Design of EM Wave Based MAC Protocols for Underwater Sensor Networks with TDMA based Control Channel

A Thesis Submitted

in Partial Fulfillment of the Requirements for the Degree

of

MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

by

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May 2017

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Declaration of Originality

This is to certify that this thesis titled "**Design of EM Wave Based MAC Protocols for Underwater Sensor Networks with TDMA based Control Channel**", is the result of my study for partial fulfillment of M. Sc. degree under the supervision of Dr. Md. Farhad Hossain, Associate Professor, Department of EEE, BUET, and this thesis or any part of it has not been submitted elsewhere for award of any other degree or diploma.

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Dedicated to

my beloved parents

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Acknowledgements

I express deep sincere gratitude from the bottom of my heart to the Almighty Allah for bestowing me with the blessings to perform this work.

Foremost, I would like to express my indebtedness and sincere respect to my supervisor Dr. Md. Farhad Hossain, Associate Professor, Department of Electrical and Electronic Engineering (EEE), Bangladesh University of Engineering and Technology (BUET), Dhaka-1205, Bangladesh, for his continuous support in completing my research. It is his wise knowledge, motivation, patience and guidance, which made it possible to complete my thesis.

Finally, my deepest gratitude goes to my parents, whose unconditional love and inspiration has kept me patient to endure the hard work and complete this thesis.

List of Acronyms

Ac-Ac	Acoustic based control and data channels
ALOHA-AN	ALOHA Advanced Notification
ALOHA-CA	ALOHA Collision Avoidance
aTDMA	adaptive slot TDMA
AUV	Autonomous Underwater Vehicles
CDMA	Code Division Multiple Access
COPE-MAC	Contention based Parallel Reservation MAC
CSMA	Carrier Sense Multiple Access
CTS	Clear to send
CUMAC	Cooperative Underwater multi-channel MAC
DACAP	Distance-Aware Collision Avoidance Protocol
DC-MAC	Data-Centric MAC
DSSS	Dynamic Slot Scheduling Strategy
EM	Electromagnetic
EM-Ac	EM based control and Acoustic based data channel
EM-EM	EM based control and data channel
EMI	Electromagnetic Interference
FAMA	Floor Acquisition Multiple Accesses
FDMA	Frequency Division Multiple Access
HF	High Frequency
H-MAC	Hybrid MAC
HSR-TDMA	Hybrid Spatial Reuse TDMA
ISI	Inter Symbol Interference
LOS	Line Of Sight
MAC	Medium Access Control
MACA-U	Multiple Access Collision Avoidance for Underwater
MM-MAC	Multi-channel MAC protocol
OFDMA	Orthogonal FDMA
PDAP	Propagation Delay Aware Protocol
PDT- ALOHA	Propagation Delay Tolerant ALOHA

PLAN	Protocol for Long-latency Access Networks
POCA-CDMAMAC	Path Oriented Code Assignment CDMA-based MAC
PR-MAC	Priority Reservation MAC
QoS	Quality of Service
RCAMAC	Reservation Channel Acoustic Media Access protocol
RF	Radio Frequency
RTS	Request to Send
SNR	Signal to Noise Ratio
SST-MAC	Spatially Shared TDMA MAC
ST-CG	Spatial-Temporal Conflict Graph
ST-MAC	Spatial-Temporal MAC
STUMP	Staggered TDMA Underwater MAC Protocol
TDMA	Time Division Multiple Access
T-Lohi	Tone- Lohi
UMIMO- MAC	Underwater Multiple Input Multiple Output MAC
US	United States
UW- FLASHR	Underwater FLASHR
UWC/UC	Underwater Communication
UW-OFDMAC	Underwater Orthogonal Frequency Division Multiple Access Control
UWSN	Underwater Sensor Networks

Abstract

Underwater communication is the major tool for exploring vast underwater space, which is extremely critical for the progress of human race. To perform communication in underwater, sensors are deployed to form underwater networks, which in return provides an efficient robust communication system. For the past few decades, almost inevitably, underwater communication systems have grown deploying acoustic based signal propagation. However in recent times, the demand of low latency and high throughput applications, and the emergence of short-range underwater communications has drawn notable attention of many academia and industries for developing electromagnetic (EM) wave based underwater sensor networks (UWSNs). In light of this, this thesis work proposes novel multiple access control (MAC) protocols by integrating EM based communications in single-hop communications based UWSNs. Proposed protocols use a separate TDMA based control channel and single or multiple data channel(s) for data packet transmission. EM wave is proposed for the control channel, whereas EM or acoustic wave can be used in the data channel(s).

Performance of the proposed MAC protocols is investigated considering both protocol interference model and physical interference model. A MATLAB based simulation platform is developed for thoroughly investigating the performance of the proposed MAC protocols. Performance is evaluated in terms of throughput, packet collision rate, waiting time, energy requirement, network coverage, etc. Impact of system parameters, such as offered load, network size, data packet size, control packet power, water conductivity and channel bandwidth are analyzed thoroughly. A comparison and feasibility study of the proposed protocols is also presented demonstrating better performance compared to CSMA, ALOHA-CS and ALOHA-AN MAC protocols. Our investigation using physical interference model also identifies that EM-EM based scenario can be used for short distance communication achieving improved network performance. This also suggests that EM-EM based multi-hop communications might be a better choice for long-range UWSNs, which will be considered in our future works.

Chapter 1

Introduction

This chapter describes the background and the motivation for this research work by briefly introducing the field and explaining the principal research problem. The objectives of this thesis are also presented in brief. Finally, a concise outline of the thesis is provided at the end of the chapter.

1.1 Underwater Sensor Networks

More than 70% of the Earth's surface is covered by water with nearly 97% seas and oceans [1]. The environment in underwater holds a great deal of uncertainty and potentially hostile in many cases for human being. However, this huge underwater area is abundant in natural resources, both marine life and minerals. Furthermore, if we can closely monitor the seismic activity in underwater, it would be possible to predict the tsunami as well as the earthquake. The chemical, biological and nuclear pollution in underwater can be monitored and we can get an idea of the overall pollution of our environment. We can identify hazards on seabed, locate mine, shipwrecks and can detect intrusion by the communication in underwater. Therefore extracting information from underwater carries extreme importance for which underwater communications (UWC) can play a major role. Consequently, research on UWC for exploring such a vast and resourceful domain carries substantial importance.

On the other hand, sensor technologies being matured enough to be used in any type of environment, underwater wireless sensor networks (UWSNs) as a tangible, low-cost solution have drawn a significant interest amongst the researchers [2], [3], [4]. UWSNs consist of nodes that have the ability to communicate between each other and can sense and process data. Purposes served by the deployment of UWSNs include tactical surveillance for protecting maritime boundaries, mine reconnaissance, search and rescue operations, assisted navigations, disaster prevention, offshore explorations, oceanography and aquatic applications [1], [3].

Most of today's underwater communications are based on acoustic wave technology since it is capable of providing long-range communications in underwater [1], [2], [5], [6], [7]. Acoustic waves however result in poor performance in shallow water environments, and have extremely low data rates due to lower bandwidth and slower acoustic transmission [8], [9]. Acoustic transmission is affected by multipath propagation, susceptibility to environmental noise (e.g., marine life at the seabed and wind speed), turbidity, salinity gradients, pressure gradients, and has adverse impact on marine life. More importantly, increasing number of fast moving underwater vehicles and autonomous weapons around the world as well as the requirement of faster data rate for modern applications [3], [10], there is an urgency for an alternative faster transmission media like optical or electromagnetic (EM) waves [4], [9]. However, optical waves are impractical for major underwater applications as it requires line-of-sight (LOS) path with tight alignment and clear water between transmitter and receiver [11].

