frame error probability. Finally, performance comparison between the proposed BMF-MAC protocol and contemporary CMRT protocol is shown. Our comparison shows that proposed protocol outperforms the contemporary Cascading Multi-hop Reservation and Transmission (CMRT) protocol in terms of throughput, end-to-end delay, and energy consumption.

Chapter 1

Introduction

Underwater Acoustic Sensor Network (UW-ASN) is an emerging technology that has a diverse set of applications for vehicles and vessels navigating below the surface of the water. Environmental monitoring, resource investigation, disaster recovery and military surveillance are some of the extensively used applications [5]. Such a network normally consists of a large number of distributed nodes that organize themselves into a multi-hop network. Each node has one or more sensors, embedded processors and acoustic modem, and is normally battery operated. Typically, these nodes coordinate to perform collaborative monitoring tasks over a predetermined area.

Medium Access Control (MAC) protocol in underwater sensor networks has an important role to enable the successful operation of the network. One fundamental task of the MAC protocol is to avoid collisions so that two interfering nodes do not transmit at the same time. The proposed protocols for UWSNs generally can be classified into three types: ALOHA-based, time division multiple accesses (TDMA)-based and carrier sense multiple access (CSMA)-based in recent year.

Underwater sensor nodes are expensive as well as the sensing areas of ocean environments are large. Therefore, the sparse network deployments and the widespread use of mobile sensors are required. Furthermore, underwater sensors suffer from corrosion problem and the capacity of batteries are limited as well. Additionally, it is hard to access power sources such as solar in underwater, so the battery cannot be recharged in simple way [6]. The fundamental differences between terrestrial WSN and UW-ASN are discussed in the following. The propagation time of terrestrial WSN can be avoided as the network uses radio frequency (RF) electromagnetic signals with the speed of light (3×10^8 m/s) to transmit packet [7]. On the contrary, UW-ASN uses acoustic wave (1,500 m/s) as the communication carrier. As a result, the propagation delay will be one of the important characteristics due to the fact that the propagation time is much longer than RF electromagnetic signals. Thus, problem called "space-time uncertainty" arises. Furthermore, transmitting power consumption in UW-ASN is expensive. The transmitting power is typically 100 times more than the receiving power in acoustic links [8]. For this reason, some terrestrial protocols using packet exchange frequently are unsuitable when they are used in UW-ASN. Moreover, in underwater environment, the bandwidth is limited by the characteristics such as path loss, noise, multi-path, high delay variance, and Doppler-spread [9]. Hence, the physical media which is used in acoustic networks are characterized with long propagation delay, low data rate and high packet loss [2]. As a result, the wide variety of MAC protocols formerly proposed for wireless terrestrial networks do not perform well in underwater due to the above-mentioned uniqueness of underwater networks.

1.1 Related Work

The long propagation delay of the acoustic signal makes the designing of handshaking-based MAC protocol more complex to avoid any collision in under water environment. A number of works have been proposed to reduce handshaking significantly [3,7,10–14]. Some protocols have improved the channel utilization by sending multiple packets at once in a packet-train form [7, 10]. Furthermore, handshake-sharing approach is introduced in [3,11] has permitted multiple nodes to participate in a common handshake. Furthermore, some of the works adopted sender-initiated approach to provide solution while others adopted receiver-initiated approach to provide solution. In this thesis, we focus on the study of handshaking approach to improve performance of the sensor networks.

The multiple-access collision avoidance (MACA) protocol uses the request-to-send (RTS)/clear-to-send (CTS) handshake for reserving the shared channel which is a popular terrestrial handshake-based MAC protocol [15]. For implementing MACA in an underwater environment, MACA for underwater (MACA-U) was proposed which can revise the state transition rules considering the long propagation delay [16]. However, due to the long propagation delay in the underwater acoustic channel, the simple RTS/CTS exchange can not fully address the hidden-node problem. Moreover, the requirement of increased time for exchanging the control packet makes the performance of the protocol severely constrained. Furthermore, a spatial unfairness problem arises due to the long propagation delay in underwater environment.

The slotted floor acquisition multiple access (Slotted-FAMA) protocol, one of the pioneer MAC schemes, combines both carrier sensing and handshaking mechanisms that prevents collisions [17]. In this protocol, packets are transmitted at the beginning of a slot whose length is equal to the maximum propagation delay. However, the throughput performance is significantly reduced by the excessive length of the slot, though the protocol can prevent collisions caused by hidden nodes.

Bidirectional concurrent MAC (BiC-MAC) protocol [18] improves the channel utilization by transmitting data packets to a sender-receiver pair simultaneously for each successful handshake. The protocol adopts a packet bursting method that allows the sender and receiver node pair to exchange multiple rounds of bidirectional packet transmissions. Thus, the entire set of data packets is actually transmitted over several discontinuous packet bursts. Therefore, single sender and receiver is considered for bidirectional data transmission. However, multi-flow scenario is not considered.

A receiver-initiated MAC protocol named Receiver-Initiated Packet Train (RIPT) protocol is proposed in [10]. When a node wishes to become a receiver, it initiates the four-way ready-to-receive (RTR)/SIZE/ORDER/DATA handshake that schedules the packets from multiple neighbors to arrive at the receiver in a packet train. Although RIPT can get multiple data packets from neighbors, the four-way handshake takes a long time to receive the first packet train at the receiver node, especially in the underwater environment.

In MACA-MN [12], the communication with multiple neighbors to request for data transmission is established by the sender in each successful handshake. MACA-U with packet trains (MACA-UPT) was also introduced in [16]. MACA-UPT is derived from MACA-U, except that a sender transmits multiple data packets in a single handshake in the former.

In [11], the author introduces the Reverse Opportunistic Packet Appending

(ROPA) which is a hybrid MAC protocol and can be initialized by both sender and receiver. ROPA enables a sender to coordinate multiple neighbors by opportunistically transmitting their data packets and thus, improves channel utilization. However, ROPA faces more collisions as more control packet exchange is needed.

Additionally, to reduce unexpected collisions at the receiver due to hidden neighbors, Hybrid sender- and receiver-initiated (HSR) protocol [3] allows all nodes to avoid hidden-node-induced collisions according to an elaborately calculated waiting time. The protocol proposes a method for sharing the handshakes of control packets among multiple nodes. Handshake-sharing can be achieved by inviting neighbors to join the current handshake and by allowing them to send their data packets without requiring extra handshakes.

In multi receiver MAC (MR-MAC) [7] protocol, more than two nodes can communicate in one handshake holding by a main receiver. The protocol schedules the packet transmission time by sending the data packet in a packet train manner; thus, the receiver can receive data packet without collision. But, the protocol is too complicated to effectively improve network throughput and need too much control packets which will influence the network performance.

Additionally, reserving multi-hop channels at once in cascading manner, Cascading multi-hop reservation and transmission (CMRT) protocol [4] delivers the data packets to the destination by relaying data packets progressively. Furthermore, CMRT adopts a method based on packet train model in order to improve utilization of channel [12].

1.2 Motivation

While designing underwater MAC protocols; the long propagation delay is becoming leading feature to be considered in underwater acoustic channels circumstances. More specifically, the exchanging of control packets is time-consuming in handshaking-based MAC protocols. This causes a large signaling overhead. Furthermore, the end-to-end delay significantly rose while of multi-hop relaying take place in a hop-by-hop handshaking manner. By reserving the multi-hop channels at once with the help of cascading reservation control packets, CMRT [4] overcomes the problem of handshaking-based MAC protocols. Without stopping at intermediate nodes, the CMRT protocol delivers the data packets in the same manner until they reach the destination node. Therefore, CMRT plays different role from other conventional MAC protocols by this multi-hop reservation approach and thus, employs for multi-hop transmission. Moreover, for improving channel utilization, the protocol adopts a packet-train method [12] by sending multiple data packets together with only one handshaking signal. Thus the protocol is capable of reducing the control packet exchange time and increasing the throughput compared with conventional protocols accordingly. However, CMRT is based on single packet based flow setup. It cannot support multiple flow construction from a single node and transmit data simultaneously over multiple streams. Moreover, simultaneous transmission of regular and reverse data packets over a same flow can not be held by this protocol. As a result, the protocol poorly respond to heavy traffic loads. Therefore, an energy efficient MAC protocol with high channel utilization and low latency for UW-ASN in varying traffic conditions is necessary.

1.3 Research Objectives

Maximizing the network lifetime and throughput are the common objectives of sensor network research. Since sensor nodes are assumed to be disposed when they are out of battery, the proposed MAC protocol must be energy efficient by reducing the potential energy wastes. The core objective of this thesis is to design a new energy efficient bidirectional multi-flow multi-hop medium access control protocol for underwater acoustic sensor networks under different traffic load patterns.

During the process of designing this proposed protocol the following basic milestones are identified as the objectives of this thesis.

1. To develop a new multi-flow MAC protocol called BMF-MAC for multi-hop under water acoustic sensor networks in varying traffic conditions.

2. To improve the channel utilization and to reduce the end-to-end delay of the networks.

3. To carry out the performance analysis such as energy, throughput and latency of the proposed protocol.

4. Finally, to investigate the efficiency of the proposed BMF-MAC protocol, a performance comparison between BMF-MAC protocol and other existing protocols will be carried out.

1.4 Organization of Thesis

This thesis consists of five chapters. Brief description of its different chapter is as follows.

Chapter one briefly introduces MAC protocol of underwater sensor networks. Related researches regarding handshaking based MAC protocol as well as motivation and objective of this research are presented in this chapter.

Fundamentals of MAC protocol are explained in chapter two. Issues related to protocol design for the MAC sub layer of data link layer in OSI reference model and different types of medium access protocols (MAC) are illustrated in this chapter.

The details of the proposed BMF-MAC protocol are elucidated in Chapter three. In order to carry out performance analysis, an analytical model is derived which includes the equation of energy consumption, throughput, end to end delay, and frame error probability.

The performance of the proposed approach is investigated in terms of performance parameters such as number of throughput, end-to-end delay, and energy consumption in chapter four. Moreover, in order to show the effectiveness of the proposed scheme, a performance comparison between proposed BMF-MAC protocol and existing CMRT protocol is carried out in this chapter as well.

Finally, chapter five concludes this thesis along with some limitations and future research scopes.

1.5 Summary

Related research works of MAC protocol of UWSN is discussed in this chapter. Few barriers that must be taken into considerations while designing a MAC protocol is also depicted in this chapter. Furthermore, motivations for conducting this thesis are succinctly described. Finally, the objectives of this research, i.e, to propose a new energy efficient low latency MAC protocol, BMF-MAC protocol, based on

CMRT protocol to handle variable traffic load patterns for UWSNs, are mentioned in this chapter.

Chapter 2

FUNDAMENTAL ISSUES OF MAC DESIGN

A MAC layer protocol is critical to the UWSNs because it plays an important role to achieve the quality of service (QoS) in UWSNs. It is necessary to make a detailed study on different aspects of the design of MAC protocol to evaluate the performance of existing MAC protocols. In underwater acoustic environment, radio waves attenuate rapidly. For that reason, the signals can only travel over short distances. The optical signals are rapidly absorbed by water. Moreover, the optical signals cannot travel far in adverse conditions as the optical scattering caused by suspending particles and planktons is significant [19]. Besides, acoustic waves attenuate less and they are capable to travel farther distances than radio waves and optical waves [20]. As a result, UWSNs utilize acoustic waves to have information exchange dissimilar to terrestrial networks that rely on radio waves for communication. Therefore, in this chapter, we describe the underwater acoustic environment and identify the major challenges to the design of MAC protocols for UWSNs.

2.1 Differences between Underwater and Terrestrial Sensor Networks

UWSNs consist of a variable number of sensors and vehicles that are deployed both at underwater and at the surface to perform collaborative monitoring tasks over a given area. To achieve this objective, sensors and vehicles self-organize in an autonomous network which can adapt to the characteristics of the ocean environment. The nodes can exchange and share information among themselves and base stations.

Table 2.1 shows the difference of some features of WSN and UWSN. The main differences between terrestrial and underwater sensor networks are mentioned be-

Table 2.1: Difference between WSN and UWSN

Features	Terrestrial sensor networks	Underwater sensor networks
Communication medium	Air	Water
Communication carrier	Radio frequency	Acoustic wave
Transmission Speed	$3X10^8$ m/s	1,500 m/s
Deployment	Densely deployed	Sparsely deployed
Power	Lower compare to UWSN	Higher compare to WSN
Propagation delay	Negligible	Long
Cost	Less expensive	Expensive
Memory	Limited capacity	Higher compare to WSN

low [1]:

1. **Power:** Due to higher distances and more complex signal processing at the receivers to compensate for the impairments of the channel in underwater environment, the power needed for acoustic underwater communications is higher than in terrestrial radio communications.

2. **Memory:** Terrestrial sensor nodes have very limited storage capacity. UW-sensors may need to be able to do some data caching as the underwater channel may be intermittent.

3. **Cost:** Now a days, terrestrial sensor nodes are becoming increasingly inexpensive. On the other hand, underwater sensors are expensive devices. Because, underwater transceivers are more complex and strong hardware protection is needed in the extreme underwater environment.

4. **Deployment:** Terrestrial sensor networks are densely deployed. On the other hand, the deployment is deemed to be more sparse in underwater as the cost involved and the challenges associated to the deployment itself is high.

5. **Spatial correlation:** From terrestrial sensors, the readings are often equated. On the contrary, this happens rarely in underwater networks as the distance is high among sensors.

2.2 Underwater Sensor Hardware Design

In Figure 2.1, the typical internal architecture of an underwater sensor is demonstrated. The sensor contains a main controller/CPU which is interfaced with an oceanographic instrument or sensor through a sensor interface circuitry. The controller can receive data from the sensor and store it in the on board memory. Then the CPU processes data and send; it to other network devices by controlling the acoustic modem. The electronics are generally mounted on a frame that is protected by a PVC housing. Constantly, all sensor components are protected by bottom-mounted instrument frames. This frames grants azimuthally omni direc-

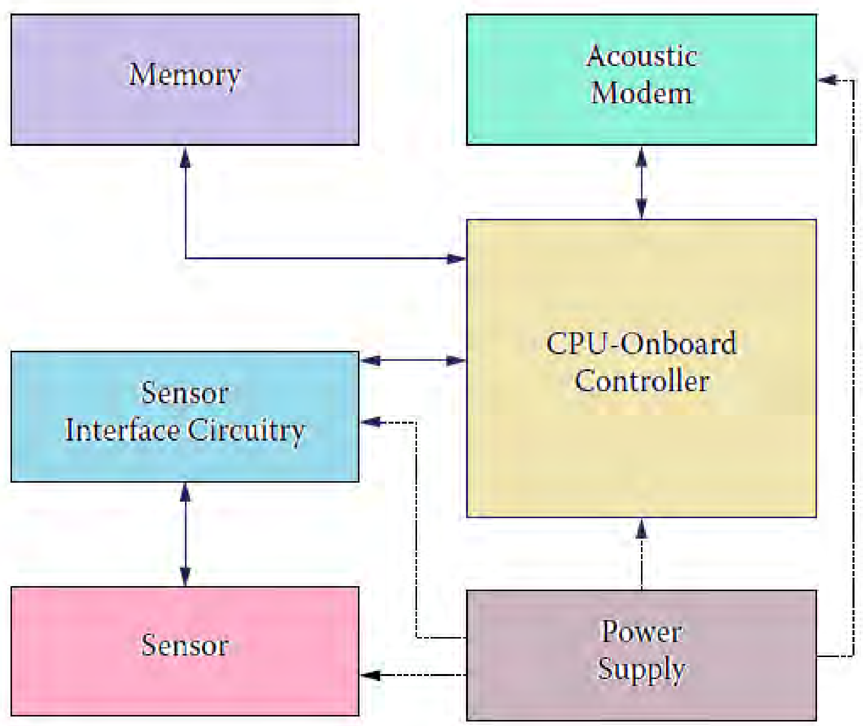

Figure 2.1: Internal architecture of an underwater sensor node

tional acoustic communications and defends sensors and modems from potential impact of trawling gear, especially in areas subjected to fishing activities. By housing all components beneath a low-profile pyramidal frame, in [21], the author design the protecting frame to deflect trawling gear on impact [1].

Underwater sensors are consist of sensors which can measure the quality of water and study its characteristics like temperature, density, salinity, acidity, chemicals, conductivity, pH, oxygen, hydrogen, dissolved methane gas, and turbidity. Disposable sensors can detect ricing, the highly poisonous protein found in costar beans and thought to be a potential terrorism agent. Furthermore, to monitor both abundance and activity level variations among natural microbial populations, DNA micro arrays are used. Quantum sensors can measure light radiation and harmful algal blooms as well.

The challenges related to the deployment of low cost, low scale underwater sensors, are listed as follows:

- To develop less expensive, robust "nano-sensors", e.g., sensors based on nanotechnology is crucial.
- To improve accuracy and precision of sampled data for robust, stable sensors is necessary; since sensor drift of underwater devices may be a concern.
- To devise periodical cleaning mechanisms against corrosion, fouling is needed, which causes impaction on the lifetime of underwater devices.
- For synoptic sampling of physical, chemical, and biological parameters, new integrated sensors are required which can improve the understanding of processes in marine systems.

2.3 Communication Architecture of Underwater Acoustic Sensor Networks

The underwater sensor network topology is an open research issue that needs more analytical and simulative investigation from the research community. The communication architecture of underwater acoustic sensor networks are described in this section. Here we describe the reference architectures which are used as a basis for discussion of the challenges associated with underwater acoustic sensor networks [22].

Static UW-ASNs are established by sensor nodes that are anchored to the bottom of the ocean. There common applications are environmental monitoring, or monitoring of underwater plates in tectonics [23].

Figure 2.2 displays a reference architecture for underwater networks. Here, we observe a group of sensor nodes are anchored to the bottom of the ocean with deep ocean anchors. Underwater sensor nodes are interconnected to one or more underwater sinks (UW-sinks) with the help of wireless acoustic links. These are network devices in charge of relaying data from the ocean bottom network to a surface station. Generally, UW-sinks are equipped with two acoustic transceivers called a vertical and a horizontal transceiver. UW-sink uses the horizontal transceiver for communicating with the sensor nodes. They can send commands and configuration data to the sensors (UW-sink to sensors), collect monitored data (sensors to UW-sink). Furthermore, UW sinks use the vertical link as well. They can relay data to a surface station. Vertical transceivers should be long range transceivers for deep water applications as the ocean can be as deep as 10 km. The surface station which is capable to handle multiple parallel communications with the deployed UW-sinks is equipped with an acoustic transceiver. Moreover, it is endowed with a long range

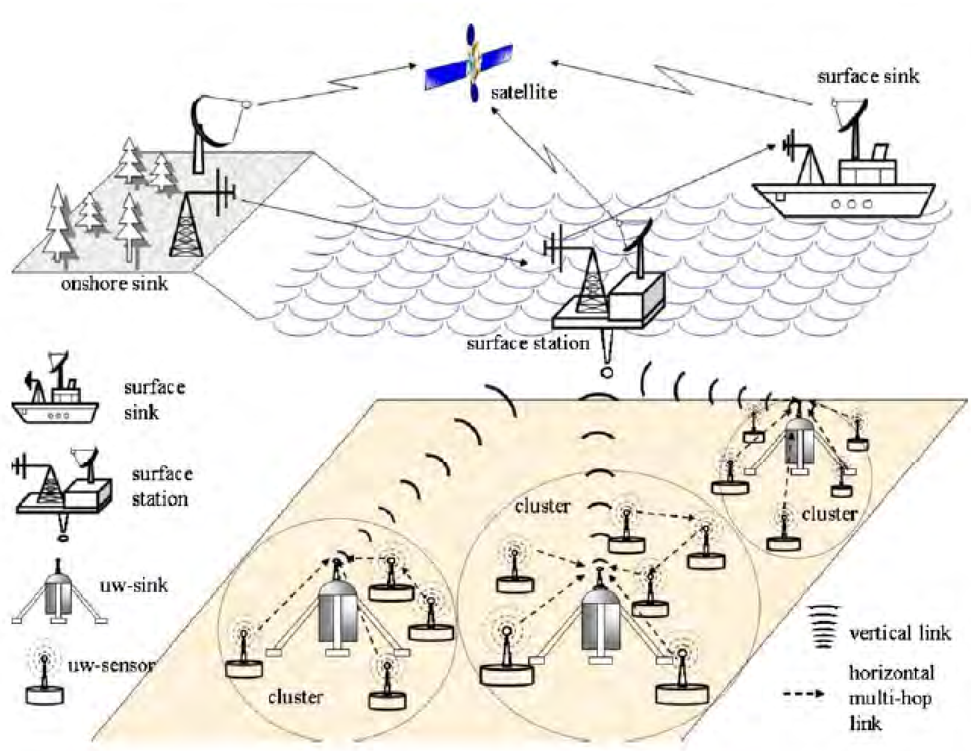

Figure 2.2: Architecture for underwater sensor networks (from [1])

RF and/or satellite transmitter to communicate with the onshore sink (OS-sink) or to a surface sink (s-sink).

By means of direct links or through multi-hop paths, sensors are connected to UW-sinks . Each sensor directly sends the gathered data to the selected UW-sink in the first case. Though this is the easiest way to network sensors, it is less energy efficient. Because, the sink may be far from the node and the power necessary to transmit may decay with powers greater than two of the distance. Moreover, due to increased acoustic interference caused by high transmission power, direct links are very likely to reduce the network throughput. As in terrestrial sensor networks [24], for multi-hop paths condition, the data accomplished by a source sensor is forwarded by intermediate sensors until it reaches the UW-sink. This causes more energy savings and increases network capacity. However, this increases the complexity of the routing functionality. Every network device usually takes part in a collaborative process. Their key responsibility is to diffuse topology information such that efficient and loop free routing decisions can take place at each intermediate node. This can be achieved by the mechanism which consists of signaling and computation. From above discussion we can conclude that, energy and capacity are precious resources in underwater environments. The essential goal in UW-ASNs is to deliver event features by exploiting multi-hop paths and minimizing the signaling overhead necessary to construct underwater paths at the same time.

2.4 Basic Characteristics of Acoustic Communications

Underwater acoustic communications are generally effected by path loss, noise, multi-path, Doppler spread and high, and variable propagation delay. These factors regulate the temporal and spatial variability of the acoustic channel, and make the available bandwidth of the Underwater Acoustic (UW-A) channel limited and dramatically dependent on both range and frequency. There are long-range systems which can operate over several tens of kilometers but have a bandwidth of only a few kHz. At the same time, a short-range system operating over several tens of meters may have more than a hundred kHz bandwidth. These factors lead to low bit rates [25] for both cases. Furthermore, comparing with the terrestrial radio channel, the communication range is diminished dramatically.

There are different kinds of underwater acoustic communication links. They can be classified according to their range as very long, long, medium, short, and very short links [26]. According to the direction of the sound ray, there are various kind of acoustic links named as vertical and horizontal. Their propagation characteristics differ consistently, especially with respect to time dispersion, multi-path spreads, and delay variance. Shallow water refers to water with depth lower than 100m, while deep water is used for deeper oceans in oceanic literature [22].

In order to state the challenges posed by the underwater channels for underwater sensor networking, the factors that influence acoustic communications are analyzed here. These include:

1. **High delay and delay variance:** In the UW-A channel the propagation speed is five orders of magnitude lower than in the radio channel. This large propagation delay (0.67 s=km) can reduce the throughput of the system considerably. For designing an efficient protocol, the very high delay variance is even more harmful. Because, it prevents from accurately estimating the round trip time (RTT) which is the key measurement for many common communication protocols.

2. **Path loss:** Water depth plays a major role in determining the attenuation which is mainly provoked by absorption due to conversion of acoustic energy into heat, which increases with distance and frequency. Moreover, it may occurred by scattering and reverberation (on rough ocean surface and bottom), refraction, and dispersion (due to the displacement of the reflection point caused by wind on the surface).

3. **Geometric Spreading:** Geometric Spreading increases with the propagation distance. It is independent of frequency. This refers to the spreading of sound energy by cause of the expansion of the wavefronts.

4. **Noise:** Man made different types of noise. This is mainly caused by machinery noise produced from pumps, reduction gears, power plants and shipping activity, etc. Ambient noise is connected to hydrodynamics (movement of water including tides, currents, storms, wind, rain, etc.), seismic and biological phenomena.

5. **Multi-path:** Multi-path propagation generates Inter-Symbol Interference (ISI) may cause for severe degradation of the acoustic communication signal.

   The multi-path geometry depends on the link configuration. Vertical channels are characterized by little time dispersion. In fact, horizontal channels may have extremely long multi-path spreads, whose value depend on the water depth.

6. **Doppler spread:** The Doppler frequency spread can be significant in UWA channels [26]. This causes a deterioration in the performance of digital communications. Transmissions at a high data rate cause many adjacent symbols to interfere at the receiver, requiring sophisticated signal processing to deal with the generated ISI.

The chemical physical properties of the water medium such as temperature, salinity and density and spatio-temporal variations are the cause of the above mentioned factors. These variations, together with the wave guide nature of the channel, cause the acoustic channel to be temporally and spatially variable. Specifically, in both deep and shallow water, the horizontal channel is by far more rapidly varying than the vertical channel.

2.5 Features of the Underwater Acoustic Environments

For designing of MAC protocol compared to that of terrestrial networks, the underwater acoustic environment poses more severe circumstances [2, 22, 27].

1. **High and Variable Propagation Delay:** The propagation speed of sound is about 1500m/s in underwater [28]. Hence, the propagation delay in underwater is five orders of magnitude higher than that of radio frequency (RF) terrestrial channels over air. Moreover, the propagation delay in underwater is extremely variable that depends on temperature, salinity and depth of water. As a result, propagation delay is negligible for short range RF, whereas it is a critical for underwater communications. This causes serious implications on the design of MAC protocols.

2. **Limited Bandwidth and Data Rate:** The available acoustic bandwidth depends on the transmission distance due to high environmental noise at low

medium frequencies. This can be lower than 1 kHz or high-power absorption at high frequencies or can be greater than 50 kHz [26]. Only a few kHz may be available at tens of kilometers, while tens of kHz will be available at a few kilometers. Acoustic modems generally work at the frequencies from merely a few Hz to tens of kHz. Therefore, the data rate for underwater acoustic sensors can hardly exceed 100 kbps. Compared with the bandwidth in the order of several hundred MHz offered by RF radios, the very limited bandwidth of acoustic channels needs concerned design of coding schemes and MAC protocols used in UWSNs.

3. **Noise:** Environment noises consist of man-made noise and ambient noise. Man-made noise mainly refers to machinery noise like pumps while natural noise refers to seismic and biological phenomena can cause ambient noise.

4. **Energy Consumption:** In sensor nodes batteries are energy constrained and cannot be recharged easily. Moreover, the acoustic transceivers under water have transmission powers in the order of magnitude higher than that of the terrestrial devices with a higher ratio of transmit to receive power, so the protocols which utilize the acoustic radio effectively become much more important in UWSNs [29].

5. **High Bit Error Rates:** Due to multi-path fading, the underwater channel is severely impaired. Multi-path propagation is accountable for severe degradation of the acoustic communication signals as it generates Inter Symbol Interference (ISI). Higher value of ISI may cause in higher bit error rates. Shadow zones and temporary losses of connectivity can be experienced in addition to the high bit error rates. Long paths and the frequency-dependent attenuation can cause "Shadow zone". It shows almost no acoustic signal existing in it. Therefore, to design a MAC protocol great challenge is to provide certain reliability and maintain connectivity in such a harsh propagation conditions. The application of MAC protocols used for UWSNs will lead to inefficient results for these characteristics. Finally to develop MAC protocols suitable for underwater acoustic communications, it is necessary to take all the characteristics into account.

2.6 Challenges to the Design of MAC Protocols for UWSNs

The challenges which have to be focused in the design of UWSNs MAC protocols are explained in this section [27]. Conceiving a MAC protocol is a major challenge for the deployment of UWSNs. An optimal underwater MAC protocol should consider higher network throughput, and lower energy consumption, taking into account of the rough characteristics of the underwater acoustic environment [2].

1. **Network Topology and Deployment in UWSNs:** In practical, the performance of any MAC protocols for UWSNs is hugely responsible on the deployment of underwater nodes which could be sparse or dense. For the reason of the sensors nodes can monitor as well as communicate at long distance due to the availability of long range acoustic modems, event readings of sparsely deployed nodes would be extremely uncorrelated.

2. **Synchronization:** The MAC protocols such as the duty cycling approach work generally based on the time synchronization of the nodes. So, synchronization is a critical challenge in the design of MAC protocols. If synchronization can not take place accurately, the duty cycling approach cannot assure effective operation of sensor networks by handling time uncertainty between sensor nodes. Because, the propagation delay is much higher and changes from time to time.

3. **Hidden Node and Exposed Node Problem:** The problems of hidden nodes and exposed nodes arise more particularly in contention-based collision avoidance MAC protocols. Hidden node situation takes places when one node cannot sense one or more nodes that can interfere with its transmission. Besides, when a station delays transmission because of another overheard transmission that would not collide with it, an exposed node appears. There will be collision and the nodes have to keep attempting for successful transmission for hidden node problem.

4. **High Delay Associated in Handshaking:** The conventional handshaking schemes need time and energy to exchange control information. Thus, can reduce the effect of hidden terminal and exposed terminal. The most of the

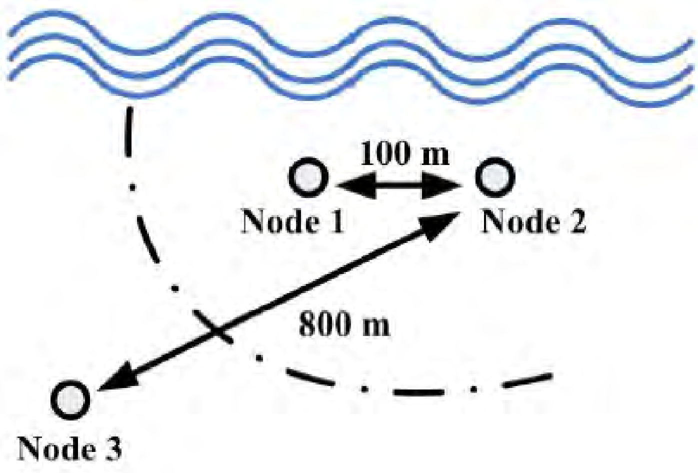

Figure 2.3: Near-Fear Problem (from [2])

communication time is required because of exchanging of control information. For this reason, the nodes have not much time for the payload delivery. The channel utilization rate is very low. The big challenge to the design of efficient handshaking protocols is high propagation delay in underwater environment.

5. **Power Waste in Collision:** In underwater environment a node consumes more power on transmission than on reception. More specifically, the ratio of power required for reception to transmission is typically 1/125 [30]. Moreover, frequently appear of collisions makes the ratio becomes worse due to the lack of an appropriate collision avoidance mechanism. Therefore, a MAC protocol should be designed such a way that it can avoid or minimize collisions.

6. **Near-Far Effect:** When the signals received by a receiver from a sender near the receiver is stronger than the signals received from another sender located farther then the near-far effect happens. The transmission power should be selected at the transmitter such a manner that the signals transmitted from the transmitter to the intended receiver should be correctly received with the desired SNR which is neither lower nor higher than the required SNR. In Figure 2.4 [31] the scenario of this problem is explained. From figure, we can see that nodes 1 and 3 can transmit simultaneously without causing collisions as they are far away. Here, as a result of high level of noise produced by the signals coming from node 1, at node 2, the SNR level of the signals originated

from node 1 is higher than that from node 3. For this reason, node 2 can receive both signals but it cannot decode the messages from node 3. So, node 1 is unintentionally screening the transmissions from node 3.

7. **Centralized Networking:** In UWSNs centralized solutions are not a suitable solution over an acoustic channel. The communication between nodes happens through a central station in a centralized network scenario. The presence of a single failure point is the major disadvantage of this configuration. Furthermore, the network cannot cover large areas due to the limited range of a single modem [32].

2.7 Hidden-Node Problem in UWSNs

By means of exchanging RTS/CTS control packets, handshake-based protocols normally try to reserve the channel which are probably overheard by neighbors. Then, the neighbors are informed that the channel will be reserved. Therefore, they remain in the sleep mode as far as the occupied channel is released by stopping any

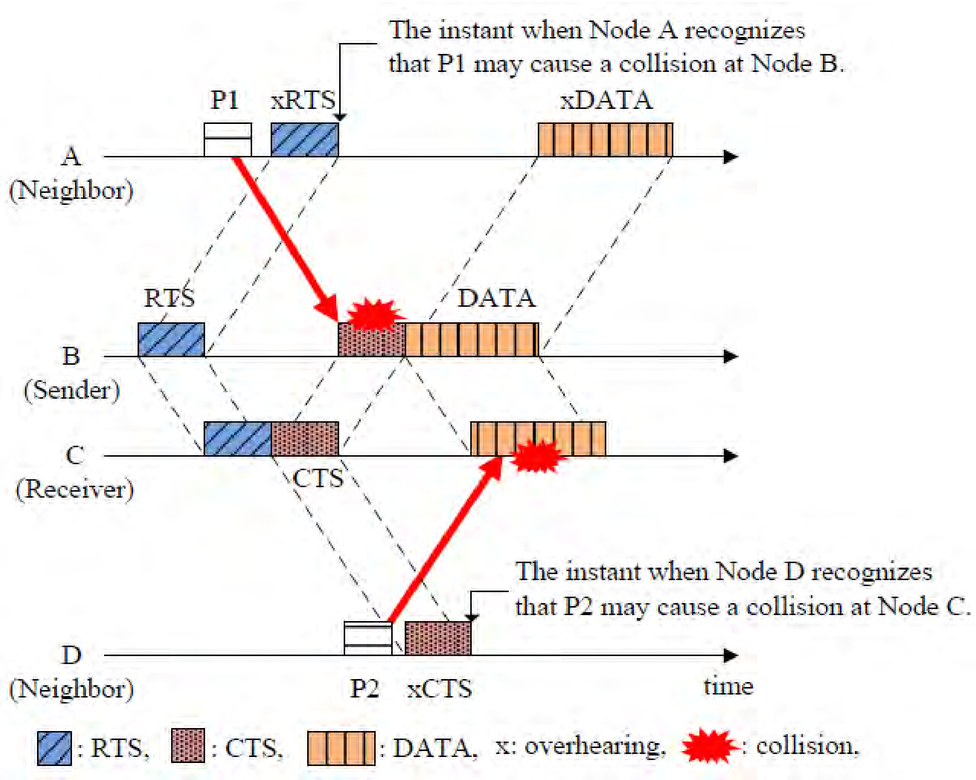

Figure 2.4: Hidden-node problem in UWSNs (from [3])

transmissions. Thus they can avoid any possible collisions caused by neighboring hidden nodes.

As a result of long propagation delay, a new type of hidden-node problem is introduced yet in the underwater acoustic channel. Figure 2.5 illustrates the hidden node problem. Here, nodes A and D are the neighbor nodes. They may identify a channel reservation too late by overhearing the RTS or CTS after completing the transmission of their control packets, P1 and P2. This causes the early departure of packets without observing channel reservation. This may result collisions at the sender node B and receiver node C, which is indicated by the solid arrows. Nodes A and D are hidden from nodes B and C in this example. In a terrestrial radio channel, a hidden node is located beyond the signal's coverage; so its existence is not recognized. On the contrary, due to the long propagation delay, a hidden node problem may also appear even when it is located within the region covered in an underwater acoustic channel.

2.8 Space-Time Uncertainty

Space-Time Uncertainty problem is highlighted in Figure 2.5. Here, a collision that occurs in RF-based terrestrial WSNs where the propagation delay is negligible is explained. The y-axis denotes the distance between nodes. If node A and C are transmitting packets, the packets may collide at destination node B. This collisions can be refrained by scheduling such a manner that the durations of the transmission

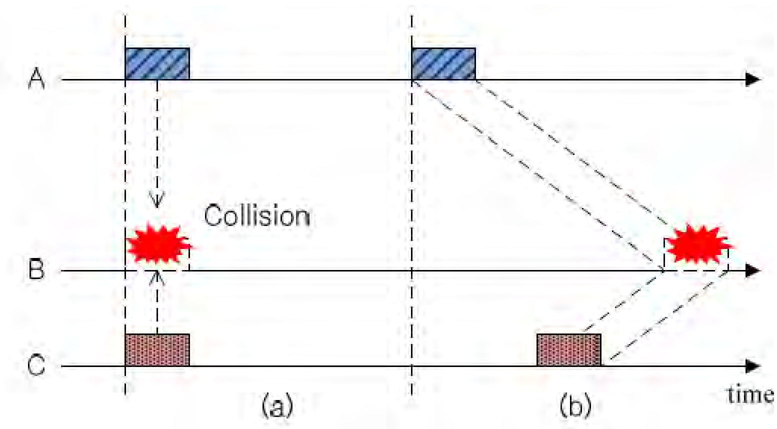

Figure 2.5: Space-time uncertainty a) terrestrial RF channel b) underwater acoustic channel (from [4])

time do not overlap. Therefore, only the transmission time uncertainty should be acknowledged. Additionally, the long propagation delay of the acoustic signal makes it more complex to avoid any collisions in under water environment. Therefore, we have to consider not only the transmission time, but also the distance between nodes. From Figure 2.7(b), we see that, two packets transmitted from Nodes A and C at different times collide at node B. This type of two-dimensional uncertainty in determining a collision at the receiver is named as space-time uncertainty [33].

2.9 Contention-free MAC protocols

Pioneer research studies focused on contention-free MAC protocols for UWSNs. The contention-free MAC protocols and their variations are studied in this section. Generally, three major multiple access techniques FDMA, TDMA, and CDMA are used [2].