Therefore, how to exploit the EM wave's faster transmission and higher bandwidth capability in underwater to make real-time low latency and high-throughput applications feasible is grabbing the attention of the related scientific community [9], [12], [13], [14], [15], [16]. Despite having a relatively shorter range in deep water, EM technology is a promising technology for UWSNs as they have the ability to provide much higher data rates than those achievable with acoustic waves in harsh environments with no direct path. Also, unlike acoustic UWSNs, EM based networks are unaffected by temperature, salinity, turbidity, pressure gradients, and wind speed of the sea. Moreover, EM wave suffers less attenuation in shallow water enabling longer range UWSNs, whereas the seeming drawback of higher attenuation of EM wave in deep water can be exploited in a beneficial way for multi-user parallel data transmission enabling localized communications in UWSNs [9]. Further, the relatively lower cost of RF nodes will further add to the aforementioned reliability making EM UWSNs a clear winner. Lastly, EM UWSNs have no known impact on the marine life and ecosystem. Therefore, this new breed of UWSNs can provide real-time deep-sea oil and gas explorations, military surveillance, search and rescue operations, and environmental monitoring, which acoustic networks fail to afford [9], [12].

1.2 Medium Access Control

A Medium Access Control (MAC) protocol allows the nodes in a network to share the common broadcast channel. Thus, a MAC protocol is critical to the UWSNs as it plays an important role to achieve the quality of service (QoS). The main task of a MAC protocol is to prevent simultaneous transmissions or resolve transmission collisions of data packets while providing higher throughput, low channel access delays, longer network life-time and fairness among the nodes in a network [2], [5], [17]. Therefore, designing an efficient MAC protocol for UWSNs is of paramount importance because the MAC layer protocol coordinates nodes access to the shared wireless medium.

The development of MAC protocols for underwater communication (UC) became a popular research area from the beginning of communication networks. One class of MAC protocols can allow the nodes of a network to share the channel in a mutually exclusive manner leading to a collision free system. Another class of MAC protocols allows the nodes to transmit randomly with no coordination among themselves and thus collision is inevitable. Various techniques, such as carriers sense, collision detection and re-transmission, etc. can also be integrated with such MAC protocols to minimize collisions. On the other hand, there can be MAC protocols which can combine the features of both collision-free and collision-inevitable MAC protocols. Classifications of MAC protocols will be further discussed in Chapter 2.

1.3 Research Motivations

As discussed above, research community as well as the industries are extremely eager to introduce EM wave in underwater networking for supporting many modern underwater applications, which otherwise cannot be provided by acoustic networks. Whatever the network architecture to be used, there must be an efficient MAC protocol at the center of network operation. This research particularly focuses on the design of MAC protocols for UWSNs incorporating EM wave for communications. As identified from our extensive literature survey, although several research projects and experiments are going on EM bases UWSNs, to the best of our knowledge, there is no such work on design and developing EM wave based MAC protocol.

There exists many MAC protocols in literature for acoustic wave based UWSNs. However, in addition to the huge difference in speed, there exists some other fundamental distinctions between the propagation characteristics of acoustic and EM waves in underwater. It is to be noted that the physical layer, namely the channel characteristics, has great impact on the design of MAC protocol since it has direct coordination with MAC [2], [17]. Thus, the existing acoustic MAC protocols are inappropriate for EM wave based UWSNs [2]. Similarly, due to the substantial differences in the propagation speed of EM wave in terrestrial and underwater environments, delay characteristics as well as the differences in network topology and deployment scenario, MAC protocols designed for EM terrestrial sensor networks will not perform efficiently as in EM UWSNs [4], [9], [15], [18]. Therefore, design of MAC protocols incorporating EM wave for communications over UWSNs is of extreme significance.

1.4 Research Objectives

The main objective of this research is to integrate EM wave in the designs of MAC protocols for UWSNs with the aims to improve the delay performance and network throughput. Proposed protocols use separate time-division multiple access (TDMA)-based control channel for signaling purpose along with the data channel for packet transmission. The data channel can be either single channel or multi-channel. On the other hand, network nodes are assumed to be deployed using mesh topology for performing single-hop communications. Thus the objectives of this thesis can be summarized as below:

- To propose single-channel EM-Acoustic Hybrid and EM-EM MAC protocols for UWSNs

- To propose multi-channel EM-Acoustic Hybrid and EM-EM MAC protocols for UWSNs
- To develop a simulation platform for evaluating the performance of the proposed protocols in terms of throughput, packet collision rate, waiting time, energy requirement, network coverage, etc. The proposed protocols will be investigated using both protocol interference model and physical interference model.
- To investigate the impact of various network parameters, such as offered load, network size, data packet size, control packet power, water conductivity and channel bandwidth on the proposed protocol performance
- To compare the proposed MAC protocols with the existing counterparts in terms of various parameters for determining their feasibility to be used in practice

1.5 Organization of the Thesis

Chapter 2 provides an essential background on the basics of UWSNs including its applications, a comparative study on the transmission media and a summary of design challenges. A comprehensive literature survey on the existing MAC protocols classifying them into different approaches is also presented.

Chapter 3 first proposes and investigates a hybrid single channel MAC protocol considering a TDMA based control channel using EM wave and a data channel employing acoustic wave. Then the protocol is extended to use EM wave for both the control channel and the data channel. Proposed protocols incorporate a guard-time for compensating the signal propagation delay. Performance of the protocols is first investigated considering protocol interference model, where the propagation path-loss is not considered assuming that any transmitted packets reaches the destination. Then the protocols are investigated using physical interference model by taking the propagation path-loss into account.

Chapter 4 extends the works of the previous chapter to multi-channel transmission scenario. Here, first a hybrid multi-channel MAC protocol considering a TDMA based control channel using EM wave and multiple data channels using acoustic wave is proposed. Then a multi-channel protocol is proposed using EM wave for both the control channel and the data channels. Similar to Chapter 3, performance of the protocols is investigated considering both protocol interference model and physical interference model.

Chapter 5 presents a feasibility study of the proposed protocols through a comprehensive comparison with some of the existing MAC protocols. Throughput, energy requirement, successful packet delivery, etc. are compared. Moreover, the applicability of the proposed protocols in fresh water as well as in saline water, and the suitable network size are also investigated.

Chapter 6 concludes the thesis by summarizing the major findings, as well as identifying several potential research opportunities for the improvements and extensions of the proposed MAC protocols.

1.6 Chapter Summary

This chapter has identified the necessity of higher throughput and fast responsive UWSNs for supporting modern applications. It also exposed the limitations of the existing acoustic based UWSNs and thus has validated the motivations of incorporating EM wave in UWSN communications. A concise form of the research objectives is then provided. Finally, for the convenience of the readers in following this research, a chapter-wise outline of the thesis is presented.

Chapter 2

UWSN MAC Protocols: Background and Research Trends

This chapter first presents the basic concepts of UWSNs including architectures and typical applications. Challenges in UWC as well as in designing MAC protocols for UWSNs are then discussed. Then a brief overview on the existing MAC protocols for UWSNs is given. The chapter is finally concluded by presenting a brief discussion on the state-of-the-art research on the EM wave based UWSNs.

2.1 Basics of Underwater Sensor Networks

UWSNs have gained wide acceptance for efficiently exploring and studying underwater environment, especially in ocean. UWSNs are comprised of sensors, buoys, gateways, sinks, anchors, and autonomous underwater vehicles (AUVs). These underwater devices can communicate with each other and are coordinated to do specific tasks as a whole system. These sensors and vehicles have a self-organizing autonomous network by which they can adapt to the characteristics of the ocean environment. Such networks with devices capable of sensing, processing and communicating are often integrated with water surface sinks and stations, submarines, satellite networks, aviation systems, and onshore base stations (sinks) enabling extended functionalities. Real-time communication protocols among the network devices should be ensured to make underwater applications viable. FORCEnet, a project of US Navy is one example of such systems [3]. An artist's conception of the system is shown in Fig. 2.1.