2.9.1 Frequency Division Multiple Access (FDMA)

In FDMA, the available frequency band is divided into sub bands and each sub band is assigned to an individual user. Thus, the channel is used only by the user until it is released. The bandwidth of the total of the FDMA channels is smaller than the coherence bandwidth of original transmission channel. Therefore, the simple FDMA multiple access technique is not suitable for UWSNs, as the limited bandwidth of underwater acoustic channels and the vulnerability of limited band systems to fading and multi path.

2.9.2 Time Division Multiple Access (TDMA)

TDMA divides a time interval, called a frame, into time slots which are assigned to an individual user. Time slots and overhead bits are combined into frames. Furthermore, by adding guard times collisions of packets from adjacent time slots are prevented [32]. Therefore, TDMA is more simple and flexible and better multiple access technique applied to UWSNs. The guard time periods need be designed to separate different channels for large propagation delay and delay variance over the acoustic channels. Thus, it can minimize the probability of collisions in data transmissions, which can lead to lower channel utilizations [34]. Furthermore, the implementation of a precise synchronization with a common timing reference is required for TDMA which is very much tough due to the variable delay [35].

FDMA medium access has limited bandwidth and frequency selectivity on the acoustic channels. Therefore, TDMA medium access technique becomes the major candidate for the underwater acoustic communications for overcoming the inherent inefficiency. Various types of contention free MAC protocols based on TDMA multiple access technique have been developed to control the medium access recently. They focus on overcoming the lacking of the TDMA medium access technique such as inaccurate synchronization and low channel utilization. The design challenges of synchronization and high delay associated are mainly faced by the TDMA-based protocols.

The staggered TDMA Underwater MAC Protocol (STUMP) [36] allows nodes to use simple or more energy efficient synchronization schemes. Therefore, it does not require tight node synchronization to achieve high channel utilization. Four possible conflicts and the propagation delay have made the scheduling to be constrained in STUMP protocol.

2.9.3 Code Division Multiple Access (CDMA)

Multiple users are allowed to operate simultaneously over the entire frequency band by CDMA. CDMA can distinguish signals from different users with the help of pseudo-noise (PN) codes which are used for spreading the user messages [32]. Thus, the receiver can filter noise by the spreading-code to gain the correct signal. CDMA does not require synchronization and becomes the promising medium access technique. However, the CDMA technique suffers from near-far problem, which is the major design challenge for the MAC protocols. Therefore, the development of contention-free CDMA-based MAC protocol is few. A power control algorithm is used to handle the reduction of the output power level of each node such a manner that it can deal with the near-far problem.

2.10 Contention-based MAC protocols

Exploiting the full bandwidth of the communication channel is the main focus of the most of the contention-based MAC protocols while designing for UWSNs [37].

The nodes compete for a shared channel resulting in probabilistic coordination in the contention based protocols. The Contention-based protocols can be classified further into random access and handshaking protocols [2].

2.10.1 Random Access

There are generally two approaches ALOHA and Carrier Sense Multiple Access (CSMA) for random access scheme. Whenever a node has data ready for the delivery, it simply starts its transmission in the random access approaches. If a data packet arrives at a receiver and it is not receiving any other packets and there is no other packet coming in the period, then the receiver can receive this packet successfully. Therefore, multiple nodes share the transmission medium randomly without any control with the help of the random access approaches. RCAMAC is one of random access scheme where the entire bandwidth is shared by many stations which easily suffer various collisions.

2.10.1.1 ALOHA protocols

In ALOHA approach, there is no prevention of collisions. Thus, it is the simplest random access MAC protocol to be easily implemented. When a node has data ready to send, it will send the data at its will. Therefore, if two nodes transmit packets at the same time, a collision occurs. A retransmission is required in this case. The protocol works in this manner.

In [38], author presents an explanation of Slotted ALOHA protocols for UWSNs. A node cannot send its packets at any time in the Slotted ALOHA protocol. Therefore, the node has to wait for the beginning of a time slot. Hence, the protocol reduces the chances of collisions.

2.10.1.2 CSMA protocols

CSMA is a typical class of random access protocols. In CSMA, each node has to sense the channel for a certain period of time before the channel access. If users listen to the channel before transmitting a packet, then the scarce resources of the channel can be utilized much better.

In [39], a new class of CSMA-based MAC protocols named Tone-Lohi (T-Lohi) has been proposed to solve the problem of space-time uncertainty. Nodes contend to reserve the communication channel to send data in T-Lohi protocol.

2.10.2 Handshaking

The handshaking protocol is another important type of the contention-based MAC protocol. The protocol is essentially a group of the reservation-based protocols. A transmitter has to capture the channel before sending any data is the core idea of the handshaking or the reservation-based schemes. The handshaking MAC protocols can be classified into two categories: the MAC protocol with single channel and the MAC protocol with multiple channels.

2.10.2.1 MAC protocols with single channel

By the MAC protocols with single channel, only one channel is utilized for data communication. Exchanging of the handshaking messages for capturing the channel will be executed before any transmission of payload over only one channel.

Slotted FAMA, MACA-U, MACA-MN, RIPT, DOTS, R-MAC, ROPA, SF-MAC are renowned handshaking-based MAC protocol which are described in [10–12, 16, 17, 40–42] respectively.

2.10.2.2 MAC protocols with multiple channels

The multiple channel protocols utilize more than one channel for communication dissimilar from single channel MAC protocols. By this protocol, the node with outgoing packets will sends a RTS message over the control channel. Furthermore, the RTS frame have to consist of the sender/receiver identifier, the available channel set and the packet length.

2.11 Cascading Multi-Hop Reservation

The cascading multi-hop reservation and transmission (CMRT), reserves the multi-hop channels at once with the help of cascading reservation control packets. Here, relay nodes between a source and a destination can start handshaking in advance for the next-hop relaying before handshaking for the previous node is completed. The protocol delivers the data packets in the same manner until they reach the destination node without stopping at intermediate nodes. Furthermore, the protocol adopts a packet-train method [12] by sending multiple data packets together with only one handshaking signal, thus improves channel utilization,

CMRT assumes that every node knows the inter-nodal distance to its neighbors within a one-hop range and has the routing table to facilitate multi-hop relay [41]. A node shifts between six different states such as $Idle$, $Wait\_Resp$ (Wait for response), $Delay\_Data$ (Delay Data transmission), $Wait\_Data$ (Wait for Data reception), $Data\_Rx$ (Data Reception) and $Silence$.

The CMRT operation is illustrated in Figure 2.6. Here, R1 and R2 relays exist between source S and destination D. By transmitting RTS to relay R1, a multi-hop relay begins with the source S staying in the Idle state. Node S enters the $Wait\_Resp$ state after transmitting RTS packet. The RTS packet consists of the following information: the address of the final destination; batch size, the number of data packets to be transmitted, B_{size}; the busy duration of Node S, $d_{busy,S}$; and hop count to denote the number of hops from the source node. With the progress of reservation of channel, the value of the hop count will be increased by one.

For reserving the channel for the next hop, upon receiving RTS, the relay node R1 transmits a control packet named request-to-reserve (RTR) to the next node. CMRT introduces a new control packet named RTR which is paired with a responding control packet named clear-to-reserve (CTR) similar to the pairing of RTS with CTS. RTR packet contains the same information like RTS. The RTR is adopted

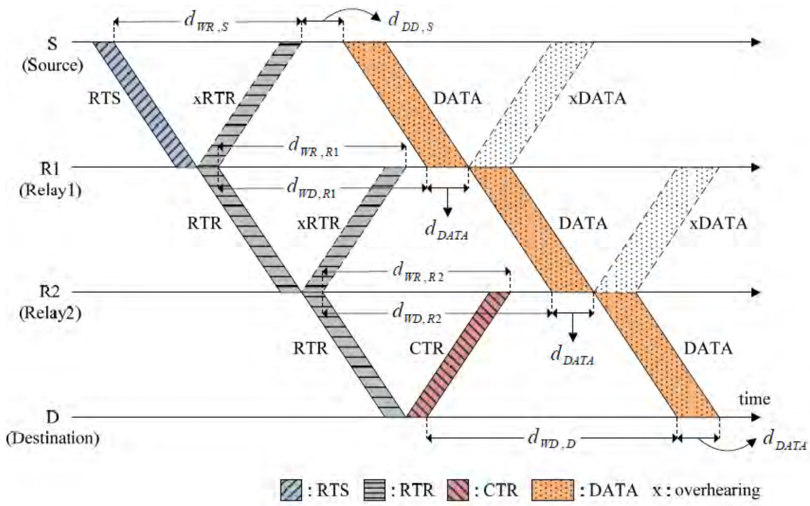

Figure 2.6: Operation of CMRT protocol (from [4])

for both reserving the channel for the next hop and to respond to RTS/RTR of the previous hop for allowing backward overhearing. After relaying RTR from node R1 to node R2 in the forward direction, node S overhears RTR in the backward direction, which is denoted by xRTR and is helped to recognize that the node's previous request (RTS) was successfully sent and processed for the next-hop relay. Node R1 enters $Wait\_Resp$ and $Wait\_Data$ states at the same time after relaying RTR. On the other hand, node R1 would not transit to the Idle state immediately, instead, Node R1 will stop the data forwarding and transit to the Idle state after the *Data_Rx* state regardless of whether it successfully receives a train of data packets. Each relay node works in the same way as node R1. Instead of transmitting RTR destination D transmits CTR to the previous relay node as a response to RTR. The CTR packet (as well as the CTS packet) contains the information about the busy duration of destination D ($d_{busy,D}$).

In CMRT, the RTR perform a key role for cascading reservation information through multiple hops. In this manner, the protocol reduces handshaking and data delivery times efficiently. To avoid causing possible collisions with the hidden nodes, source S delays data transmission for the length of *Delay_Data* ($d_{DD,S}$).

2.12 Summary

This chapter provides a brief overview of the communication architecture of underwater sensor networks, role of MAC layer in network architecture, different types of multiple access techniques in MAC layer, problems that may encounter during MAC protocol design, different classes of MAC protocols and the issues that should be considered during MAC protocol design. Furthermore, the challenges of different types of under water sensor network MAC protocols that should be considered during MAC protocol design are also depicted in this chapter as well.

Chapter 3

A BIDIRECTIONAL MULTI-FLOW MAC PROTOCOL

This chapter presents a new energy efficient, low latency medium access control protocol, Bidirectional Multi-flow MAC protocol (BMF-MAC), for UW-ASNs. This protocol is based on handshaking-based MAC protocol to handle variable traffic load patterns for UW-ASNs. The proposed BMF-MAC protocol is aimed at improving the performance of existing CMRT protocol [4]. At first, the operation cycles of proposed MAC protocol along with its control frame structure is illustrated. Multi-hop multi-flow data forwarding with reverse packet method is outlined here as well. Transition diagram and algorithm for data transmission technique for both sender and relay node are also laid outed. Finally, in order to evaluate the performance of the proposed MAC protocol, mathematical model is derived which includes energy consumption, latency, throughput and frame error probability.

3.1 System Description

In this thesis, we have proposed a multi-flow MAC protocol in static underwater sensor networks. We consider that every node is equipped with an omni-directional half-duplex acoustic modem. It is assumed that nodes estimate the propagation delay using information obtained from their two-hop neighbors. While the network is initialized, the distance between nodes are calculated with the help of control packets that measure round-trip time (RTT) or by information sharing between neighboring nodes [4]. Moreover, we consider all nodes have routing tables which aid to relay through multi-hop nodes.

3.2 Flow Setup Communication

BMF-MAC is designed to schedule multiple bidirectional packets over multiple flows, each of which requires multi-hop communication with per round channel reservation similar to [43]. During scheduling of allocation of channels, the proposed MAC protocol takes into account all outstanding packets in routing layer while considering all pending requests for flow setup. Therefore, the MAC layer detects the variations of traffic load as well as the reserved time for packet transmission. In BMF-MAC, nodes can setup communication by means of multi-flow setup packets (MFP) which is uniquely structured to efficiently address multiple destinations. MFP is a series of control packets, across multiple hops through multiple flows. An MFP serves both as an RTS and as a CTS packet to the destination and source nodes respectively, similar to [43]. Furthermore, some cross-layer information like the address of the final destination and the hop count for the current flow are enclosed in MFP as well. The network layer is responsible to pass down this final destination address. When the source node generates the data packet, it sets the hop count to zero. In the process of channel reservation, the value is increased by one. Moreover, MFP includes the number of data packets to be transmitted, batch size B_{size}, the busy duration of Node

Extend (1)	Length (1)	Type (1)	Previous Node Address (2)	Current Node Address (2)	Next Hop Node Node Address (2)	Duration of Trans.(2)	Final Destination Address (2)	Number of Hop (1)	CRC (1)

(a)

Batch Size(4)	Busy Duration(4)

(b)

Figure 3.1: (a) RTR packet of CMRT (b) Extend of RTR in CMRT

Extend (2)	Length (1)	Type (1)	Previous Node Address (2)	Current Node Address (2)	Next Hop Node Node Address (2)	Duration of Trans.(2)	Final Destination Address (2)	Number of Hop (1)	CRC (1)

(a)

Batch Size(4)	Busy Duration(4)	Number of flows(3)	Flow ID(3)	Reverse Flag(2)

(b)

Figure 3.2: (a) MFP packet of BMF-MAC (b) Extend of MFP in BMF-MAC

S, $d_{busy,S}$ like [4]. Furthermore, it has the ability to address several destinations, i.e., one MFP can operate as an RTS up to k different destinations. Additionally, the number of flows, flow ID and reverse flag are enclosed in MFP packet. The control packet structures of CMRT and proposed BMF-MAC are illustrated in Figure 3.1(a) and 3.2(b) respectively.

3.3 Network Model

In our proposed protocol flow is set in this manner that, multiple flows can be constructed from single node, thus a node can transmit multiple packets over multiple flows. Furthermore, a sender can sends different packets to different multiple destination nodes. From intermediate node of the flow may add additional final destinations. The network model is considered with multiple sinks. The network model is illustrated in Figure 3.3.

3.4 Definition of States

In BMF-MAC protocol, a node shifts between fourteen different states. Six states are defined in the same way as CMRT protocol. Four new states are introduced to handle data transmission over reverse flow direction. Figure 3.4 illustrates the states of the protocol.

The state where a sender waits for a response to a request control packet (e.g., RTS) from a receiver is called $Wait\_Resp$ state. After transmitting a request control packet, the sender stays in the $Wait\_Resp$ state until receiving a response control

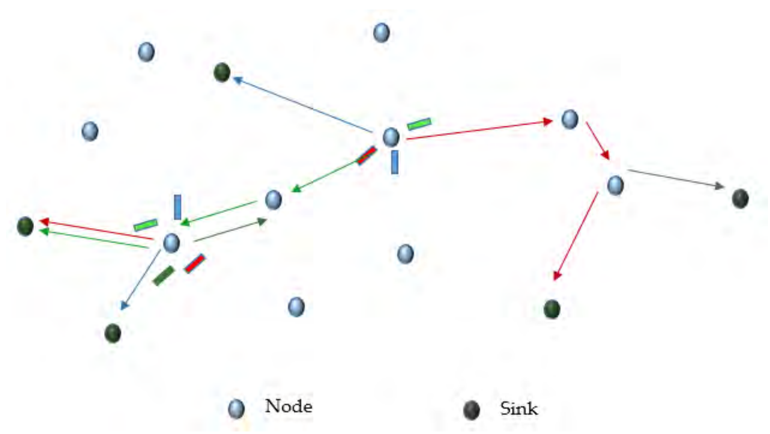

Figure 3.3: Network Model

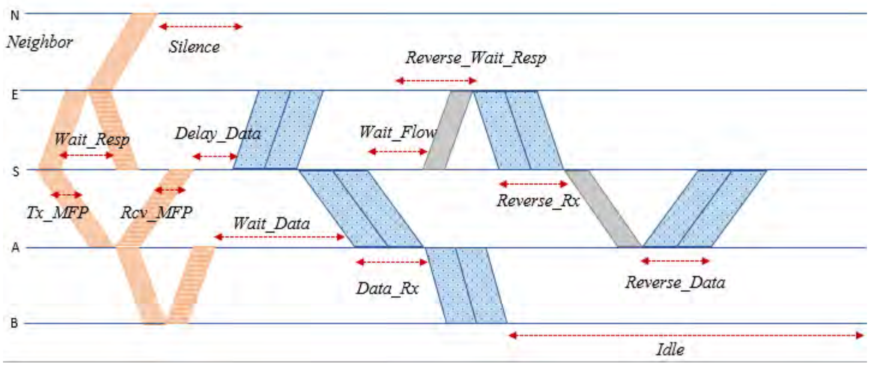

Figure 3.4: States of BMF-MAC protocol

packet. Within the duration of *Wait_Resp* state, if the sender does not receive a response control packet, it will transit to the *Idle* state.

The state where a sender delays data transmission to avoid possible collisions caused by the hidden nodes is called *Delay_Data* state. After receiving a response control packet from the receiver, the sender enters the *Delay_Data* state and remains there until it starts transmitting data packets. The length of the *Delay_Data* state is elaborately calculated, and the calculation procedure is presented in Section 3.7.

The state where a receiver waits for data packets from a sender is called *Wait_Data* state. After transmitting a response control packet, the receiver enters the *Wait_Data* state directly and remains there until it starts receiving data-packets.

A receiver receives data packets in *Data_Rx* state.

The state where neighbors who overheard the exchange of control packets for channel reservation remain silent is named *Silence* state. As the node do nothing they do not cause collisions. Neighbors enter the Silence state after overhearing the control packets involved in other nodes' channel reservation until the channel becomes free of reservation. The Silence state ensures that any transmissions from neighbors arrive after data reception is completed at a receiver.

The *Idle* state is a state where a node has no activity to do.

Here, we introduce a state named *Tx_MFP* where a node sends requested MFP packet to relay node. Furthermore, a state *Rcv_MFP* is defined where a node receives confirmed MFP from receiver node.

A state named *Wait_Flow* is introduced where a receiver waits for forward data transmission to be finished over a flow. The receiver enters the Wait_Flow state directly after transmitting batch data packets and stays there until it starts transmitting CTS for reverse data transmission to be received.

A sender waits for a response (e.g., CTS) from a receiver in state $Reverse\_Wait\_Resp$. After finishing forward data transmission, if a sender finds its reverse flag is set, it waits to start its data transmission of the same flow in reverse direction.

Another state $Reverse\_Data$ is presented where a sender delays data transmission for avoiding possible collisions caused by the bidirectional data transmission. Meanwhile sender receives a CTS from the receiver, the sender enters the Reverse_Data state and remains there until it finishes the transmission of reverse data packets.

Moreover, a state called $Reverse\_Rx$ is designed where a receiver receives data packets from reverse flow direction.

Finally, two states Tx_Retry and $Wait\_Retry$ are defined to handle any missing control packet data transmission. While a receiver node does not find data packet from its corresponding sender, it transmits another control packet named Retry Packet in Tx_Retry state. On the other hand, if any sender node misses its confirm MFP, it waits for Retry Packet(RP) from the receiver node in $Wait\_Retry$ state.

3.5 Protocol Description

Figure 3.5 and 3.6 illustrate the topology and the operation of the BMF protocol correspondingly. In Figure 3.5, it is assumed that node S denote a sender. Suppose node S has batch packets for destination nodes C and G. Here, relay nodes E and F remain between source S and destination G in one flow direction. On the other hand, between source S and destination C relay nodes A and B remain in other stream direction. Therefore, node S sends packets to destination node C through node A, and B and destination node G through E, and F respectively.

Relaying process of multi-flow is established when the source node S starts transmitting MFP, a newly introduced control packet in BMF protocol, to relay nodes E and A simultaneously. After transmitting MFP, sender S enters the $Wait\_Resp$ state like CMRT protocol [4]. Node S starts the handshake by transmitting MFP to node E and node A with the first destination address set to node E, and the second destination address set to node A. The scheduling of addresses depends on node distances; short distant node will be prioritized first.

The first destination, node E, sends an MFP packet to relay node F in the forward direction and node S overhears MFP in the backward direction. At the same time, the second destination, node A, sends an MFP packet to relay node B in the forward direction and node S overhears MFP in the backward direction. Utilizing the propagation delay between nodes due to distances, these two flows can take place simultaneously in our proposed protocol. After relaying MFP, sender node S enters state *Delay_Data*. On the other hand, both relaying node A and E go in state $Wait\_Data$. Upon receiving S's MFP, node A performs the same steps as node E.

Concurrently receiving E's MFP, F performs the same actions as E. This process of receiving a MFP and immediately transmitting another MFP continues until either the final destinations node G and C have received the MFP or the end of the current MFP period is reached. Here, the MFP performs a fundamental action for reserving information through multiple hops over multiple flows in parallel in cascading way. Therefore, it can reduce handshaking and data delivery times in an efficient manner.

As first address has given to node E, it has the first scheduling priority for both regular and reverse flow data transmissions. If node S earlier received the confirmation MFP from its next hop E, S relays the data packet to E after the time interval of *Delay_Data* ($D^{f1}_{DD,S}$) like [4]. Here, $D^{f1}_{DD,S}$ means the delay time of sender node S from transmitting data for first flow. The relay node E can transmit a train of data packets to the next relay node F continuously without having any

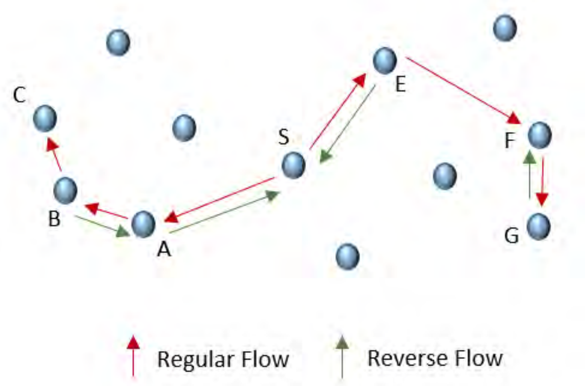

Figure 3.5: Topology

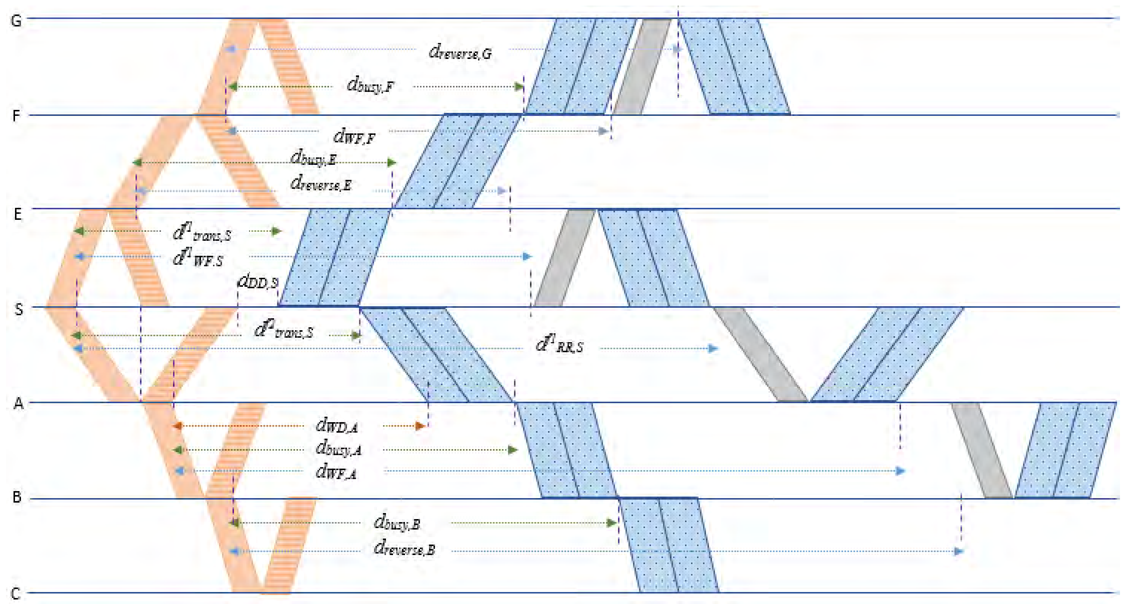

Figure 3.6: Operation of the bidirectional multi-flow MAC protocol

time duration between packets. Correspondingly, node F also forwards the train of data packets without interval for the reason that the multi-hop channels are reserved directed toward the destination nodes.

To stay away from possible collisions from data transmission over other flows, source node S delays from transmitting data for $Delay\_Data$ ($D^{f1}_{DD,S} + d_{data}$). The data delivering process of the second flow works as the same way as the first one. This data packet sending process continues at each hop until the final destination C is reached. Thus, data relaying process is very much like a pipeline process. The data from two different steams can be delivered simultaneously in our proposed protocol.

3.5.1 Transmission of Data Adopting the Reverse Packet Method

Control packet MFP adopts a data transmission technique using the reverse multi-flow packet method where multiple data packets are sent from the same flow in reverse direction. Hence, channel utilization will be increased.

Figure 3.6 illustrates how the reverse packet method is employed in BMF protocol. Here, two flows of data transmissions concurrently happened. After successful transmission of data packets from source S to G and S to C, the data transmissions of reverse packets take place. If any node has packet from similar flow in reverse direction, it sets its reverse flag to 1 when transmitting MFP packet. When a node observes that it has packet from reverse flow direction, it simply sends a CTS packet to sender and sender then sends the packet to the destination node.

Suppose, for the first flow from S to G, there are reverse packets from node E to S and node G to F. Therefore, while transmitting MFP packet from S to E, S sets its reverse flag to 1. Moreover, F transmits MFP in the same manner to node G. After the transmission of data packets from node S to E and S to A, node S enters in $Wait\_Flow$ state and transmits a CTS to node E and E immediately transmits data packet to S. Furthermore, as there is no transmission going on one hop distance of node F, after completion of forward transmission of data packets from nodes F to G, F sends a CTS to G and G sends reverse data packet to F instantly.

Algorithm 1 Reverse Waiting Time Calculation

```
1: if reverse_flag = 0 in requested MFP of R_{i-1} then
2:     d_reverse[R_i] = d_WF[R_{i-1}] + T_CTS + propagationdelay
3: else
4:     d_reverse[R_i] = d_WF[R_{i-1}] + 2T_CTS + 2 propagationdelay + d_data
5: end if
```

Imagine that node A has batch packets for destination node S and node B has batch packets for destination node A. As node A is set as second destination, after end of regular and reverse transmission of node E, node A starts its reverse flow data packet transmission. Node S transmits a CTS to node A. and A immediately transmits data packet to S. The data sending process from node B to A performs in the same way as well. The reverse waiting time calculation has been described in Algorithm 1.

3.5.2 Transmission of Data Adopting Request Packet Method

The Algorithm 2 and 3 explain the retry technique of handling any missing MFP packets.

Scenario 1: Sender misses a confirmation: Suppose in Figure 3.7, the sender node S does not receive confirmation MFP packet to its requested MFP of node A. Let, $d_{WD,A}$ waiting duration of node A in $Wait\_Data$ state. After $d_{WD,A} + T_w$ (T_w is a short waiting time) duration of time when receiver A does not receive data from sender S, node A assumes that its confirmation MFP packet does not received by

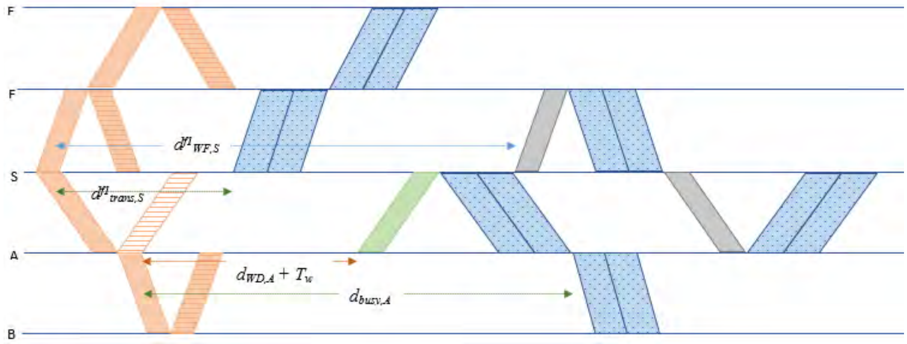

Figure 3.7: Scenario 1: Sender misses a confirmation

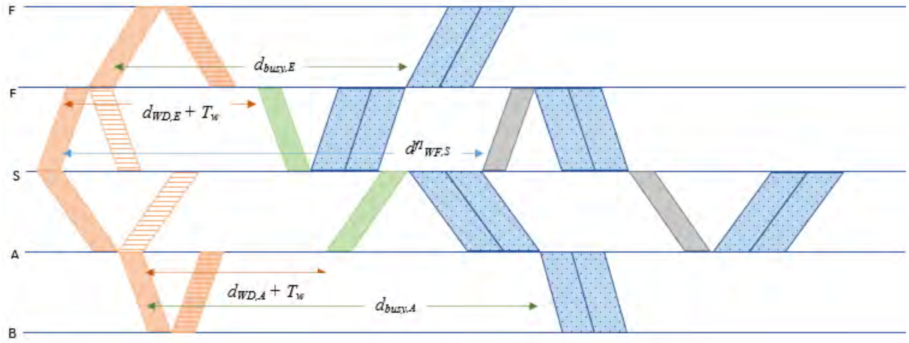

Figure 3.8: Scenario 2: Sender misses a confirmation

S. Therefore, node A sends RP packet and the sender node S begins sending data packets for second flow to node A.

Scenario 2: Sender misses all confirmation: In the second scenario which is described in figure 3.8 the sender node S does not receive confirmation to its request of both nodes E and A. After $d_{WD,E} + T_w$ duration of time when receiver E does not receive data from sender S, node E sends RP packet and the sender node S immediately starts sending data packets for first flow to node E. In the same way, $d_{WD,A} + T_w$ period later when receiver A does not receive data packet from node S, node A sends RP packet and the sender node S starts sending data packets for second flow to node A instantly.

Scenario 3: Intermediate node misses a confirmation: Assume that due to packet collision, the relay node E does not receive confirmation MFP packet of node F. When relay node F does not receive data packet from relay node E, node E transmits RP packet and the node E starts relaying data packets to node F immediately.

Scenario 4: Immediate destination node misses a confirmation: Suppose, the immediate destination nodes B does not receive confirmation to its request of desti-

Algorithm 2 Sender Missing MFP

for i numbers of flows **do**
    if $state = Delay\_Data$ and all MFP's are missing **then**
        Step 3: Go to state $Wait\_Retry$
            Wait time $d_{DD,S} + Tw$ for receiving RF
            Go to state Tx_Data
            Update time $d^{f}_{trans,S}$ and Send data
            if $i < f$ **then**
                Go to step 3
            else Go to step 1
            end if
    else if $state = Tx\_Data$ and any missing MFP find then
        for i number missing MFP **do**
            Go to state $Wait\_Retry$
            Wait for $d^{i-1}_{trans,S} + propagation\_delay + T_w$ time for RF
            if $RF = 1$ **then**
                Send data
            end if
        end for
    end if
end for

nation node C. After $d_{WD,C}+T_w$ duration of time when node C does not receive data from relay B, node C sends RP packet and node B immediately starts transmitting data to destination C.

Scenario 5: Finally, in the fifth scenario where the relay node fails to receive the requested MFP packet while the sender S has sent MFP to the relay. Hence, the relay does not wake up, and the sender waits for reception of RP packet from the relay. As sender does not receive RP packet, it will infer that its request is lost and after $Wait\_Retry$ state sender will send MFP packet again.

Algorithm 3 Relay Missing MFP

1: **for** i numbers of flows **do**
2: **if** $T = d_{WD,R_i} + T_w$ and no data request **then**
3: Go to state Tx_Retry and transmit CTS
4: **if** $T = d_{WD,R_i} + T_w + T_{CTS} + propagation\_delay$ **then**
5: Receive data
6: Update time d_{WF,R_i} and $d_{reverse,R_i}$
7: **else if** ($State = Tx\_data$ and no RMFP is received) **then**
8: Go to sate $Wait\_Retry$
9: Receive RP and send data to R_{i+1}
10: Update time d_{WF,R_i} and $d_{reverse,R_i}$
11: **if** ($Reverse\_flag = 1$ in RP) **then**
12: Go to **step 1**
13: **else** Go to state $Idle$
14: **end if**
15: **end if**
16: **end if**
17: **end for**

3.6 State Transition Diagram for Sender Node

The state transition diagram of a sender in our proposed MAC protocol BMF-MAC is interpreted in Figure 3.9. This diagram depicted the behavior of a sender how it transmits multi-flow multi-hop packets. Let us starts the transition from the *Idle*

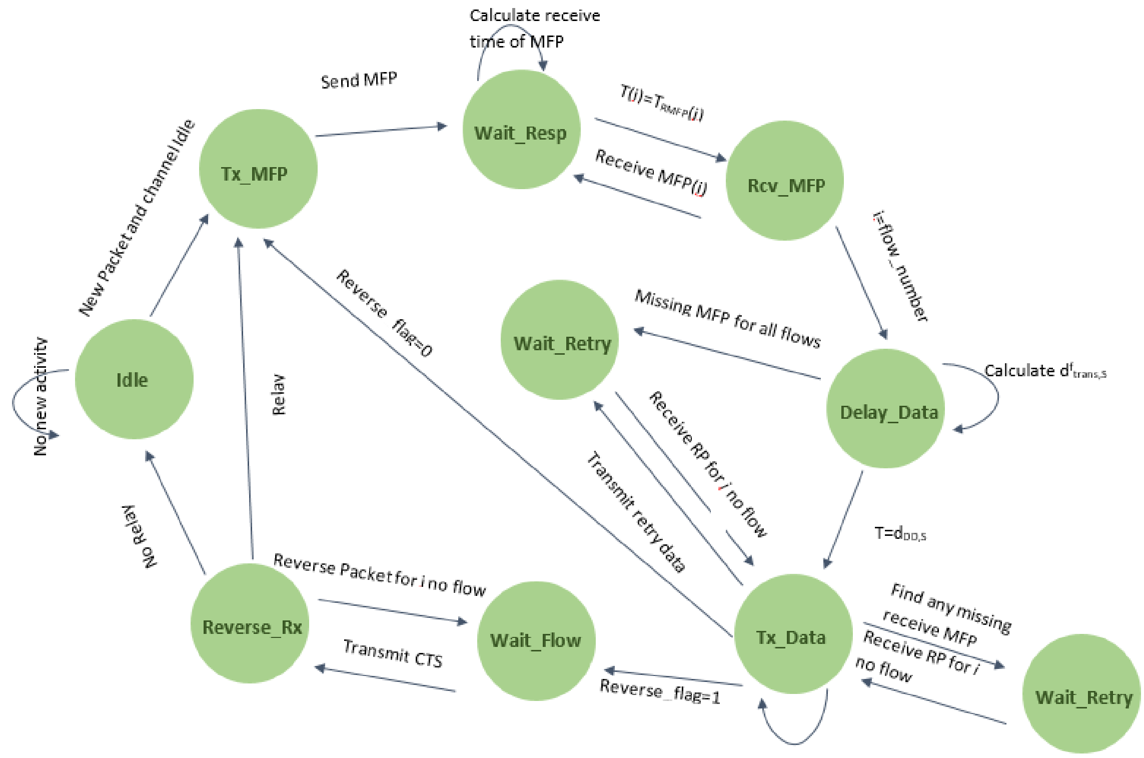

Figure 3.9: State transition diagram of a sender of the bidirectional multi-flow MAC protocol

state. When a sender has no activity to do, it remains in *Idle* state. In *Idle* state, if a sender generates new packets and channel is idle, it moves to the *Tx_MFP* state.

3.6.1 *TX_MFP* state

In *Tx_MFP* state, the sender sends the MFP packet to the relay nodes over multi-flows. After transmitting MFP packet, sender goes to the *Wait_Resp* state where it waits for the time for receiving MFP from that corresponding relays. In this state, the sender node calculates T^i_{RMFP} the receiving time of MFP. If time is equal to the time of receiving of a MFP for i number flow, the sender moves to the *Rcv_MFP* state. After receiving MFP for i number flow, the sender moves to *Wait_Resp* state. The sender waits for the waiting time of next receiving MFP T^{i+1}_{RMFP} in *Wait_Resp* state. Then if receiving time of MFP occurs, it moves to *Rcv_MFP* state again for receiving MFP of $i+1$ number flow. This switching of states *Wait_Resp* and *Rcv_MFP* continues until the number of flow i is less than the flow construction number for multi-flow data transmission.

3.6.2 *Delay_Data* state

If $f = total\_flow\_number$, the sender moves to the *Delay_Data* state. In *Delay_Data* state, the sender calculates $d^i_{trans,S}$, the time to transmit data packet for different flows i for sender S. The sender node waits for d_{DD} delay data time in this state. From state *Delay_Data* a sender can move to two different states according to the cases. In case that, the sender receives all corresponding response MFP, it moves to *Tx_Data* state. On the contrary, If the sender misses MFP for all flows, it moves to *Wait_Retry* state.

In case 1) If the sender does not miss MFP for all flows, the sender starts transmission of data packets to the relay nodes in *Tx_Data* state. The sender stays in *Tx_Data* state until it sends data packets over all flows in forward direction.

In case 2) If the sender misses MFP for all flows, it waits for receiving retry packet RP in *Wait_Retry* state. After receiving RP for i number of flow, the sender moves to the *Tx_Data* state for transmitting data packet for that specified RP packet. This shifting of states *Wait_Retry* and *Tx_Data* progresses up till the sender waits for RP packets for all constructing flows.