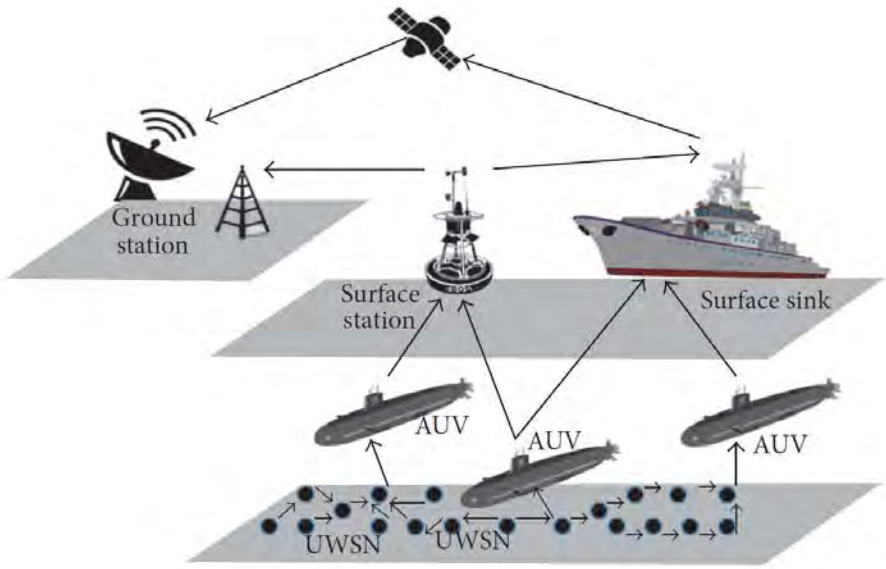

Fig. 2.1: An artist's perception of US Navy's FORCEnet project [12].

2.1.1 Two-Dimensional UWSNs

Two-dimensional (2D) UWSNs is the simpler form of UWSNs, where a group of sensor nodes are anchored to the bottom of the ocean with deep ocean anchors. Architectural demonstration for a typical 2D UWSNs is shown in Fig. 2.2. To relay data from the networks residing inside the sea to a surface station, network devices named underwater sinks (UW-sinks) are used. To accomplish this task, sinks are equipped with two transceivers, namely a vertical and a horizontal transceiver. The sinks use the horizontal transceiver to communicate with the sensor nodes in order to send commands and configuration data to the sensors (sink to sensors), and collect monitored data (sensors to sink). Underwater sensor nodes are interconnected to one or more underwater sinks (UW-sinks) by means of wireless links. Whereas, to relay data to a surface station, the sinks use the vertical links. In deep water applications, vertical transceivers must have longer ranges as the ocean can be as deep as 10 km. A transceiver that has the ability to handle multiple parallel communications with the sinks is usually mounted on the surface station. It is also equipped with a long range RF and/or satellite transmitter to communicate with the onshore sink and/or to a surface sink.

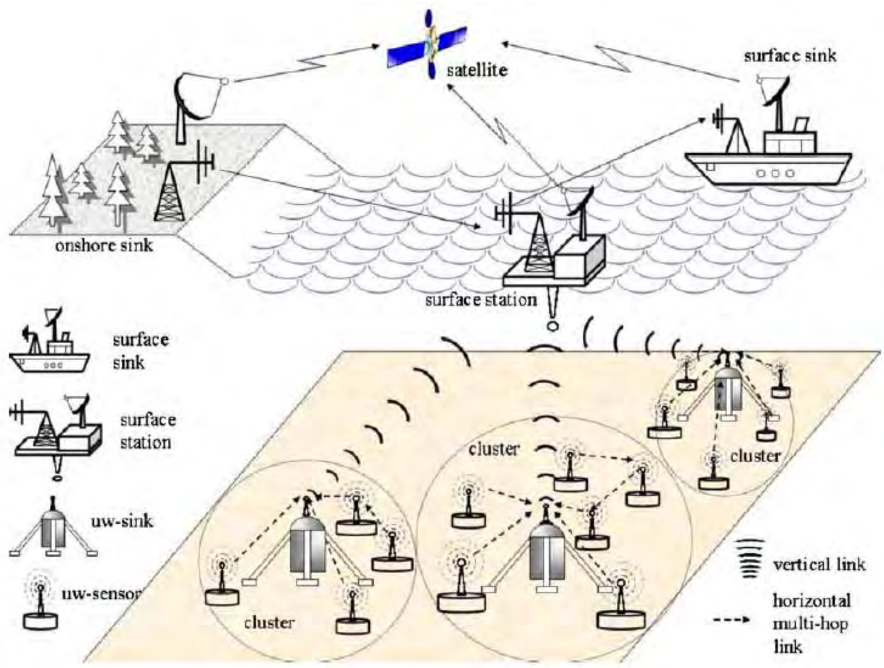

Fig. 2.2: A view of 2D UWSN architecture [19].

2.1.2 Three-Dimensional UWSNs

Three dimensional (3D) UWSNs are used for the applications for which 2D networks are not appropriate. Sensor nodes are left floating at different depths and thus creates a 3D UWSNs for observing a given phenomenon. One possible way to do this is to attach each sensor node to a surface buoy, by means of wires whose length can be regulated so as to adjust the depth of each sensor node. This technique is really easy to implement in a very short time. However, multiple floating buoys may obstruct ships navigating on the surface, or they can be easily detected and deactivated by enemies in military settings. Furthermore, floating buoys are vulnerable to weather and tampering or pilfering [19]. Therefore, a different approach to deploy the sensor nodes can be done by anchoring sensor devices to the bottom of the ocean. Such a conception is presented in Fig. 2.3. Here each sensor is anchored to the ocean bottom and equipped with a floating buoy that is inflated by a pump. The buoy pushes the sensor towards the ocean surface. By adjusting the length of the wire that connects the sensor to the anchor, the depth of the sensor can be adjusted. This can be accomplished using an electronically controlled engine residing on the sensor. Ocean current is a major challenge in maintaining the depth of the sensors under such deployment scenarios.

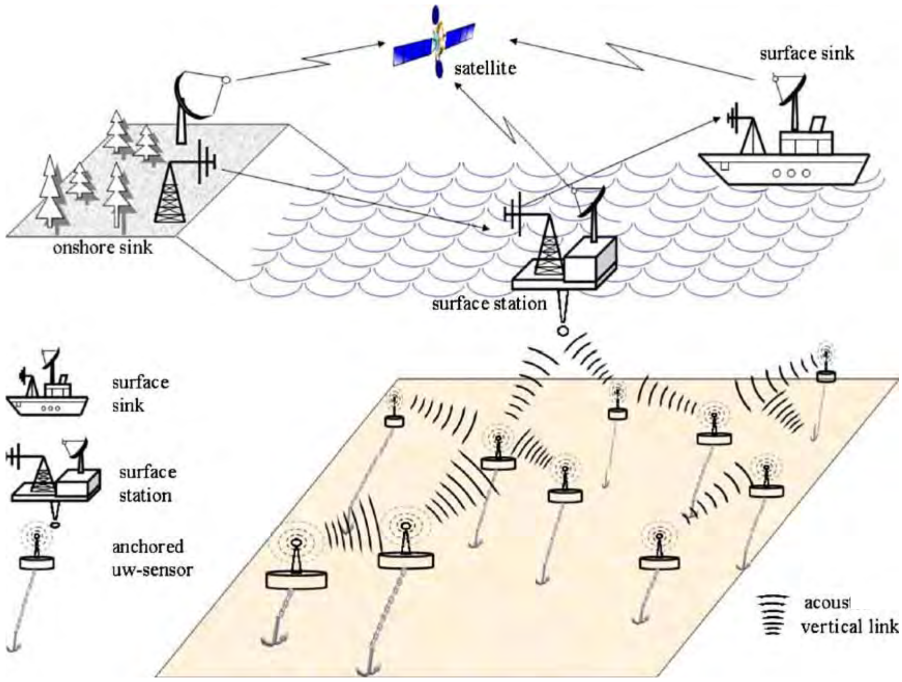

Fig. 2.3: A view of 3D UWSN architecture [19].