3.6.3 *Tx_Data* state

In *Tx_Data* state, three situations can take place. Case 1) If the sender does not miss MFP for any flow and $reverse\_flag = 1$ in confirm MFP, the sender goes to *Wait_Flow* state for beginning data transmission over reverse flow. Case 2) If the sender finds any missing confirm MFP for any flow and $reverse\_flag = 1$, the sender goes to *Wait_Retry* state. Case 3) If sender recognizes that $reverse\_flag = 0$, sender understands that there is no data transmission over reverse flow direction, therefore; it goes to the *Idle* state.

3.6.3.1 Reverse data transmission

In case 1) If the sender does not miss MFP for any flows and *reverse_flag* is set, the sender waits for $d^i_{WF,S}$ (wait duration for relay i in *Wait_Flow* state) time in the state *Wait_Flow* for avoiding collision. Then after this duration of time, the sender transmits CTS packet and moves to *Reverse_Rx* state. In *Reverse_Rx* state, the sender receives reverse data packets over that similar flow. After receiving reverse data packets, it goes to the state $Wait\_Flow$ again and waits for $d^{i+1}_{trans,S}$ time for receiving reverse data transmission over next flow $i+1$. The sender switches between these two states $Wait\_Flow$ and $Reverse\_Rx$ as far as the data transmission is finished over reverse flow for all f number of flows.

Algorithm 4 Sender Transmission Process over reverse flow

if $state = Wait\_Flow$
    for i number of flows **do**
        if $T = d^{i}_{trans,S} + propagation\_delay$ **then**
        Step 2: Send CTS to R(1) relay of i flow
            Go to state $Reverse\_Rx$
            if $T = d^{i}_{WF,S} + propagation\_delay$ **then**
                Receive reverse data from R(1)
            if $reverse\_flag = 1$ in confirm MFP for $i+1$ number flow
                Go to step 2
            else Go to state $Idle$
            end if
        end if
    end for
end if

3.6.3.2 Retry transmission

In case 2) If the sender misses response MFP for any flow, the sender waits for time T_w in $Wait\_Retry$ state. After receiving RP packet for particular MFP, sender node then enters in Tx_Data state for receiving data from the relay node. If more than one response MFP is missed, then node shifts between this two states Tx_Data and $Wait\_Retry$. Then, if node has reverse data to receive it goes to $Wait\_Flow$ state, transmits CTS and moves to $Reverse\_Rx$ state.

3.6.3.3 $Reverse\_Rx$ state

In case 3) In state $Reverse\_Rx$ the node receives data over reverse flow direction. If the sender node has no data to relay, it goes to state $Idle$; otherwise, the sender goes to state Tx_MRP. Algorithm 4 describes the reverse flow transmission process

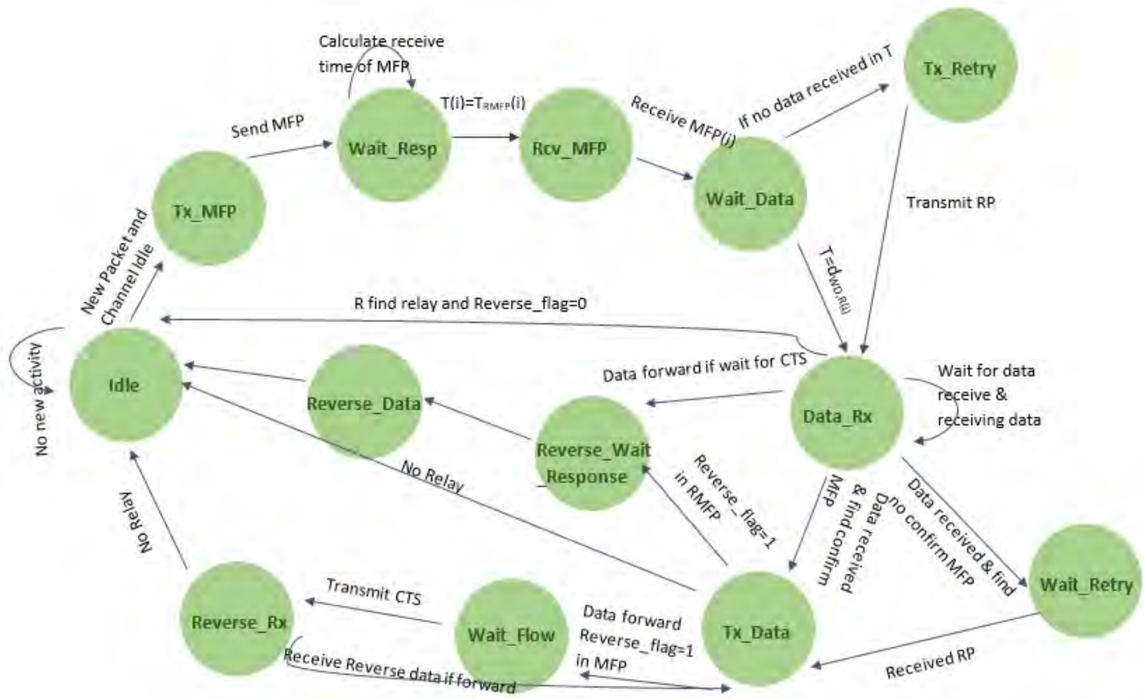

Figure 3.10: State transition diagram of a relay of the bidirectional multi-flow MAC protocol

of sender node S.

3.7 State Transition Diagram for Relay Node

Figure 3.10 illustrated the state transition diagram of a relay node of BMF-MAC protocol. How relays transmit and receive multi-hop packets through multiple flows is explained in the diagram. Let us starts the transition from the $Idle$ state. When a relay has no activity to do, it remains in $Idle$ state.

In $Idle$ state, if a relay node wants to relay packets and channel is idle, it moves to the TX_MFP state.

3.7.1 TX_MFP state

In TX_MFP state, relay sends the request MFP to the next relay $R_{(i+1)}$ node over multiple flows. After transmitting MFP packet, relay enters in the $Wait\_Resp$ state where it waits for the time T_{RMFP} for receiving MFP from the next relay. In this state, the relay node calculates the receiving time of response MFP T_{RMFP}. If time is equal to the time of receiving of a MFP, the relay moves to the Rcv_MFP state where it receives the confirm MFP packet.

3.7.2 $Wait\_Data$ state

After receiving the MFP packet from next relay, the relay node enters in $Wait\_Data$ state. In $Wait\_Data$ state relay nodes calculate the waiting time d_{WD,R_i} and wait for the duration to receive the data packets from relay $R_{(i-1)}$ or the sender node. In $Wait\_Data$ state two different circumstances may occur: Case 1) If the $T = d_{WD,R_i} + T_w$ and no data is received in time T, the nodes moves to the Tx_Retry state. Case 2) If the $T = d_{WD,R_i}$ and data is received in time T, the nodes moves to the $Data\_Rx$ state.

In case 1) If the relay does not receive data packet in time T, the node transmits RP packet in Tx_Retry state. After transmitting RP, the relay node goes to $Data\_Rx$ state.

In case 2) If the relay receives data packet in time T, the node starts receiving relaying data from its corresponding relay $R_{(i-1)}$ or sender node in $Data\_Rx$ state.

3.7.3 $Data\_Rx$ state

From state $Data\_Rx$, relay can move to four different states according to the following cases. Case 1) In case that the relay node receives data and finds confirm MFP, it moves to Tx_Data state. Case 2) If the relay receives data but misses confirm MFP, it moves to $Wait\_Retry$ state. Case 3) If the relay receives data and $reverse\_flag = 1$, the node moves to $Reverse\_Wait\_Resp$ state. Case 4) Finally, if the relay receives data and relay node is the last node over the flow and $reverse\_flag = 0$, the node moves to $Idle$ state.

In case 1) After receiving data packets, the relay starts transmission of data packets to its next relay node in Tx_Data state.

In case 2) If the node misses confirm MFP, it waits for receiving retry packet RP in $Wait\_Retry$ state. After receiving RP from corresponding relay node, the node moves to the Tx_Data state for transmitting data packet for that specific RP packet.

Algorithm 5 Relay Transmission Process over reverse flow

if $state = Tx\_Data$ and final RMFP from R_{i+1} relay **then**

  if $reverse\_flag = 1$ in confirm RMFP **then**

    Step 1: Calculate Reverse waiting time $d_{Reverse,R_i}$

    Go to state $Reverse\_Wait\_Resp$

    if $T = d_{reverse,R_i} + T_{CTS} + propagation\_delay$ **then**

      Receive CTS and go to state $Reverse\_Data$

      Transmit reverse data and go to state $Idle$

  end if

  else if ($Reverse\_flag = 1$ in MFP)

    Calculate flow waiting time d_{WF,R_i}

    Go to state $Wait\_Flow$

    Transmit CTS and go to state $Reverse\_Rx$

    if $T = T_{WF,R_i} + T_{CTS} + propagation\_delay$ **then**

      Receive reverse data and go to state $Idle$

    end if

  end if

end if

3.7.4 *Tx_Data* state

A node transmits data packet to its next relay node in *Tx_Data* state. In *Tx_Data* state, three situations may occur: Case 1) In case that, the relay node forwards data and finds $reverse\_flag = 1$ in requested MFP, it moves to *Wait_Flow* state. Case 2) In other case, while the node forwards data and finds $reverse\_flag = 1$ in responded MFP, it enters in *Reverse_Wait_Resp* state. Case 3) If relay has no data to relay, it goes to *Idle* state.

In Case 1) A node goes to *Wait_Flow* state from *Tx_Data* state when it wants to receive reverse data packet. The relay calculates the time d_{WF,R_i} and waits for d_{WD,R_i} time duration for avoiding collision in *Wait_Flow* state. After sending CTS packet to the interrelated relay node, the node moves to the state *Reverse_Rx* state. In *Reverse_Rx* state, the node receives data over reverse flow direction. If data have to forward then the node moves to *Tx_Data* state. After forwarding data in *Tx_Data* state, if there is no data to relay, the node enters in *Idle* state.

In Case 2) When the relay wants to send reverse data packet, it moves to *Revese_Wait_Resp* state from *Tx_Data* state. In this state, the node calculates the time $d_{Reverse,R_i}$ and waits for $d_{WD,R_i} + T_{CTS}$ time duration for avoiding collision. After receiving response packet CTS from the specific relay node, the node moves to *Reverse_Data* state. The node transmits reverse data in *Reverse_Data* state. If there is no relay node, the relay moves to the *Idle* state. Algorithm 5 explains the transmission process over reverse flow of relay nodes.

3.8 Calculation of the Time Duration Parameters

Depending on the number of flows, the batch size of data, the number of bidirectional data packets, the busy duration should be computed.

Here we consider that τ_{max} is the maximum propagation delay between nodes. *T_control* is the common transmission time of all control packets. The busy duration of node S for first flow in Figure 3.6 is as follows

$$d^{f1}_{busy,S} = 2\tau_{max} + T_{control} + d^{f1}_{DD,S} \tag{3.1}$$

Assume d^{f1}_{data} and d^{f2}_{data} are the transmission time of batch data packets for flow one and two respectively. The waiting and busy duration of Node E is

$$d_{WD,E} = 2\tau_{max} + T_{control} \tag{3.2}$$

$$d_{busy,E} = d_{WD,E} + d_{data}^{f1} \tag{3.3}$$

Assume T_{data} is a single data packet transmission time and B_{SIZE} is the batch data size. That means, $d_{data} = T_{data}\ B_{SIZE}$. Therefore, the busy duration of Node F is given by:

$$\begin{aligned} d_{busy,F} &= (d_{busy,E} - T_{control}) + B_{size}T_{data}^{f1} \\ &= 2\tau_{max} + 2B_{size}T_{data}^{f1} \end{aligned} \tag{3.4}$$

Thus the busy duration of relay node R_i for first flow can be generalized as well.

$$d_{busy,R_i} = 2\tau_{max} + iB_{size}T_{data}^{f1} - (i-2)T_{control} \tag{3.5}$$

The busy duration of Node S for second flow in Figure 3.6 is as follows

$$d_{busy,S}^{f2} = d_{busy,S}^{f1} + d_{data}^{f1} \tag{3.6}$$

The waiting and busy duration of Node A is

$$d_{WD,A} = 2\tau_{max} + T_{control} + d_{data}^{f1} \tag{3.7}$$

$$d_{busy,A} = d_{WD,A} + d_{data}^{f2} \tag{3.8}$$

Like Node A, the waiting and busy duration of B is:

$$\begin{aligned} d_{busy,B} &= (d_{busy,A} - T_{control}) + B_{size}T_{data}^{f1} \\ &= (2\tau_{max} + T_{control} + d_{data}^{f1} - T_{control}) + B_{size}T_{data}^{f2} \end{aligned} \tag{3.9}$$

Imagine f is the total number of flows. Therefore, we can derive the busy duration of relay node R_i for second flow as well.

$$d_{busy,R_i} = 2\tau_{max} + d_{data}^{f1} + iB_{size}T_{data}^{f2} - (i-2)T_{control} \tag{3.10}$$

$$d_{busy,R_i} = 2\tau_{max} + (f-1)\,d_{data} + iB_{size}T_{data}^{f2} - (i-2)T_{control} \tag{3.11}$$

The waiting time for ongoing first flow of Node S in Figure 3.6 is given by:

$$d_{WF,S}^{f1} = d_{busy,S}^{f2} + d_{data}^{f2} \tag{3.12}$$

Assume T_{CTS} is the transmission time of a CTS packet. Hence, the delay time for reverse flow of node E for first flow is given by:

$$d_{reverse,E} = d^{f1}_{WF,S} + T_{CTS} \tag{3.13}$$

The waiting time of node F and delay time of node G is:

$$d_{WF,F} = d_{busy,F} + d^{f1}_{data} \tag{3.14}$$

$$d_{reverse,G} = d_{WF,F} + T_{CTS} \tag{3.15}$$

The delay time for reverse flow of node A for the second flow is:

$$d_{reverse,A} = d_{WF,S} + T_{CTS} \tag{3.16}$$

In the same way the waiting time of node A and delay time of node B is:

$$d_{WF,A} = d_{reverse,A} + d^{f2}_{data} \tag{3.17}$$

$$d_{reverse,B} = d_{WF,A} + T_{CTS} \tag{3.18}$$

The wait time of first flow and second flow for node S are accordingly stated below.

$$d^{f1}_{WF,S} = d_{busy,S} + f.d_{data} \tag{3.19}$$

$$d^{f2}_{WF,S} = d^{f1}_{WF,S} + T_{CTS} + d^{reverse}_{data} \tag{3.20}$$

Thus the generalized formula of wait time calculation for other than first flow is

$$d^{f_n}_{WF,S} = d^{f_{n-1}}_{WF,S} + T_{CTS} + d^{reverse}_{data} \tag{3.21}$$

If the node E has reverse data then the wait flow time is

$$d_{WF,E} = (d_{busy,S} - T_{control}) + f.d_{data} + T_{CTS} + d^{reverse}_{data} \tag{3.22}$$

When previous hop node has reverse data for transmission then the equation for first flow relay node R_i is

$$d_{WF,R_i} = (d_{busy,R_{i-1}} - T_{control}) + f.d_{data} + i.T_{CTS} + i.d^{reverse}_{data} \tag{3.23}$$

As in our example relay E does not have any reverse data thus the wait flow time of relay F is

$$d_{WF,F} = d_{busy,F} + d_{data} \tag{3.24}$$

Therefore, if previous hop relay does not have any data over reverse flow direction then the wait flow time can be generalized as

$$d_{WF,R_i} = d_{busy,R_{i-1}} + d_{data} \tag{3.25}$$

For the second flow, the wait time of node A is

$$d_{WF,A} = (d_{busy,S} - T_{control}) + f.d_{data} + 2T_{CTS} + 2d_{data}^{reverse} \tag{3.26}$$

More specifically, the generalized formula of wait flow for other than first flow is

$$d_{WF,R_i} = (d_{busy,R_{i-1}} - T_{control}) + f.d_{data} + f_n.T_{CTS} + f_n.d_{data}^{reverse} \tag{3.27}$$

3.9 Frame Error Probability

The bit error rate (BER) is the number of bit errors divided by the total number of transferred bits during a studied time interval. Here, p is the frame error probability, which is related to the bit error rate (BER) p_e. l is the data packet size (bits) and l_{oh} is the frame overhead size (bits). From [44] we can get frame error probability.

$$p = 1 - (1 - p_e)^{l+l_{oh}} \tag{3.28}$$

The probability of no error of frame transmission is p_c.

$$p_c = (1 - p_e)^{l+l_{oh}} \tag{3.29}$$

3.10 Throughput

The network throughput is defined as the total number of packets delivered at the sink node per time unit.

$$Throughput = (NumberofPacket.NumberofBitsPerPacket)/RequiredTime \tag{3.30}$$

Here, we consider two version of BMF-MAC. One is BMF-M which is a version of BMF protocol, where only multi-flow data transmission is considered. On the other hand, BMF-R contemplates multi-flow data transmission with reverse packet method. In our experiment control packet collision is not considered.

We assume that *T_control* denotes the common transmission time of one MFP frame and i is the number of packet to be transmitted. Then, to transmit single MFP frame it needs time

$$TimeforMFP = 2(T_{control} + \tau_{max}) \tag{3.31}$$

The duration to transmit a single data frame is $(T_{data}+\tau_{max})$ and B_{SIZE} is the batch data size. That means, $d_{data} = T_{data}\ B_{SIZE}$. Then to transmit one batch data frame, it requires time:

$$TimeforDATA = (d_{data} + \tau_{max}) \tag{3.32}$$

$$TimeforDATA = (T_{data}.B_{SIZE} + \tau_{max}) \tag{3.33}$$

We assume that the required time to send packets to a relay node that is one hop away from the sender node will be

$$Time_1 = TimeforMFP + TimeForDATA \tag{3.34}$$

The required time to send packets from a node that is h multiple hops away from the sender node will be

$$Time_2 = h.TimeforMFP + h.TimeForDATA \tag{3.35}$$

Now, for i number of packets over f number of flows it needs time for BMF-M protocol:

$$Time_3 = (1 - p_e)^{l+l_{oh}}.i.Time_2 \tag{3.36}$$

For reverse packet it needs time

$$Time_4 = (1 - p_e)^{l+l_{oh}}.i.h.Time_1 \tag{3.37}$$

Hence, for BMF-M protocol, required time is

$$RequiredTime = Time_3 + Time_4 \tag{3.38}$$

On other hand, for BMF-R, to transmit packets in reverse direction it needs time

$$Time_5 = (1 - p_e)^{l+l_{oh}}.i.T_{CTS} + \tau_{max} + TimeforDATA \tag{3.39}$$

Therefore, for BMF-R, required time is

$$RequiredTime = Time_3 + Time_5.h \tag{3.40}$$

The $Time_3$, $Time_4$ and $Time_5$ can be calculated from equation (3.27), (3.28) and (3.30) respectively. Hence, placing the values of the above mentioned times into equation (3.29) and (3.31) RequiredTime can be measured for both version of BMF-MAC. Then, the throughput can be derived from the equation (3.21) using the measured RequiredTime.

3.11 Latency

Latency is an important design and performance characteristic of underwater sensor network. Latency is the end to end delay of a packet that is the amount of time it takes a packet to travel from source to destination. Latency measures the amount of time between the start of data transmission and its completion.

We assume that T_{contol} denotes the transmission time of one MFP frame, i is the number of packet to be transmitted. Then, in multi hop scenario, to transmit a single MFP frame, it needs $2.(T_{contol} + \tau_{max})$ time and a MFP have to wait ($T_{control}$ $+\tau_{max}$)time before transmitting. Therefore, total latency of a single packet to transmit will be

$$LatecyforMFP = 3.(T_{control} + \tau_{max}) \tag{3.41}$$

The duration to transmit a data frame is d_{data}. Then, to transmit a data frames, it requires (d_{data} $+\tau_{max}$) time and a data have to wait $(d_{WD,R_i} - 2.T_{contol} - 2\tau_{max})$ time before transmitting. Therefore, total latency of a single packet to transmit will be

$$LatencyforDATA = (d_{data} + \tau_{max}) + (d_{WD,R_i} - 2.T_{contol} - 2\tau_{max}) \tag{3.42}$$

The contention window size is CW. The latency to send packets from a sender node to h hop relay node in multi-hop scenario will be

$$Latency_1 = CW + d_{DD,S} + h.LatencyforMFP + h.LatencyforDATA \tag{3.43}$$

Now, for i number of packets to be transmitted in probability p_c, latency will be

$$Latency_2 = CW + d_{DD,S} + p_c.i.h.LatencyforMFP + p_c.i.h.LatencyforDATA \tag{3.44}$$

In the same way, for data transmission in reverse flow direction, latency of r number of packets will be

$$Latency_3 = CW + d_{DD,S} + p_c.r.h.LatencyforMFP + p_c.r.h.LatencyforDATA \tag{3.45}$$

Hence, for BMF-M protocol, total latency will be

$$Latency = Latency_2 + Latency_3 \tag{3.46}$$

On the other hand, for BMF-R protocol for reverse packets latency for control frame will be

$$Latency_4 = (T_{CTS} + \tau_{max}) + (d_{WF,R_i} - 2.T_{control} - 2\tau_{max}) \tag{3.47}$$

On the other hand, for BMF-R protocol for reverse packets latency for data frame will be

$$Latency_5 = (d_{data} + \tau_{max}) + (d_{Reverse,R_i} - 2.T_{control} - 2\tau_{max}) \tag{3.48}$$

Hence, for BMF-R protocol overall latency will be

$$Latency = Latency_2 + Latency_4 + Latency_5.h \tag{3.49}$$

The $Latency_2$, $Latency_3$, $Latency_4$ $Latency_5$ can be determined from equation (3.35), (3.36), (3.38), and (3.39) respectively. Therefore, inserting the values into equation (3.37) and (3.40) latency can be measured for both version of BMF-MAC protocol.

3.12 Energy Consumption

Energy consumption is one of the core issue in underwater sensor networks. Energy consumption is the total energy consumption to deliver a certain number of packets from sources to sink. This metric shows the energy efficiency of the MAC protocols. On the other hand, energy consumption is calculated by multiplying power consumption with required time.

$$Energy\_consumption = Power\_consumption.Required\_time \tag{3.50}$$

Here, the RequiredTime can be determined from equation (3.29) for BMF-M and from equation (3.31) for BMF-R.

3.13 Summary

In this chapter, to solve high end-to-end delivery latency of handshaking-based MAC protocols, a new low latency medium access control protocol while ensuring energy efficient operation, Bidirectional Multi-flow MAC protocol has been depicted to handle variable traffic load patterns of UW-ASNs. The operation cycle, the control frame structure, multi-hop multi-flow data transmission and packet transmission over reverse flow direction of proposed protocol are outlined in this chapter. Transition diagram and algorithm for data transmission technique for both sender and relay node have been evolved as well. Finally, the equation of energy consumption, end to end delay, throughput and frame error probability of proposed BMF-MAC protocol are derived to carry out performance evaluation.

Chapter 4

RESULTS AND DISCUSSION

Results of the mathematical model explained in chapter three are presented in this chapter. At first, the network topology and necessary experiment setup for the proposed BMF-MAC protocol is described. We used system parameters of BMF-MAC protocol similar to existing CMRT protocol for comparison which are presented in Table 4.1, and 4.2. The performance of BMF-MAC protocol in terms of energy, throughput and latency is evaluated using simulation tool MATLAB [45]. Finally, in order to investigate the efficiency of the proposed BMF-MAC protocol, a performance comparison between proposed BMF-MAC protocol and existing CMRT protocols is carried out.

4.1 Analytical Analysis

For our analytical analysis we consider a multi-hop topology of 36 static nodes which are placed in a 5000 × 5000 m^2 square area which is illustrated in Figure 4.1. The distance between two nodes are 1000 m in grid spacing. The transmission range of node is 1.5 times the grid spacing, i.e., 1500 m. Here, we assume every node has

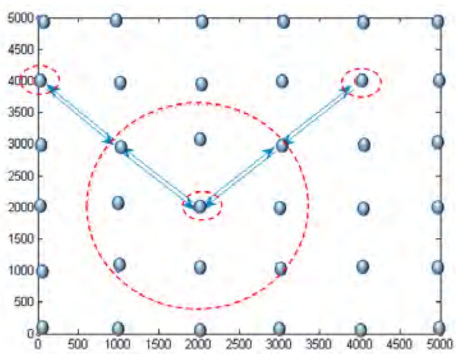

Figure 4.1: The network topology for analysis

the same transmission power. All of the nodes are assumed to have exactly eight neighbors within its range which is indicated by the dotted circle in Figure 4.1. The average transmitting and receiving power is 2W and 20 mW of the acoustic transceiver. The acoustic channel is assumed to be error-prone.

4.2 Experiment Setup

In our experiment design, the network parameters and packet parameters have been set for BMF-MAC are shown in Table 4.1 and Table 4.2 respectively. The size of data packet is fixed 1200 bits as in CMRT protocol. The size of control packet MFP is 128 bits, which is one byte longer than that of CMRT protocol.

4.3 Results and Discussions

In this subsection, we analyze the performance of the proposed BMF-MAC protocol. BMF-M is a version of BMF protocol, where only multi-flow data transmission is considered. On the contrary, BMF-R contemplates multi-flow bidirectional data transmission. Different results are studied according to three different performance

Table 4.1: Systems Parameters

Parameters	Value
Acoustic propagation speed	1500 m/s
Transmission rate	9600 bps
Buffer Capacity(N_{max})	300 packets
Minimum back-off counter	1
Maximum back-off counter (B_{max})	64
Bit Rate	1200 bps
Tx Power	2 W
Rx Power	20 mW
Idle Power	0.8 mW

Table 4.2: Packet Parameters

Parameters	Value
Data packet size	1200 bits
Control packet size	128 bits

metrics: latency, energy efficiency and throughput. Performance of both version BMF-MAC protocol is compared with the existing CMRT protocol based on the equation derived in chapter three.

4.3.1 Throughput

In this subsection, the performance of throughput of BMF-MAC protocol is evaluated. We study the performance of throughput according to different offered loads, different distances, number of flows, different network areas, number of reverse packets and BERs.

4.3.1.1 Effects of offered loads

The throughput model which is explained in section 3.9 is used. Figure 4.2 shows that the data throughput of proposed BMF-MAC protocol and existing CMRT protocol in different offered loads with BER of 10^{-3}. The x-axis shows the offered load whereas the y-axis shows the throughput in terms of bit per second (bps). It is recognized that BMF-MAC exhibits the best performance in terms of throughput in all offered load conditions. Moreover, the system throughput indicates the data packets which is received by both relay and final destination nodes successfully.

The system throughput indicates the overall channel utilization by using the MAC protocol correspondingly. Therefore, it is identical to normalized throughput per node. Hence, it can be concluded that, in terms of channel utilization, BMF-MAC surpasses other alternative. The result proves CMRT is inefficient, because it only transmits data from sender to receiver over a single flow with per-round channel reservation, which suffers from underutilization of the channel when the propagation delay is high. However, our channel reservation mechanism allows a single sender to transmit data packets to multiple nodes of different flows with per

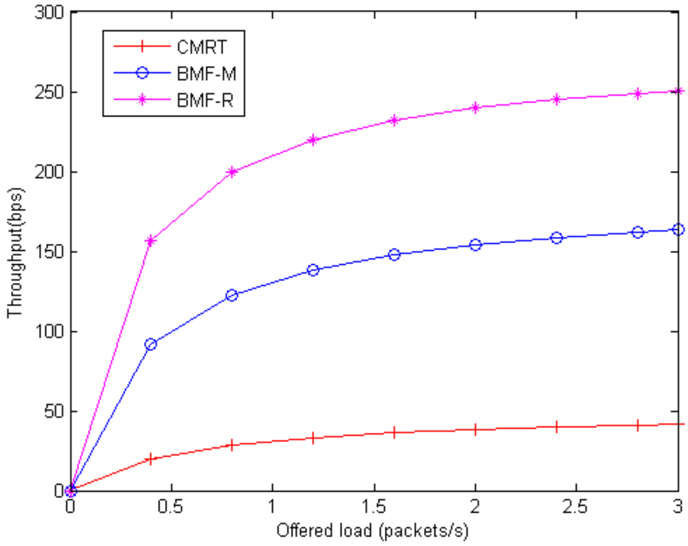

Figure 4.2: Performance comparisons of BMF-MAC with CMRT in terms of throughput

round of channel reservation and can reduce the total channel reservation overhead greatly and thus, can improve channel utilization. As a result, BMF-MAC has better data throughput than CMRT. Figure 4.2 reveals that, in case of high traffic load 3 packets/s, BMF-M can achieve the highest increase of data throughput around 39.2% higher compared to CMRT protocol as well as BMF-R can achieve the highest increase of data throughput around 67.5% higher compared to CMRT protocol. In low traffic load 0.5, BMF-M protocol can achieve throughput around 20% and BMF-R achieve 46.7% higher than that of CMRT. In summary, BMF-MAC protocol outperforms CMRT protocol with regard to data throughput in variable traffic loads.

4.3.1.2 Effects of inter nodal distance

Throughput of proposed BMF-MAC protocol and existing CMRT protocol in the variation of inter nodal distances with BER of 10^{-3} is shown in Figure 4.3. Here offered load is set to 0.8 packets/s. The x-axis shows the distances whereas the y-axis shows the throughput in terms of bit per second (bps). It is examined that the performance of each of the protocols in terms of throughput degrades with the increasing of the inter-nodal distance. This is due to the rising of the distance-related communication overhead. As the distance enhances, the busy duration along with the handshaking time raises by reason of prolonged propagation delay. Therefore, with the increasing of the extended busy duration the Silence state length enlarges. This causes a node to have less opportunity to exchange control packets. However, it is observed that, BMF-MAC can provide better result to handle variable traffic patterns in multi-hop underwater sensor networks comparing with CMRT. More specifically, from Figure 4.3 it is seen that for smaller inter nodal distance 1km, the throughput of BMF-R and BMF-M protocols can achieve around 83% and 45% higher compared to CMRT protocol respectively. In case of medium inter nodal distance 4km, BMF-R and BMF-M MAC protocol can achieve throughput around 27% and 17% greater than that of CMRT protocol respectively. For high distant node 8km, BMR-R can achieve the highest decrease of throughput around 19% high compared to CMRT whereas BMF-M gains the maximum decrease of throughput around 15% large compared to CMRT. Accordingly, BMF-MAC surpasses CMRT in respect to throughput with variable inter nodal distant nodes.

4.3.1.3 Effects of number of flows

The throughput of proposed BMF-MAC protocol and existing CMRT protocol with the increase of number of flows is illustrated in Figure 4.4. For BER 10^{-3} and offered load 3.2 packets/second, the x-axis shows the number of flows whereas the y-axis shows the throughput in terms of bit per second (bps). Figure 4.4 depicts the per-

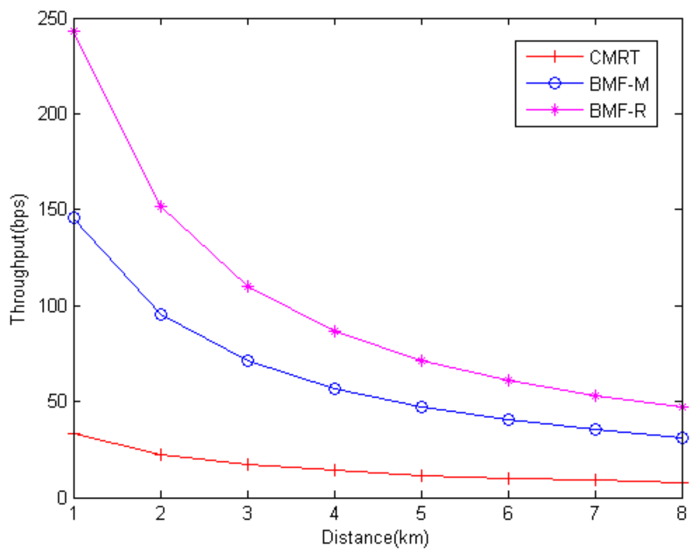

Figure 4.3: Performance comparisons of BMF-MAC with CMRT in terms of throughput

formance of both CMRT and BMF-MAC protocols in terms of throughput degrades with the increasing of the number of flows. As with the increase of number of flows more time is required to deliver packet. Moreover, multiple flows cause the traffic pattern more complex and hard to handle by MAC protocol in underwater sensor networks scenario. From Figure 4.4, it is observed that in double flow data transmission, the throughput of BMF-R and BMF-M protocols can achieve around 70.1% and 40.1% higher compared to CMRT protocol respectively. In case of six number of flows, BMF-R and BMF-M MAC protocol can accomplish throughput around 39.5% and 14.5% greater than that of CMRT protocol respectively. Accordingly, BMF-MAC exceed CMRT in respect to throughput in different flows condition.

4.3.1.4 Effects of number of reverse packets

Throughput of proposed BMF-MAC protocol and existing CMRT protocol in the different number of reverse packets with BER of 10^{-3} is shown in Figure 4.5. The x-axis shows the number of reverse packets whereas the y-axis shows the throughput in terms of bit per second (bps). It is demonstrated that the performance of both version of the BMF-MAC protocols in terms of throughput raises with the increase of the number of reverse packets. BMF-MAC introduces four types of states to handle reverse packets. Thus, data transmission over multi-flow adopting with reverse

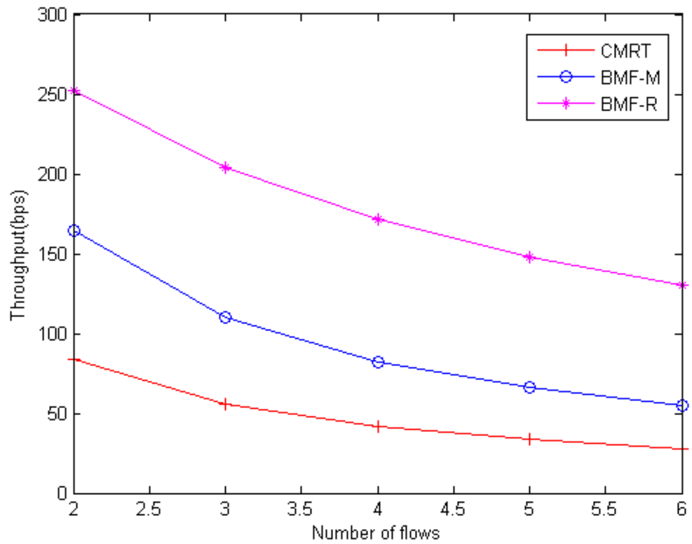

Figure 4.4: Performance comparisons of BMF-MAC with CMRT in terms of throughput

data transmission technique can take place without any collision. This causes a node to have significant opportunity to exchange bidirectional packets over multi-flows in less time requirement. From Figure 4.5, it is identified that while reverse packet number is one, the throughput of BMF-R and BMF-M protocols can achieve around 39% and 17% higher compared to CMRT protocol respectively. If number of reverse data packets is increase to 6, BMR-R can achieve the highest achievement of throughput around 78% high compared to CMRT whereas BMF-M gains the maximum increase of throughput around 46% large compared to CMRT. Accordingly, BMF-MAC surpasses CMRT with the rising number of reverse packets.

4.3.1.5 Effects of number of nodes

For different number of nodes, Figure 4.6 shows the throughput for 0.4 packets/s offered load. The x-axis shows number of nodes whereas the y-axis shows the throughput in terms of bps. With the increasing of the number of nodes, the number of source nodes increases. Therefore, more multi-flow constructions can take place which facilitates BMF-MAC protocol to deliver more data packets which results improvement of throughput. More specifically, for number of nodes 5, BMF-M MAC protocol can achieve throughput around 5.6% higher compared to CMRT. On the other hand, BMF-R gains throughput around 9.6% higher compared to CMRT pro-

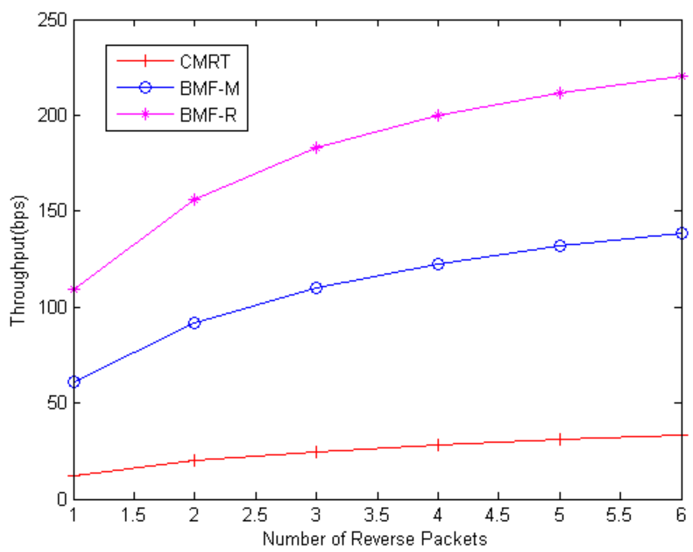

Figure 4.5: Performance comparisons of BMF-MAC with CMRT in terms of throughput

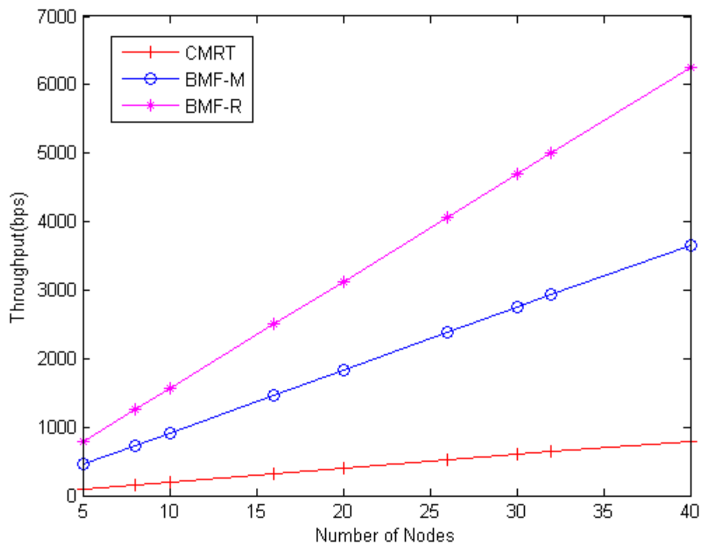

Figure 4.6: Performance comparisons of BMF-MAC with CMRT in terms of throughput

tocol. When the number of node is increased to 40, BMF-M MAC can achieve the highest improvement of throughput around 38.2% higher and BMF-R can gain 74.2% more than that of CMRT protocol. That reveals BMF-MAC protocol is more throughput efficient for large area network. The above mentioned information indicates that, BMF-MAC outperforms CMRT with respect to throughput with the increase of network size. Finally, we conclude that the fourteen states in BMF-MAC significantly contributes to the improvement of throughput with the increase of number of nodes.