2.2 UWSN Applications

UWSNs can offer many civilian and military applications. Some of such applications are presented below [2], [19].

- *Ocean sampling*: Synoptic, cooperative adaptive sampling of the 3D coastal ocean environment can be performed by the networks of sensors and vehicles.
- *Environmental monitoring*: UWSNs can be used for monitoring chemical, biological and nuclear pollution in underwater environment.
- *Undersea explorations*: To detect underwater oil fields or reservoirs, determine routes for laying undersea cables, and assist in exploration for valuable minerals, UWSNs can play a vital role.
- *Disaster prevention*: Sensor networks that measure seismic activity from remote locations can provide tsunami warnings to coastal areas, or investigate the effects of earthquakes.
- *Assisted navigation*: Underwater sensors can be used to identify hazards on the seabed, locate dangerous rocks in shallow waters, mooring positions, submerged wrecks, and to perform bathymetry profiling.
- *Distributed tactical surveillance*: AUVs and fixed underwater sensors can

collaboratively monitor areas for surveillance, reconnaissance, targeting and intrusion detection systems.

- *Mine reconnaissance*: The simultaneous operations of multiple AUVs with acoustic and optical sensors can be used to perform rapid environmental assessment and detect mine-like objects.

2.3 Media for Underwater Communications

Throughout the past few decades, research and development on underwater acoustic networks has been carried out extensively [18], [20], [21]. For underwater sensor applications, acoustics based communication is a established technology which offers long transmission ranges of up to 20 km [22]. However certain challenges and limitations have also been revealed about the acoustic link [4]. Acoustic waves yield poor performance in shallow water where signal flow can be affected by turbidity, ambient noise, salinity, and pressure gradients. In addition, acoustic technology can have an adverse impact on marine life [23].

The optical wave technology with its very high capacity has recently motivated the researchers to take several attempts at research on underwater optical communications, of which the latest include [24], [25], [26], [27]. However, to deliver good performance, optical waves need very clear water and tight alignment of the nodes. To use optical communications, line of sight (LOS) is needed to be maintained precisely and therefore has imposed a significant constraint on its underwater applications. Still efforts have been made in [26] to try to overcome such a limitations.

On the other hand, though RF-EM suffers from limited transmission range and electromagnetic interference (EMI), it also has some useful features that can facilitate flexible deployment of UWSNs in coastal regions. Researchers nowadays are gaining more interests on underwater EM communication day by day [9], [28], [29]. Table 2.1 summarizes the three major underwater communication technologies in terms of advantages and limitations. From the table, it is quite clear that EM wave has some distinct advantages compared to acoustic and optical technologies, which make it suitable for underwater environments.

The first distinguishable advantage of EM is that EM waves can cross water-to-air or water-to-earth boundaries easily following the path of least resistance [9]. In this way, both air and seabed paths will act to extend the transmission range. However, both acoustic and optical waves cannot perform smooth transitions through the air/water interface. If this feature of EM can be fully utilized, it can make a significant contribution to network design and implementation. Secondly, EM waves are robust to turbulence caused by tidal waves or human activities, whereas acoustic and optical waves are not. This feature is extremely crucial for the better performance of EM UWSNs in random and unpredictable underwater environments. Thirdly, EM waves are not that much affected in dirty water conditions, while optical waves are highly susceptible to particles and marine fouling. Consequently, EM wave has the advantage when water has a high level of sediment and aeration. Moreover, acoustic noise has no impact on EM signal, and there is no known effect of EM wave on marine life.

Table 2.1: Advantages and limitations of UWC using acoustic, EM and optical signals [2], [9], [12], [17].

Technology	Advantages	Limitations
Acoustic	▪ Significantly lower signal attenuation ▪ Longer transmission area in the range of km ▪ Can function in the absence of LOS path between transmitting and receiving nodes	▪ Significantly slower response as propagation speed is much lower (1500 m/s) than that of EM wave ▪ Significantly lower data rate (up to 20kbps) as bandwidth is low ▪ Surface repeater is required as strong reflections and attenuation occurs in crossing water/air boundary ▪ Variable delays ▪ Poor performance in shallow water ▪ Less reliable and robust communication as easily affected by

		turbidity, ambient noise, temperature, salinity, and pressure gradients ▪ Adverse impact on the marine life and ecosystem ▪ Higher cost of network nodes
EM	▪ Large bandwidth ▪ High data rates in the range of few Mbps ▪ Faster response due to higher propagation speed and significantly lower delay ▪ LOS for communication is not essential ▪ No need of clear water ▪ No noticeable impact of underwater environment, such as temperature, turbidity, salinity, bubbles and pressure gradients, and thus improve robustness in unpredictable underwater environment ▪ Not affected by sediments and aeration ▪ Immune to other noise except electromagnetic interference (EMI) ▪ Lower Doppler shift ▪ More reliable communication	▪ Easy to be affected by EMI ▪ Higher attenuation, which increases with the salinity of water ▪ Limited communication range in high data rate applications (e.g., 90m for 500 kbps and less than a meter for 20 Mbps range) ▪ Large antenna requirement ▪ Dense deployment of nodes is required for higher frequency range

	▪ Can cross water-to-air or water-to-earth boundaries easily ▪ No impact on marine life ▪ Lower cost of nodes ▪ Good performance in shallow water ▪ Higher attenuation is beneficial in an environment of multi-user interference	
Optical	• Ultra-high bandwidth: gigabits per second • Low cost	• Does not cross water/air boundary easily • Susceptible to turbidity, particles, and marine fouling • Needs LOS • Requires tight alignment of nodes • Very short range

2.4 Path-Loss Model for Underwater Communications

1.4.1 Underwater Propagation Model for EM Waves

Path loss P_L in dB of EM wave in underwater can be expressed as [30]

$$P_L = L_{\alpha,\varepsilon} + L_R \tag{2.1}$$

where $L_{\alpha,\varepsilon}$ is the attenuation loss in water due to water conductivity and complex permeability in dB and L_R is the reflection loss at the water–air boundary in dB due to the impedance mismatch between the two media. Considering all the nodes immersed into water, reflection loss L_R can be neglected. The propagation constant can be expressed as below [31]

$$\gamma = j\omega\sqrt{\mu\varepsilon - j\frac{\sigma\mu}{\omega}} \tag{2.2}$$

where μ is the permeability, ε is the permittivity, σ is the conductivity and $\omega = 2\pi f$ is the angular frequency. Thus P_L at a distance D (meter) can be expressed as [32]

$$P_L = L_{\alpha,\varepsilon} = \Re(\gamma) \times \frac{20}{\ln(10)} \times D \tag{2.3}$$

where $\Re(x)$ is the real value of x.

1.4.2 Underwater Propagation Model for Acoustic Waves

Propagation path loss P_L for acoustic wave in underwater expressed in dB can be given by [33]

$$P_L = 10\log(r) + \alpha r \times 10^{-3} \tag{2.4}$$

where α represents the absorption coefficient in dB/km and r is transmission range expressed in meters. The absorption coefficient α can be calculated using Thorp's expression at frequencies above a few hundred Hz as below [34]

$$\alpha = \frac{0.1 f^2}{1+f^2} + \frac{40 f^2}{4100+f^2} + 2.75 \times 10^{-4} f^2 + 0.003 \tag{2.2}$$

where f is frequency in Hz.