4.3.1.6 Effects of BER

For different number of BERs, Figure 4.7 interprets the data throughput with offered load 0.8 packets/s. Here, x-axis shows the BER whereas the y-axis shows the throughput in terms of bit per second. Different lines present the results collected with different protocols: BMF-MAC, RMAC LO-MAC. Throughput decreases when the bit error rate increases from 0 to 1. It is observed that, the bidirectional multi flow data transmission technique in BMF-MAC significantly contributes to the improvement of throughput with the decrease of BER.

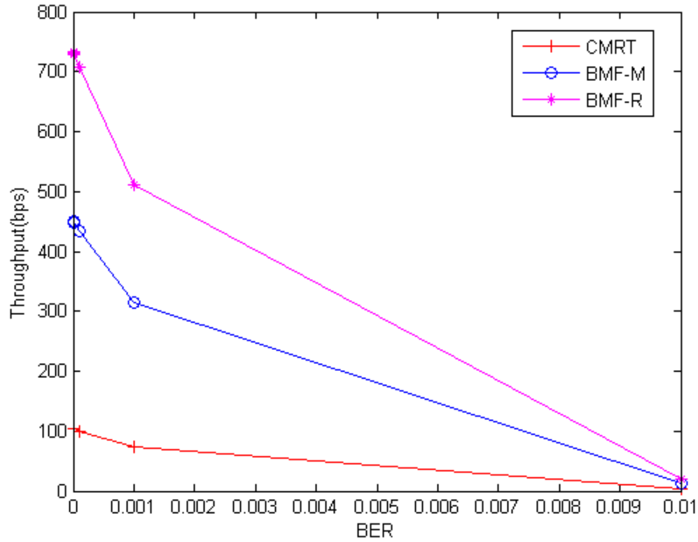

Figure 4.7: Performance comparisons of BMF-MAC with CMRT in terms of throughput

4.3.2 Latency

In this subsection, the performance of end to end delivery latency of BMF-MAC protocol is evaluated. We study the performance of latency according to different number of hops, different distances, number of flows, and different bit error rates (BERs). The latency model which is deliberated in section 3.6 is used.

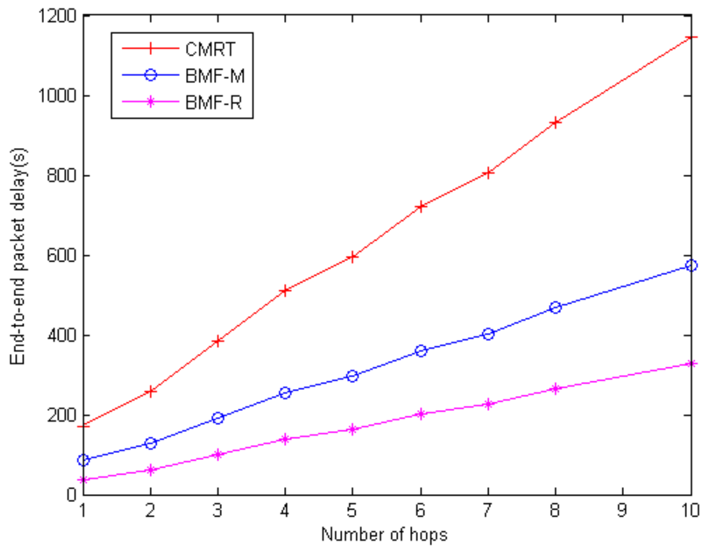

Figure 4.8: Performance comparisons of BMF-MAC with CMRT in terms of end to end packet delay

4.3.2.1 Effects of number of hops

End to end packet delay of proposed BMF-MAC protocol and existing CMRT protocol in the variation of number of hops with BER of 10^{-3} is presented in Figure 4.8. The x-axis shows the number of hops whereas the y-axis shows the latency in terms of second (s). Different lines present the results collected with different protocols: BMF-M MAC, BMF-R MAC and CMRT. As can be seen from the figure, latency increases when the number of hops increases from 1 to 10. However, packets experience longer delay while using CMRT scheme compared to BMF-MAC scheme with the increase of number of hops. More precisely, in case of medium number of hop 5, BMF-M MAC protocol provides 25% less packet delay compared to CMRT. Whereas in high number of hop count 10, BMF-M MAC protocol can achieve latency around 50% lower than that of CMRT protocol. On the other hand, in medium number of hop 5, BMF-R MAC protocol provides 35% less packet delay compared to CMRT protocol. Furthermore, in high number of hop number 10, BMF-R MAC can achieve the significant reduction of latency around 72% lower compared to CMRT protocol. As with the increasing of number of hops, more packets can be delivered over different flows in the same time requirement by BMF-MAC protocol. Moreover, in the process of increasing of the hop number, BMF-MAC can relay more bidirectional packets in reverse flow direction. Therefore, it is observed that, BMF-MAC protocol outperforms the existing CMRT protocol in terms of latency with the increase of number of hops.

Packets experience longer delay while using CMRT scheme compared to BMF-MAC scheme with the increase of number of hops. That is because, CMRT only transmits train of data per round handshake to multi-hop relaying nodes in a single flow. In BMF-MAC, exchange of control packets and data packets in different flows can be held simultaneously. The protocol permits more scheduled transmissions per round handshaking. Hence, the protocol is capable to significantly reduce the time spent in data transmission and handshaking by means of bidirectional data-transmission over multiple flows.

4.3.2.2 Effects of inter nodal distance

Throughput of proposed BMF-MAC protocol and existing CMRT protocol in the different number of reverse packets with BER of 10^{-3} is shown in Figure 4.9. The x-axis shows the number of reverse packets whereas the y-axis shows the throughput in terms of bit per second (bps).

Figure 4.9 reveals end-to-end delay of proposed BMF-MAC protocol and existing CMRT protocol with the increasing of inter nodal distance of node while BER is set to 10^{-3}. As the distance increases, the busy duration along with the handshaking time raises by reason of prolonged propagation delay. Therefore, with the increasing of the extended waiting duration the $Wait\_Flow$ state length enlarges. This causes a node to need more time to transmit bidirectional packets in multi-flow scenario. From Figure 4.9 it is shown that, while the distance is 1km, BMF-M MAC protocol provides 10% less packet delay compared to CMRT protocol. Furthermore, while the distance is increased to 4km, BMF-M MAC protocol obtains latency around 25% lower than that of CMRT. If the distance further is increased to 8km, BMF-M MAC can achieve the significant reduction of latency around 45% lower compared to CMRT protocol. Straightway, BMF-R MAC protocol gains 15.2% less packet delay compared to CMRT protocol for inter nodal distance 1km. For the distance 4km,

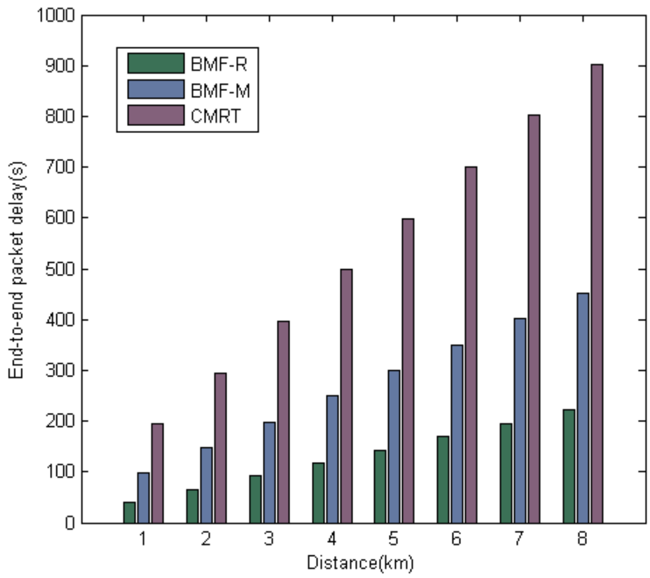

Figure 4.9: Performance comparisons of BMF-MAC with CMRT in terms of end to end packet delay

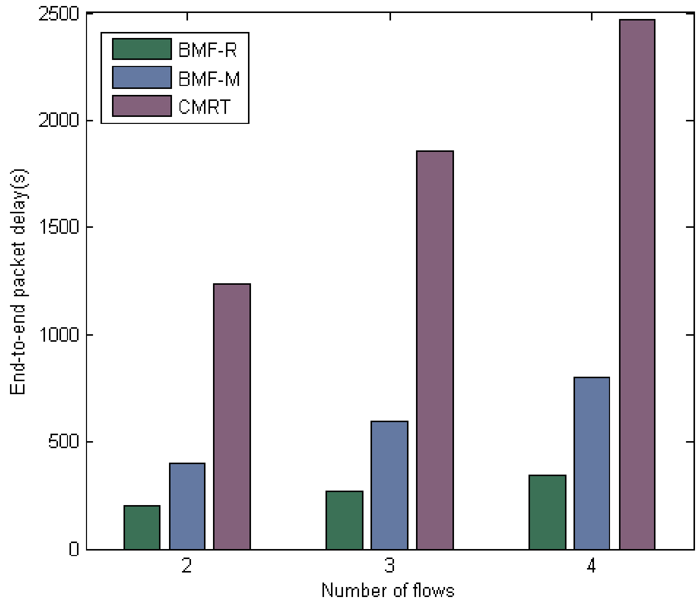

Figure 4.10: Performance comparisons of BMF-MAC with CMRT in terms of end to end packet delay

BMF-R MAC protocol provides latency around 39.5% lower than that of CMRT. While the distance is increased to 8km, BMF-M MAC can obtain the highest reduction of latency around 69% lower compared to CMRT protocol. Hence, it is observed that, BMF-MAC can provide better result to handle variable traffic patterns in multi-hop underwater sensor networks comparing with CMRT.

4.3.2.3 Effects of number of flows

The end-to-end delay of proposed BMF-MAC protocol and existing CMRT protocol with the increase of number of flows is illustrated in Figure 4.10. For BER 10^{-3}, the x-axis shows the number of flows whereas the y-axis shows the end-to-end delay in terms of second. Figure 4.10 depicts the performance of both CMRT and BMF-MAC protocols in terms of end-to-end delay declines with the increasing of the number of flows. Literally from Figure 4.10 it is shown that, data transmission over double flows, BMF-M MAC protocol provides 34% less packet delay compared to CMRT. Whereas in high number of flow number 4, BMF-M MAC protocol can provide latency around 76% lower than that of CMRT protocol. Additionally, data transmission over double flows, BMF-R MAC protocol gains 40% less packet delay compared to CMRT protocol. Furthermore, for number of flow 4, BMF-R MAC

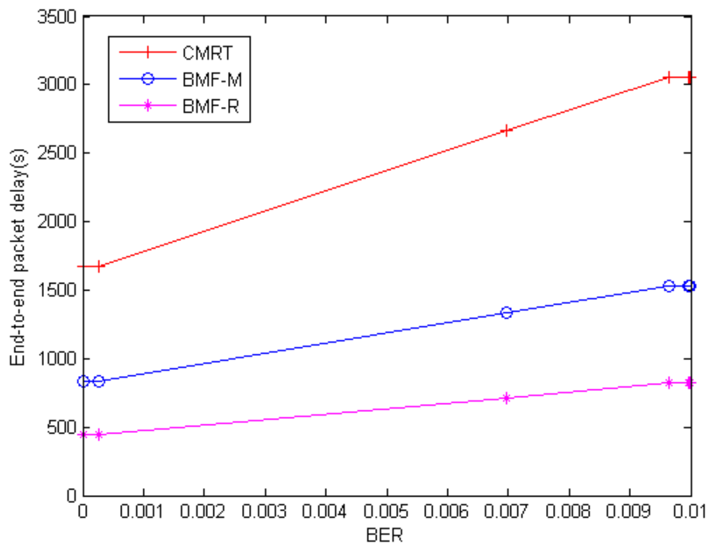

Figure 4.11: Performance comparisons of BMF-MAC with CMRT in terms of end-to-end delay

can obtain the apical degradation of latency around 88% lower compared to CMRT protocol.

4.3.2.4 Effects of BER

For different number of BERs, Figure 4.11 interprets the end-to-end delay. Here, x-axis shows the BER whereas the y-axis shows the end-to-end delay in terms of bit per second. Different lines present the results collected with different protocols: BMF-MAC, CMRT. Throughput decreases when the bit error rate increases from 0 to 1. The six new states in BMF-MAC significantly contributes to the improvement of latency with the increase of BER. It is observed that, the bidirectional multi flow data transmission technique in BMF-MAC significantly contributes to the improvement of end-to-end delay with the decrease of BER.

4.4 Energy Consumption

The performance of energy consumption of BMF-MAC protocol is evaluated in this subsection. We study the performance of energy consumption according to inter nodal distance, different number of flows, various offered loads and different number of nodes. The energy model which is presented in section 3.7 is used.

4.4.1 Effects of offered loads

The energy consumptions of proposed BMF-MAC protocol and existing CMRT protocol with the increase of offered loads is illustrated in Figure 4.12. The x-axis shows the offered loads whereas the y-axis shows the energy consumption in terms of joule (J). BMF-MAC reduces transmission time as it allows nodes to transmit simultaneously when there is multiple data to transmit over multi flow. Hence, it needs less energy than CMRT protocol in all traffic load scenario. Since BMF-MAC needs less control packets exchange than CMRT protocols it also requires less energy in all traffic load condition. Moreover, data packets can be delivered over regular and reverse flow direction without collusions using six different states in BMF-MAC protocol. More specifically, it is seen that in low traffic load for offered load .2 packet/s, the energy consumption of BMF-M MAC protocol can achieve around 28% lower compared to CMRT protocol. On the other hand, BMF-R consume energy around 30% less compared to CMRT protocol. For high traffic load, when the offered load is 1.6 packets/s, BMF-M MAC can achieve the highest decrease of energy consumption around 74% less compared to CMRT. Furthermore, BMF-R gains 81% less energy consumption compared to that of CMRT. Accordingly, BMF-MAC surpasses CMRT in respect to energy consumption under variable traffic loads.

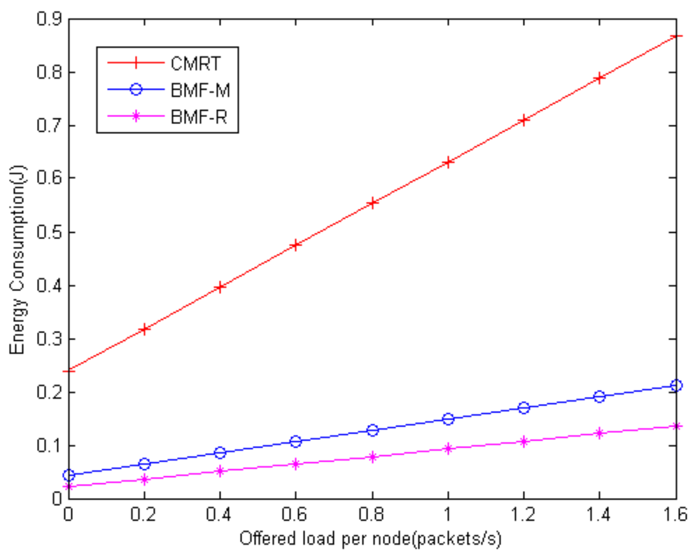

Figure 4.12: Performance comparisons of BMF-MAC with CMRT in terms of energy consumption

4.4.2 Effects of number of nodes

For different number of nodes Figure 4.13 shows the energy consumption for offered load. The x-axis shows number of nodes whereas the y-axis shows the energy consumption in terms of joule. For number of nodes 20, BMF-M MAC protocol can achieve energy consumption around 37.5% less compared to CMRT. On the other hand, BMF-R gains energy consumption around 49.2% less compared to CMRT protocol. When the number of node is increased to 40, BMF-M MAC can achieve the highest improvement of energy consumption around 76% lower and BMF-R can gain 87.5% less than that of CMRT protocol. That reveals BMF-MAC protocol is more energy efficient for large area network. The above mentioned information indicates that, BMF-MAC outperforms CMRT with respect to energy consumption with the increase of network size. As the number of source nodes increases With the increasing of the number of nodes. Therefore, more bidirectional multi-flow constructions can take place which facilitates BMF-MAC protocol to reduce control packets overhead which results improvement of energy consumption. Finally, we conclude that, the bidirectional multi-flow data transmission technique in BMF-MAC significantly contributes to the improvement of energy consumption with the increase of number of nodes.

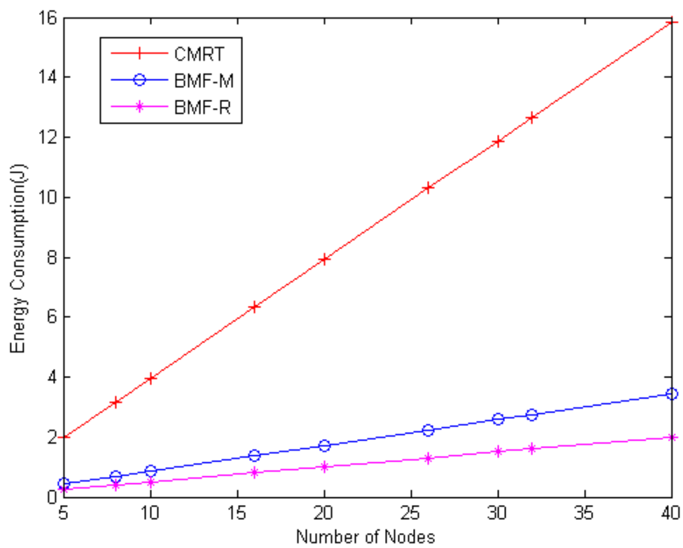

Figure 4.13: Performance comparisons of BMF-MAC with CMRT in terms of energy consumption

4.4.3 Effects of number of flows

Energy consumption of proposed BMF-MAC protocol and existing CMRT protocol in the variation of inter nodal distances with BER of $10^{-}3$ is shown in Figure 4.14. Here, offered load is set to 0.8 packets/s. The x-axis shows the distances whereas the y-axis shows the energy consumption in terms of Joule(J). It is exhibited that the performance of each of the protocols in terms of energy consumption degrades with the increasing of the inter-nodal distance, due to the rising of the distance-related communication overhead. As the distance enhances, the busy duration along with the handshaking time raises by reason of prolonged propagation delay. However, it is observed that, BMF-MAC can provide better result to handle variable traffic patterns in multi-hop underwater sensor networks comparing with CMRT.