2.5 Challenges in Acoustic Communications in Underwater

- *High and Variable Propagation Delay*: Sound wave in underwater propagates with a speed of about 1500m/s [35]. Therefore, the propagation delay in underwater is five orders of magnitude higher than that of radio frequency (RF) terrestrial channels over air. On the other hand due to the formation of shadow zones, surface scattering, bubbles and noise due to breaking waves, biological sources and rain, propagation speed of sound varies resulting variable propagation delay [36]. Delay variation is also highly dependent on temperature, salinity and depth of water. Collision detection/avoidance is the primary function of any MAC protocol, which is closely correlated to the propagation delay. The high and variable delay is the major barrier in immediate collision detection or avoidance mechanism and thereby results in reduced throughput of the acoustic channel.

- *Limited Bandwidth and Data Rate:* Acoustic waves with low to medium frequencies face high environmental noise and the available acoustic bandwidth depends on the transmission distance. The bandwidth can be lower than 1 kHz with longer range or with high-power absorption it can be greater than 50 kHz [37]. For a range (distance between two communicating nodes) of 1000km, the available bandwidth is less than 1kHz, whereas available bandwidth for a range of 10-100km, 1-10km, 100m-1km and less than 100m are 2-5kHz, 10kHz, 20-50 kHz and greater than 100 kHz respectively [38].Typical acoustic modems work at the frequencies from merely a few Hz to tens of kHz. Hence, the data rate for underwater acoustic sensors can hardly exceed 100 kbps. Comparing with the bandwidth offered by RF radios which is several hundred MHz, the very limited bandwidth of acoustic channels requires careful design of coding schemes and MAC protocols used in UWSNs.

- *Noise*: Environment noises are mainly made up with man-made noise and ambient noise [2]. Man-made noises are mostly machinery noises coming from motors, while natural noise refers to seismic and biological phenomena which cause ambient noise.

- *Energy Consumption*: The acoustic transceivers used in under water require quite high transmission powers compared to the terrestrial devices with a higher ratio of transmit to receive power, so the efficient use of the acoustic link by the protocol is of outmost importance in UWSNs [39]. Batteries are energy constrained and cannot be recharged easily.

- *Low Battery Power*: Sensor nodes are generally powered through small batteries of limited power, which cannot be usually recharged. Replacement of these low cost batteries in underwater is a challenging task and uneconomical too [17]. On the other hand, bigger batteries make the nodes too heavy to operate properly. Therefore, life of a sensor node depends on its battery power.

- *High Bit Error Rates*: The underwater channel is severely impaired, especially due to multi-path and fading. By generating inter symbol interferences (ISI), multi-path propagation is responsible for severe degradation of the acoustic communication signals [2]. Higher value of ISI may result in higher bit error rates. Moreover, some external noise such as shipping noise, thermal noise, wind noise or turbulence noise may reduce the signal-to-noise ratio. Eventually temporary losses of connectivity (shadow zones) can be experienced in addition to high bit error rates. "Shadow zone" is mainly caused by long paths and the frequency-dependent attenuation. Almost no acoustic signal is found existing in it.

- *Node Mobility*: In a typical underwater scenario, UWSN nodes may move at speeds up to six kilometers an hour due to the ocean current [12], [40]. Hence, unlike most terrestrial sensor networks, where sensor nodes are mostly static, most sensor nodes placed underwater have slow to medium mobility. Therefore, the mobile UWSNs designed by ignoring the mobility of sensor nodes may perform sub-optimally while using for surveillance operations. It is important to note that the mobility models must be developed. The reason behind is that the node mobility pattern in an UWSN is completely different from those usually considered in the above ground wireless sensor networks literature. The new mobility models have to be 3D in nature because of the cyclic or irregular patterns in forward and backward ways of ocean waves, as illustrated in Fig. 2.4, something that is not the case in terrestrial networks.

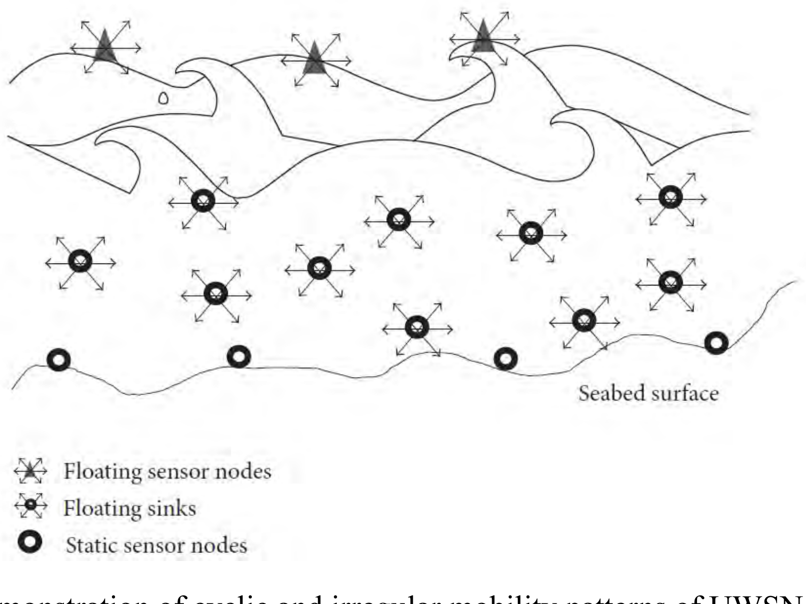

Fig. 2.4: Demonstration of cyclic and irregular mobility patterns of UWSN nodes [12].

2.6 Challenges in Designing Underwater MAC Protocols

Conceiving a MAC protocol is a major challenge for the deployment of UWSNs. Ideally, an optimal underwater MAC protocol should provide higher network throughput and lower energy consumption by taking into account of the harsh characteristics of the underwater environment. We describe the challenges which have to be addressed in the design of UWSNs MAC protocols in this section [2], [17].

- *Network Topology and Deployment in UWSNs:* The performance of the MAC protocols for UWSNs is highly dependable on the deployment of underwater nodes which could be sparse or dense. As the sensor nodes can monitor and communicate at long distance due to the availability of long range acoustic modems, sparse nodes can do event readings. However these readings of sparsely deployed nodes would be highly uncorrelated to the densely deployed nodes and has little significance.
- *Synchronization:* A critical challenge in the design of MAC protocols is the time synchronization. Due to the high and variable propagation delay it is really tough to synchronize the nodes using acoustic links. The duty cycling approach of MAC protocols work generally based on the time synchronization of the nodes. Without accurate synchronization, the duty cycling approach cannot ensure effective operation of sensor networks by handling time uncertainty between sensor nodes.
- *Hidden Node and Exposed Node Problem:* The problems of hidden nodes and exposed nodes usually arise in contention-based collision avoidance MAC protocols. A situation of a hidden node occurs when one node cannot sense one or more nodes that can interfere with its transmission. A situation of an exposed node occurs when a station delays transmission because of another overheard transmission that would not collide with it. In the first case, there will be collision and the nodes have to keep attempting for successful transmission. Whereas in the second case there will be a delay in transmission which was not needed.
- *High Delay Associated in Handshaking*: The conventional handshaking schemes are aimed to reduce the effect of hidden terminal and exposed terminal. However, the handshaking technique needs time and energy to exchange control information. The exchange of control information takes the major part of the total

communication duration. Thus the nodes do not have much time for the payload delivery. The channel utilization rate becomes very low. As the handshaking schemes increase the packet transmission delay quite significantly, it is very important to design proper handshaking scheme for efficient protocols. Usually handshaking-based algorithms are efficient only when the network is fully connected and the propagation delay is small compared to the packet duration. However, handshaking becomes unattractive if the connection failure is higher or there are frequent changes in the topology.

- *Power Waste in Collision*. In underwater scenario it is observed that a node consumes a lot more power on transmission than on reception. The ratio of power required for reception to transmission is typically 1/125 [41]. Furthermore, the ratio may degrade further by frequent collisions of data packets, due to the lack of an appropriate collision avoidance mechanism. So, one of the main features of a MAC protocol should be the capability to avoid or minimize collisions.
- *Near-Far Effect*: The transmission power of a transmitter should be selected properly so that the signals transmitted from the transmitter to the intended receiver should be correctly received with the desired SNR. The signal should not have lower or much higher SNR than the required one. The near-far effect occurs when the signals received by a receiver from a sender near the receiver is stronger than the signals received from another sender located farther. There is an exemplified scenario illustrated in Fig. 2.5 [42]. Nodes 1 and 3 are far away and therefore can transmit simultaneously without causing collisions. Node 2 being the receiver, receives higher SNR level of the signal originated from node 1 than that from node 3. It is due to the reason that high level of noise produced by the signals coming from node 1 disrupts the signal of node 3. Therefore, although node 2 can receive both signals, it cannot decode the messages from node 3 properly. The result is that node 1 is unintentionally screening the transmissions from node 3.

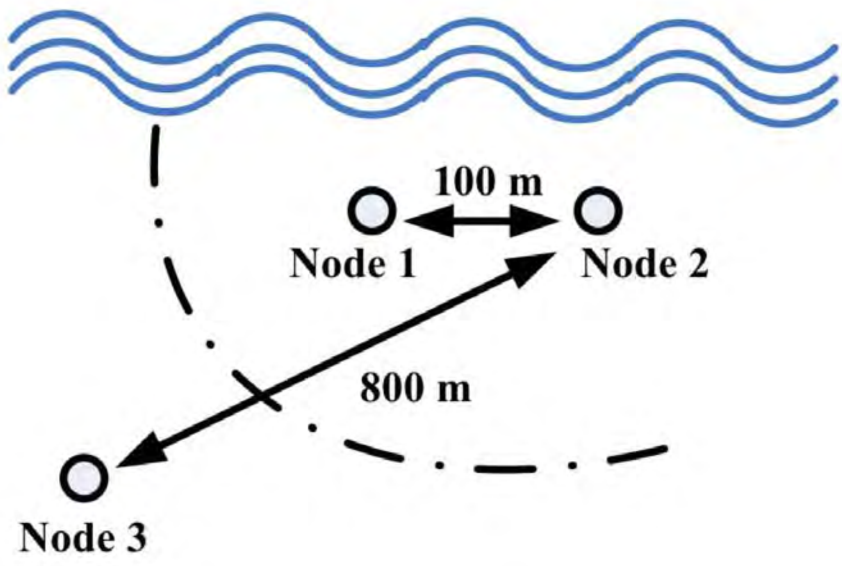

Fig. 2.5: Near-far problem [2].

- *Centralized Networking*: Centralized solutions are not suitable for UWSNs. In a centralized network scenario, the communication between nodes takes place through a central station or gateway. The presence of a single failure point is a major disadvantage of this configuration. Again, due to the limited range of a single modem, the network cannot cover large areas [43].

2.7 Acoustic MAC Protocols for UWSNs

Nodes in a network conduct communications by sharing a common channel using a MAC protocol. An efficient MAC protocol is capable to reduce collisions and increase the network throughput and also provides flexibility for various applications.

2.7.1 Classifications

An extensive literature survey has identified many MAC protocols proposed for the acoustic UWSNs, which can be mainly classified into three categories - contention-free, contention-based and hybrid type [2]. They can be further sub-divided, which is presented as a tree diagram in Fig. 2.6.

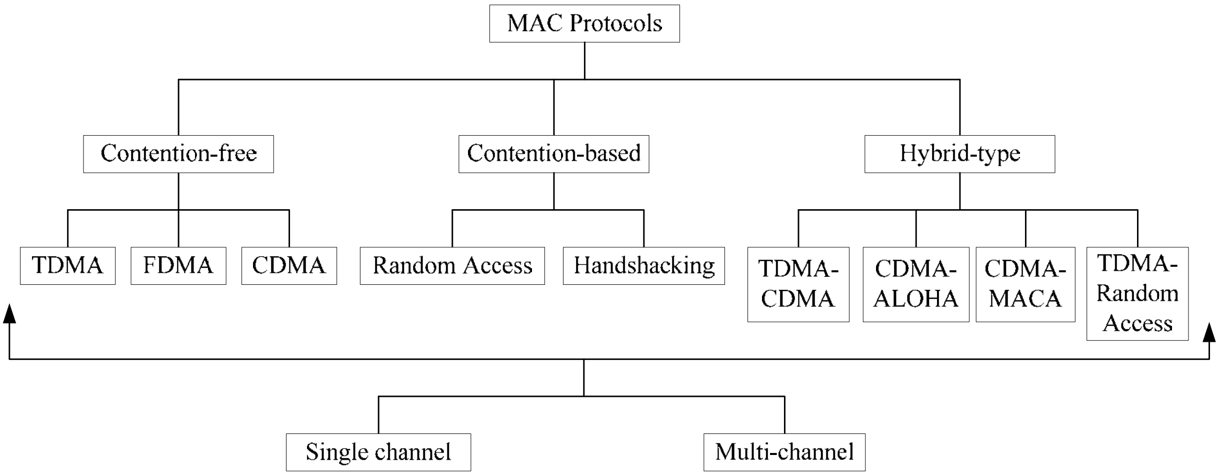

Fig. 2.6: Classification of MAC protocols for acoustic UWSNs**.**

2.7.1.1 Contention-free Protocols

In contention-free MAC protocols, the channels are shared among the nodes by creating orthogonality in time, frequency, code or space domain, and thus avoid collisions. Frequency division multiple access (FDMA), orthogonal FDMA (OFDMA), TDMA and code division multiple access (CDMA) are the common contention-free MAC protocols used in various applications. Several variants of FDMA-based (e.g., Underwater orthogonal frequency division multiple access control (UW-OFDMAC) [44]), TDMA-based (e.g., staggered TDMA underwater MAC protocol (STUMP) [45], adaptive slot TDMA (aTDMA) [46], spatial-temporal MAC (ST-MAC) [47]) and CDMA-based (e.g., path oriented code assignment CDMA-based MAC (POCA-CDMAMAC) [48], CDMA-based MAC (CDMA-B) [49]) are available in the literature.

2.7.1.2 Contention-based Protocols

Under this type of protocols, the nodes compete for a shared channel resulting in potential probabilistic coordination. Thus, collision of data from various nodes is a common phenomenon in such protocols. Minimizing collision is one of the major challenges in contention-based MAC protocols. The Contention-based protocols can be classified into random access and handshaking protocols. Multiple nodes trying to share the transmission medium randomly without any control is the main theme of random access based protocols. There are mainly two approaches of random access in the classification of contention-based MAC protocols, which are ALOHA and carrier sense multiple access (CSMA) with their variances.

By the random access approaches, a node starts its transmission whenever it has data ready to send. When a data packet arrives at a receiver, if the receiver is not receiving any other packets and no other packet comes within that period, then the receiver can receive this packet successfully. Propagation delay tolerant ALOHA (PDT- ALOHA) [50], ALOHA with carrier sense (ALOHA-CS) [51], ALOHA with advance notification (ALOHA-AN) [51], CSMA-based MAC protocols Tone-Lohi (T-Lohi) [52] and propagation delay aware protocol (PDAP) [53] are some of the random access based MAC protocols for UWSNs.

The handshaking based protocols are another important type of the contention-based MAC protocols, which are essentially a group of the reservation-based protocols. The basic idea of the handshaking or the reservation-based schemes is that a transmitter has to acquire the channel before it can send any data. Floor acquisition multiple accesses (FAMA) in [54], slotted floor acquisition multiple accesses (Slotted FAMA) [55], distance-aware collision avoidance protocol (DACAP) [56] and multiple access collision avoidance for underwater (MACA-U) [57] are some of the handshaking based MAC protocols proposed for UWSNs.