Literally from Figure 4.14, it is shown that, data transmission over double flows, BMF-M MAC protocol provides 18% less energy consumption compared to CMRT. Whereas in high number of flow number 4, BMF-M MAC protocol can provide energy consumption around 49% lower than that of CMRT protocol. Additionally, data transmission over double flows, BMF-R MAC protocol gains 23% less energy consumption compared to CMRT protocol. Furthermore, for number of flow 4, BMF-R MAC can obtain the apical degradation of energy consumption around 78%

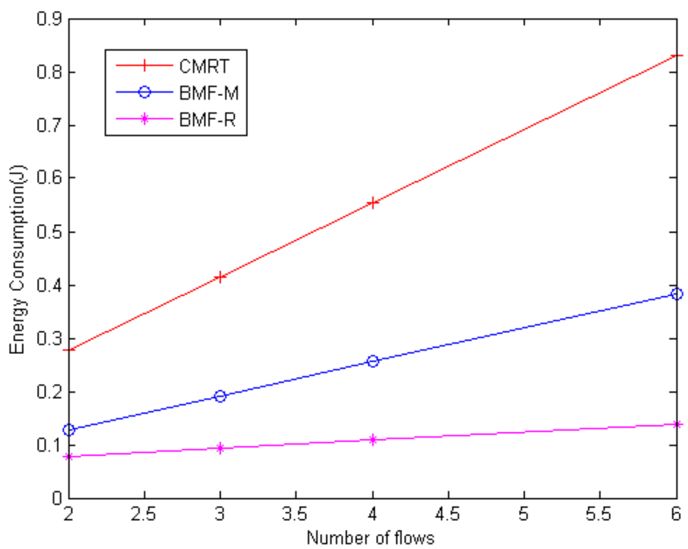

Figure 4.14: Performance comparisons of BMF-MAC with CMRT in terms of energy consumption

lower compared to CMRT protocol.

4.4.4 Effects of inter nodal distance

Energy consumption of proposed BMF-MAC protocol and existing CMRT protocol in the variation of inter nodal distances with BER of 10^-3 is shown in Figure 4.14. Here, offered load is set to 0.8 packets/s. The x-axis shows the distances whereas the y-axis shows the energy consumption in terms of Joule(J). It is exhibited that the performance of each of the protocols in terms of energy consumption increases with the increasing of the inter-nodal distance, due to the rising of the distance-related communication overhead. As the distance enhances, the busy duration along with the handshaking time raises by reason of prolonged propagation delay. However, it is observed that, BMF-MAC can provide better result to handle variable traffic patterns in multi-hop underwater sensor networks comparing with CMRT.

Specifically, From Figure 4.15 it is shown that, while the distance is 1km, BMF-M MAC protocol provides 12.9% less energy consumption compared to CMRT protocol. Furthermore, while the distance is increased to 6km, BMF-M MAC protocol obtains significant reduction of energy consumption around 74.7% lower than that of CMRT. Straightway, BMF-R MAC protocol gains 14% less energy consumption compared to CMRT protocol in inter nodal distance 1km. For the distance 6km, BMF-R MAC

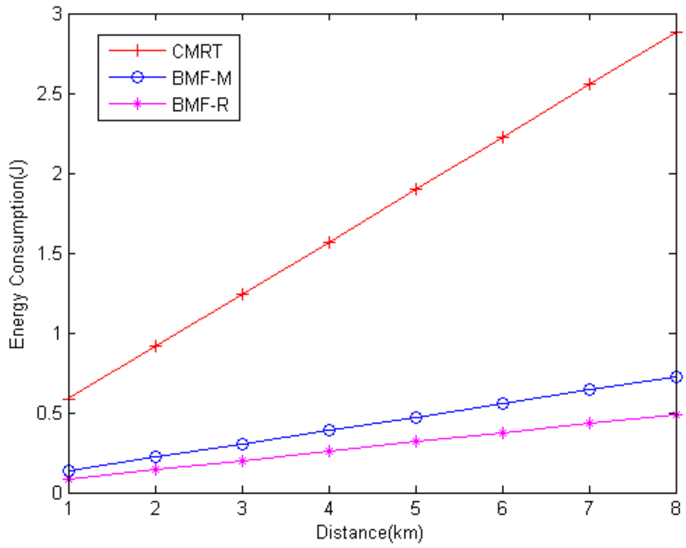

Figure 4.15: Performance comparisons of BMF-MAC with CMRT in terms of energy consumption

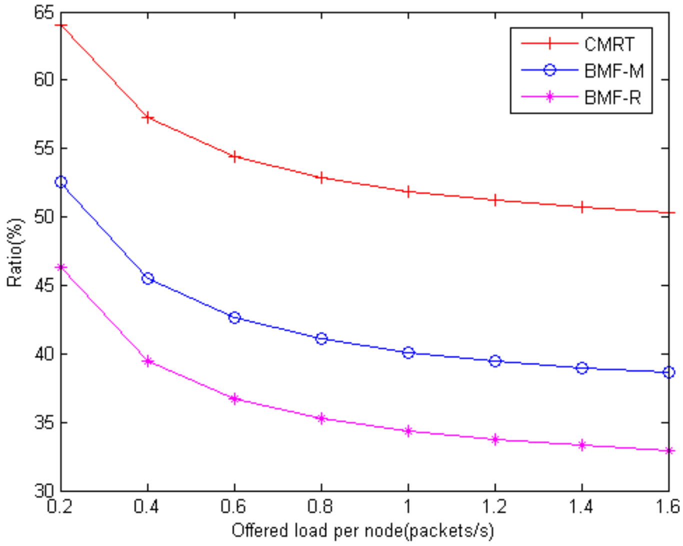

Figure 4.16: Performance comparisons of BMF-MAC with CMRT in terms of control packet time

protocol gains the highest reduction of energy consumption around 76.3% lower than that of CMRT. Hence, it is observed that, BMF-MAC can provide better result to handle variable traffic patterns in multi-hop underwater sensor networks comparing with CMRT.

4.5 Control Packet Time

Figure 4.15 shows that the control packet time of proposed BMF-MAC protocol and existing CMRT protocol in different offered loads with BER of $10^{-}3$. The x-axis shows the offered load whereas the y-axis shows the control packet time in terms of second. In BMF-MAC protocol, multiple control frames can be exchanged simultaneously; thus less control packet time is required. Furthermore, while more packets are generated less control packets are required by the BMF-MAC protocol, thus less control packet time is needed. It is recognized that, BMF-MAC exhibits the best performance in terms of control packet time in all offered load conditions.

4.6 Throughput analysis of BMF-MAC over single flow

In this subsection, the performance of throughput of BMF-MAC protocol over single flow is evaluated. BMF-S is a version of BMF protocol, where single flow data

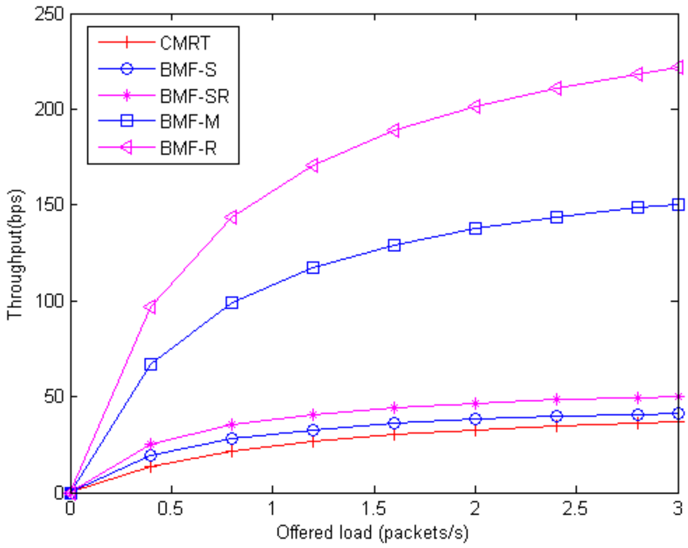

Figure 4.17: Performance comparisons of BMF-MAC with CMRT in terms of throughput

transmission is considered. On the other hand, BMF-SR contemplates single flow bidirectional data transmission. We study the performance of throughput according to different offered loads, different distances and different network areas.

4.6.1 Effects of offered loads

Figure 4.17 shows that the data throughput of proposed BMF-MAC protocol and existing CMRT protocol in different offered loads with BER of $10-^{3}$ for single flow. The x-axis shows the offered load whereas the y-axis shows the throughput in terms of bit per second (bps). Figure show that in all offered load conditions BMF-MAC exhibits the best performance for single flow data transmission. Our channel reservation mechanism allows a single sender to transmit data packets to relay nodes of single flow with retry packet method and can reduce the total channel reservation overhead greatly and thus can improve channel utilization. As a result, BMF-MAC has better data throughput than CMRT. Figure 4.17 reveals that, in low traffic load 0.5, BMF-S protocol can achieve throughput around 7% and BMF-SR achieve 12% higher than that of CMRT. In case of high traffic load 3 packets/s, BMF-S can achieve data throughput around 3.5% higher compared to CMRT protocol as well as BMF-SR can achieve the highest increase of data throughput around 13% higher compared to CMRT protocol. In summary, BMF-MAC protocol outperforms

CMRT protocol with regard to data throughput in variable traffic loads for single flow as well.

4.6.2 Effects of inter nodal distance

In Figure 4.18, throughput of proposed BMF-MAC protocol and existing CMRT protocol in the variation of inter nodal distances with BER of 10^{-3} is shown. Here offered load is set to 0.8 packets/s. The x-axis shows the distances whereas the y-axis shows the throughput in terms of bit per second (bps). The performance of each of the protocols in terms of throughput degrades with the increasing of the inter-nodal distance for single flow. More specifically, Figure 4.18 reveals that for smaller inter nodal distance 1km, the throughput of BMF-SR and BMF-S protocols can achieve around 16.5% and 8% higher compared to CMRT protocol respectively. On the other hand, BMF-SR and BMF-S MAC protocol can achieve throughput around 6% and 3.5% greater than that of CMRT protocol respectively in case of medium inter nodal distance 4km. Therefore, BMF-MAC surpasses CMRT in respect to throughput with variable inter nodal distant nodes.

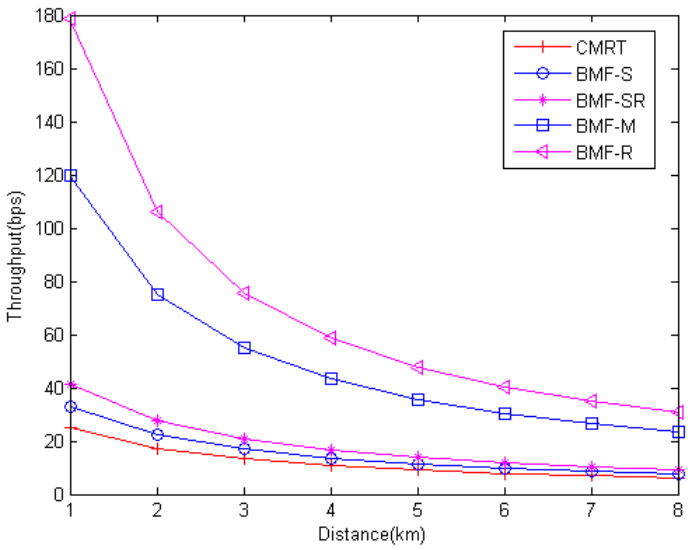

Figure 4.18: Performance comparisons of BMF-MAC with CMRT in terms of throughput

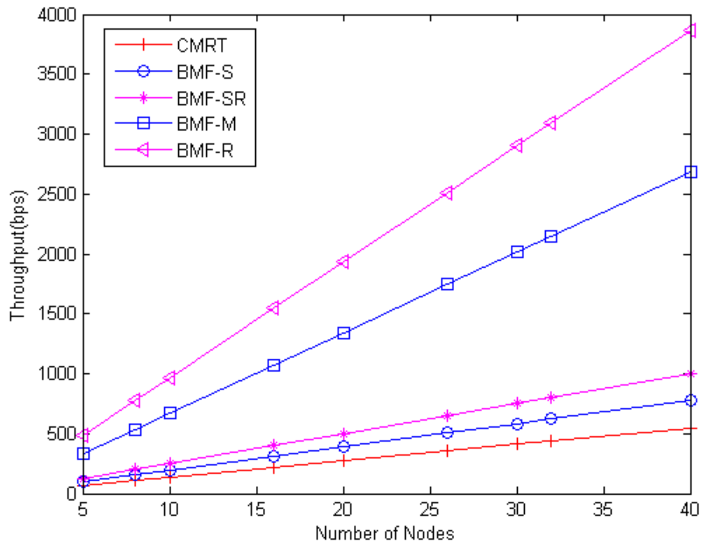

Figure 4.19: Performance comparisons of BMF-MAC with CMRT in terms of throughput

4.6.3 Effects of number of nodes

For different number of nodes, Figure 4.19 shows the throughput for 0.4 packets/s offered load. The x-axis shows number of nodes whereas the y-axis shows the throughput in terms of bps. Literally, for number of nodes 20, BMF-S MAC protocol can achieve throughput around 16% higher compared to CMRT. On the other hand, BMF-SR gains throughput around 31% higher compared to CMRT protocol. When the number of node is increased to 40, BMF-S MAC can achieve the highest improvement of throughput around 24% higher and BMF-SR can gain 45% more than that of CMRT protocol. The above mentioned information indicates that, for large area network BMF-MAC protocol is more throughput efficient. Thus BMF-MAC outperforms CMRT with respect to throughput with the increase of network size for single flow data transmission as well. It can be concluded that, the retry technique of BMF-MAC significantly contributes to the improvement of throughput with the increase of number of nodes.

4.7 Summary

The performance evaluation results in terms of energy consumption, packet latency and throughput of proposed BMF-MAC protocol are investigated in this chapter.

Furthermore, to show the suitability of proposed protocol, performance comparisons of proposed BMF-MAC protocol with that of existing CMRT protocol are carried out. Result shows that BMF-MAC protocol is superior to CMRT protocol in terms of end to end delay with the largest improvement of 88% in high number of flows. BMF-MAC saves more energy under variable traffic loads. In case of high traffic load, BMF-MAC can achieve the highest increasing of data throughput around 67.5% higher than CMRT. The analysis shows that the proposed MAC protocol performs better by decreasing the end to end latency and energy consumption while increasing the throughput in UW-ASNs under all traffic load case. Thus, the proposed BMF-MAC surpass existing CMRT protocols to handle variable traffic load patterns.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

Due to the long propagation delay in underwater environment of the acoustic signal, the designing of handshaking-based MAC protocol is more complex to avoid any collisions in under water environment. A large of works have been proposed to reduce the time-related overhead caused by the propagation delay.

This thesis aims at designing an energy efficient and low latency MAC protocol, Bidirectional Multi-Flow MAC (BMF-MAC) protocol, to handle multi-hop multi-flow data transmission under varying traffic load patters for UW-ASNs. In our protocol, data transmission with bidirectional multi-flow packet method is developed to allow sender to send multiple MFP frame to different receivers with parallel reservation of channels. Moreover, retry packets transmission technique is introduced for sending missing packets in each round handshake. Furthermore, pioneer transmission of a CTS frame is sufficient for transmission of data packets in reverse flow direction without exchanging of control packets thus reducing control packet overhead. Fourteen different states are founded for facilitating to transmit packets without any collision.

In order to evaluate the performance of the proposed BMF-MAC protocol, a mathematical model is derived which includes the equation of energy consumption, latency, throughput and frame error probability. Based on this model the performance of the proposed approach is examined in terms of performance parameters such as throughput, end-to-end delay, and energy consumption.

Furthermore, in order to show the efficiency of the proposed scheme, the performance of the proposed BMF-MAC protocol with the existing CMRT protocol has been compared. Results show that, BMF-MAC protocol can reduce end to end delay more efficiently. This is because, CMRT only transmits train of data per round handshake to multi-hop relaying nodes in a single flow. The BMF-MAC protocol permits more scheduled transmissions per round handshaking by exchanging of control packets and data packets in different flows simultaneously. Thus, in BMF-MAC protocol latency is decreased with the increase of different number of flows comparing existing CMRT protocol. The result shows that BMF-MAC protocol provides 40% less packet delay compared to CMRT protocol for data transmission over double flow, whereas for data transmission over high number of flows BMF-MAC can achieve the significant reduction of latency around 88% lower than that of CMRT protocol.

Furthermore, BMF-MAC is more energy efficient than CMRT protocol as the protocol needs less control packets than CMRT protocol. Data packets can be delivered over regular and reverse flow direction without collisions using fourteen different states in BMF-MAC protocol. Thus, the protocol requires less energy in all traffic load condition as well. Moreover, BMF-MAC can still present competitive performance advantages in terms of energy consumption over CMRT in low as well as high traffic load with variable inter nodal distance, number of nodes and data transmission over different number of flows. In case of energy reduction, the best performance is also achieved here for high traffic load patterns where around 81% lower energy is achieved compared to CMRT protocol.

Additionally, the same performance improvement has been observed for data throughput as well. The throughput is compared with CMRT in terms of different offered loads, distances, number of flows, network areas, number of reverse packets and BERs. This is due to fact that, in BMF-MAC, channel reservation mechanism allows a single sender to transmit data packets to multiple nodes of different flows with per round of channel reservation and can reduce the total channel reservation overhead greatly and thus can improve channel utilization. BMF-MAC can achieve the highest increase of data throughput, around 67.5% higher than that of CMRT protocol in high traffic load patterns. The analysis shows that the proposed MAC protocol performs better by decreasing the end to end latency as well as energy consumption while increasing the throughput in UW-ASNs. Therefore, the proposed

BMF-MAC protocol outperforms existing CMRT protocol.

5.2 Future Work

The ability of newer generations of commercially available acoustic modems used on the sensor nodes to tune their operating frequency over different channels provides an opportunity to alleviate the effects of interference and consequently improve the network performance. In future, we want to design a MAC protocol using multi-channel communication in multi-hop multi-flow scenario to improve the capacity of UW-ASNs. The idea presented in this thesis would be used as a building block for MAC protocol design.

In future, a simulation model of the proposed scheme using simulation tool AQUA-SIM will be carried out. Extensive comparisons of simulation model of the proposed BMF-MAC protocol will be investigated as well.

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