2.7.1.3 Hybrid Protocols

The hybrid MAC protocols combines different medium access techniques and different types of MAC protocols to improve the performance of UWSNs. Such hybrid type protocols aim to extract the advantages of both contention-free and contention-based MAC protocols. Recently, the design of the hybrid MAC protocols in UWSNs has become an attractive research topic. Hybrid spatial reuse TDMA (HSR-TDMA) protocol combining CDMA and TDMA [58], UW-MAC combining CDMA and ALOHA [59], protocol for long-latency access networks (PLAN) combining CDMA and MACA [60], and hybrid MAC (H-MAC) combining TDMA and random access principle [61] are some examples of proposed hybrid MAC protocols for UWSNs.

2.7.2 TDMA-based MAC Protocols

This section provides a brief discussion on some of the existing TDMA-based MAC protocols for UWSNs. In TDMA based protocols, time is divided into fixed time interval called a frame, which is again divided into time slots. Each time slot is then assigned to an individual user. By adding guard times within every time slots, collisions of packets from adjacent time slots are prevented. Therefore, TDMA with its simplicity and flexibility is a better multiple access technique applied to UWSNs [2]. However, due to the large propagation delay and delay variance over the acoustic channels, guard time periods are needed be designed properly to minimize the probability of collisions in data transmissions. Moreover, a precise synchronization with a common timing reference is required for the TDMA, which is quite challenging to implement with the variable delay of acoustic waves [19]. Some of the state-of-the-art TDMA-based MAC protocols are discussed here below.

TDMA based ST-MAC protocol proposed in [47] constructs a spatial-temporal conflict graph (ST-CG) to overcome the spatial-temporal uncertainty in the TDMA-based MAC scheduling for energy saving and throughput improvement. The STUMP protocol presented in [45] is a scheduled, collision free TDMA-based MAC protocol that leverages node position diversity and the low propagation speed of the underwater channel. Tight node synchronization is not required for STUMP to achieve high channel utilization. This allows the nodes to use simple or more energy efficient synchronization schemes. Another work [62] proposed a novel spatially shared TDMA MAC (SST-MAC) protocol. In this research both reliability and efficiency requirements of the network are taken into account to introduce a quality measure. Whereas the aTDMA [46] MAC protocol adaptively changes the TDMA frame size and slot duration. In conventional TDMA MAC protocols, if a node has no data, the corresponding time slot is wasted, leading to lower throughput. In aTDMA, a node that does not have data packets to transmit, declares that it is not using its own time slot for a certain period of time. Thus the wasting of time slots can be mitigated. This protocol also adapts the duration of slot according to the distance between nodes, leading to improved performance.

On the other hand, a priority reservation MAC (PR-MAC) protocol was proposed in [63]. Considering the long propagation delay and minimizing the conflicts and energy loss, the PR-MAC protocol is an energy efficient one. Another scheduling based MAC protocol, dynamic slot scheduling strategy (DSSS) protocol was proposed in [64]. The DSSS MAC protocol uses four heuristic strategies including grouping, ordering decision, scheduling, and shifting to improve the channel utilization and to prevent the collisions. This protocol has the ability to transmit in parallel to improve the channel utilization by increasing the transmission pairs without collisions. The DSSS MAC protocol also takes the sink-to-node, node-to-node, and node-to-sink transmissions into account to increase the network applicability.

Authors in [65] proposed a new amendment based TDMA time slot allocation mechanism (WA-TDMA). The protocol was developed for general multi-hop underwater applications. With a wave like proliferation, slot allocation starts from the node which launched as the center and then allocation moves to outward nodes. The time slot allocation and amendment continuously goes on without stopping. This scheme can shorten the initialization period of the network. The protocol can adjust the usage of the allocated time slots with the help of amendment, to improve the slots utilization and deal with slots reuse. The Underwater FLASHR (UW- FLASHR) protocol presented in [66] is a TDMA-based MAC protocol which does not require tight clock synchronization, accurate propagation delay estimation or centralized control. With two phases namely an experimental phase and an establishing phase in each cycle, UW-FLASHR operates over cycles of time. When a node has data to transmit, it requests for a new time slot by sending a data frame randomly in the experimental portion of each of several consecutive cycles. Now, as each node contends to get a time slot by randomly choosing a transmitting time and checking whether such a transmission incurs any collisions, the UW-FLASHR scheme gradually constructs a loose transmission schedule in a distributed manner so that time gaps may exist between transmissions.

2.7.3 Multi-Channel MAC Protocols

In recent time, designing multi-channel MAC protocols has drawn considerable attention due to the support of multiple channels in modern sensor platforms [67]. Unlike single channel MAC protocols, multi-channel protocols utilize more than one channel for communication [68].

A reservation channel acoustic media access protocol (RCAMAC) based on RTS/CTS handshaking was proposed in [69]. By the RCAMAC scheme, the entire bandwidth is divided into two channels. One is a control channel with less bandwidth. Another is the data channel with the remaining bandwidth. A novel contention based parallel reservation MAC (COPE-MAC) protocol was proposed in [70], where both energy efficiency and throughput was taken into consideration. The protocol introduces parallel transmission into the protocol design and makes concurrent transmission possible in the UWSNs, which enhances the system throughput. On the other hand, to avoid collisions and improve the system energy efficiency, it adopts a contention based reservation approach. Another multi-channel MAC protocol MM-MAC was proposed in [71], which aims to use a single modem to act as multiple transceivers. Nodes running with MM-MAC are guaranteed to meet their intended receivers to solve the missing receiver problem by utilizing the cyclic quorum systems. In [72], an underwater multiple input multiple output MAC (UMIMO- MAC) protocol was proposed, which utilizes MIMO capabilities to allow more flexible and high efficient utilization of the underwater acoustic channels. To be particular, the UMIMO-MAC protocol is fully distributed and relies on lightweight message exchange. Moreover, to maximize the network throughput or minimize the energy consumption according to the QoS requirements of the traffic being transmitted, the UMIMO-MAC scheme adapts its behavior to the condition of environmental noise, channel, and interference.

Similar to single channel MAC protocol, multi-channel hidden terminal and long-delay hidden terminal problems can occur. To handle the problems, a new MAC protocol, named cooperative underwater multi-channel MAC (CUMAC) was proposed in [73]. CUMAC utilizes the cooperation of neighboring nodes with a simple tone device designed for the distributed collision notification to detect collisions of data packets. The main advantage of this protocol is that it considers a cost-effective network architecture where one and only one transceiver is required at each node. Tailored for a data-centric scenario, in [74], a Data-Centric MAC (DC-MAC) protocol was proposed. The DC-MAC uses multi-channel strategy to eliminate the hidden terminal problem and offers efficient channel assignment using dynamic collision free polling strategy. The merge of these two strategies in a single design aids to achieve high performance for the considered scenario.

2.8 Research on EM Wave based UWSNs

Underwater EM communications were explored with keen interest in the last century up until the 1970s. As the range of EM is restricted by fundamental attenuation factor which must be considered as unchangeable environmental elements, significant breakthroughs with EM based communication in underwater were not to be expected [70] [75]. Therefore, despite its excellent performance in the terrestrial wireless networks, radio communication has had very few practical underwater applications to the date. Almost surely, acoustic wave is used as the physical transmission medium for underwater applications.

In the modern digital era, benefits of short-range and high-bandwidth communications systems are becoming favorable to users. Oil industry, military, and environmental operations are demanding reliable, fast response, high data rate, connector-less, and short-range data link applications [3], [9], [10]. Thus research on EM feasibility in the underwater environment has drawn considerable attention in researchers as well as in industries [9], [76], [77], [78]. EM signaling can be made suitable for many underwater applications by coupling digital technology and signal compression techniques. With its high data rate EM signaling is expected to enlarge the arena of underwater applications [32]. For instance, high data rate capable EM UWSNs can be used for coastal surveillance by deploying cameras distributed all over the shore at certain depths to monitor human activities, marine life, or any physical phenomenon [32]. Other high data rate applications includes transmitting video images between an AUV and an operator sitting in a ship, between divers and from sensors to buoys [80]. In another way, EM and Acoustic techniques can be viewed as complementary technologies. EM technology offers great potential for underwater sensor communications when compared to acoustic and optical wave technologies in underwater. Several studies also suggest that a high data rate is possible to achieve over a relatively longer range by changing the antenna technology [78].

2.8.1 Experimental Works

A pioneering experimental and theoretical research on EM wave propagation in shallow seawater using insulated antennas was carried out in [79]. It showed that it is feasible to receive signals at 14 MHz over a range of 20 m or so. This work is also considered as the foundation for modern underwater RF communications networks. Transmission at 5MHz frequency was found to be feasible in seawater with up to 90m range giving a data rate of 500kbps that allows duplex video and data streams. This research for underwater communication was conducted at Liverpool John Moores University [80]. A practical study on the behavior of EM signals in the 2.4 GHz industrial, scientific and medical (ISM) frequency band in underwater environments was performed by the authors in [71] [76]. They used devices which are compatible with the IEEE 802.11 standard. The maximum distance between sensors, the number of lost packets and the average round trip time were evaluated by them. Although the experiments provided short communication distances, it provided high data (up to 11 Mbps over a distance of 16 cm) transfer rates and can be used for precision monitoring applications such as contaminated ecosystems or for device communicate at high depth.

On the other hand, there are some commercial modems in 100 kHz band. For instance, two types of RF modems: a short range model with 100 kbps up to 15 m range and a long range model with 100 bps up to 200 m range are produced by WFS Technologies [81]. In a recent work [77], authors shared some of their test results which were carried out in sea as well as in laboratories for underwater high-frequency (HF) wave propagation in the range of MHz. They found that with such a high frequency range the communication range was over several meters. Another recent experimental work [78] demonstrates a new concept of an electromagnetic usage in the sea. The antennas are designed as electromagnetic (EM) high-Q resonators and the lowest resonant frequency is used for power transfer. For signal communications the higher frequency band is used. Experimental results showed a power efficiency over 40% and a transmission rate of 20 Mbps via seawater of the 5 cm’s thickness. It was suggested that the proposed concept can be used to achieve a compact and maintenance-free wireless usage between different underwater systems, such as AUVs. Furthermore in [82], it was demonstrated that an RF signal can be transmitted in 1-5 MHz frequency range over distances up to 100 m as an EM wave along the air-water interface. The results were found from simulations as well as independent measurements of EM wave propagation in seawater.

2.8.2 EM Underwater Propagation Model

Besides the research on exploring the transmission range in high frequencies, several works have been reported on the underwater channel modeling for EM wave. For instance, a very simple attenuation model as a function of frequency in the MHz range was presented in [83]. Whereas a channel model for freshwater environment is proposed in [30]. Obviously, the results in [30] are not applicable for the more practical scenario in seawater applications because of the relatively low salinity of freshwater compared to that of seawater. Authors in [32] proposed an UWSN for near-shore applications using EM wave. A realistic path-loss model is also developed in this paper by taking into account the variation of the seawater complex-valued relative permittivity with frequency as well as the impedance mismatch at the seawater-air boundary. Another work on the modeling of EM wave propagation in underwater suggested that the dominant propagation path to facilitate long-range communication is along the surface of the water-air interface [82]. On the other hand, authors in [84] presented a detailed relationship between propagation characteristics of EM waves, skin depth, total path-loss and frequency for different values of distance and conductivity of the water medium for the purpose. Their analysis suggest that optimum propagation distance in underwater can be achieved by proper selection of the signal frequency. On the other hand, it is interesting to know that the experimental results demonstrated very different propagation loss for EM wave in underwater in near-field and far-field regions. It is found that due to the short-circuit behavior, a drastic power-loss occurs in the near field region, while the rate of path-loss in the far-field is much slower [80], [85]. Thus the analytical models that are available for EM wave path-loss are not comprehensive. Authors in [85] proposed a more realistic distance dependent path-loss model.

2.8.3 Antenna for Underwater

From the perspective of an antenna design for UWC, the large conductivity and permittivity of water, especially in ocean, imply that any metallic antenna placed directly in contact with sea water gets "shorted out," and it becomes extremely difficult to match the antenna and launch the EM wave efficiently into seawater. Furthermore, due to higher path-loss, high frequency is also difficult to use for underwater EM communications. Thus the antenna size is relatively higher for underwater applications. Considering the practical constraints, researchers preferably use loop antennas for underwater applications as shown in Fig. 2.7 [13], [28], [80]. Authors in [13] also used double-loop antenna for experiments demonstrating a better gain and longer coverage.

Fig. 2.7: Underwater transmitter and receiver using loop antenna [75].

Furthermore, the very different behavior of EM wave in the near-field and far-field regions [80], [85] suggest that if the drastic path-loss of near-filed can be avoided, a much longer communication range is possible using EM wave in underwater. Therefore, a crucial antenna design constraint for facilitating efficient launching is to not place the antenna directly in seawater, but rather cover it with an insulating sheath [79] or place it in a water-tight housing.

2.8.4 MAC Protocol for EM Underwater Communications

Although many research projects on EM wave based UWC using UWSNs are being conducted, however based on our extensive literature survey, we have not found any proposal for MAC protocol for EM UWSNs. Two very recent works from the same group of authors approaching the issue of MAC protocol is presented in [15], [86]. The authors did not propose any new MAC protocol. Rather, performance of some of the existing MAC protocols, namely, ALOHA, multiple access with collision avoidance (MACA), CSMA without acknowledgement (CSMAWithoutACK) and CSMA with acknowledgement (CSMAWithACK) in EM based UWSNs is investigated. They also conclude that the MAC protocols do not perform as efficiently as in terrestrial sensor networks and identified the importance of designing new MAC protocols considering the characteristics of EM wave in underwater.

2.9 Chapter Summary

An introduction to the architecture, applications and design challenges of UWSNs has been presented in this chapter. Factors to be considered in developing MAC protocols for UWSNs have then been analyzed. This chapter also have briefly discussed the type of existing MAC protocols for acoustic UWSNs with a particular focus on the TDMA-based and multi-channel type MAC protocols. At the end of the chapter, a thorough discussion on the current research on the EM based UWSNs including MAC protocols has been presented.

Chapter 3

MAC Protocol for Single Data Channel

This chapter presents the MAC protocol designed by integrating EM wave based communications. Proposed protocol uses one control channel for signaling purpose and one data channel for data packet transmission. Performance of the proposed protocol is investigated through extensive simulations. Investigation is carried out considering both protocol interference model and physical interference model.

3.1 Network Model

In this chapter, we focus to develop a MAC protocol for a group of certain type of nodes in an UWSN, which can communicate with each other at single-hop distance in both directions. Thus the network topology is a mesh topology as shown in Fig.3.1. All the nodes are assumed static in nature and are scattered within the network area following uniform distribution. It is also assumed that all the nodes have equal packet generation rate and the packet arrival follows Poisson distribution. Total offered load of the system is equal to the aggregated load generated by all the nodes. We also assume no packet retransmission.

The nodes are enabled to use two types of channel simultaneously, namely, a control channel for signaling purpose and a data channel for transmitting the actual data packets.

Thus, with the objective of using EM wave for communication, we propose two different combinations of transmission media for the control and the data channels. The first option is *EM-Acoustic*, where the control channel uses EM communication, while the data channel uses acoustic based transmission. The second option we propose is *EM-EM based*, where both the control channel and the data channel employ EM wave for communication.

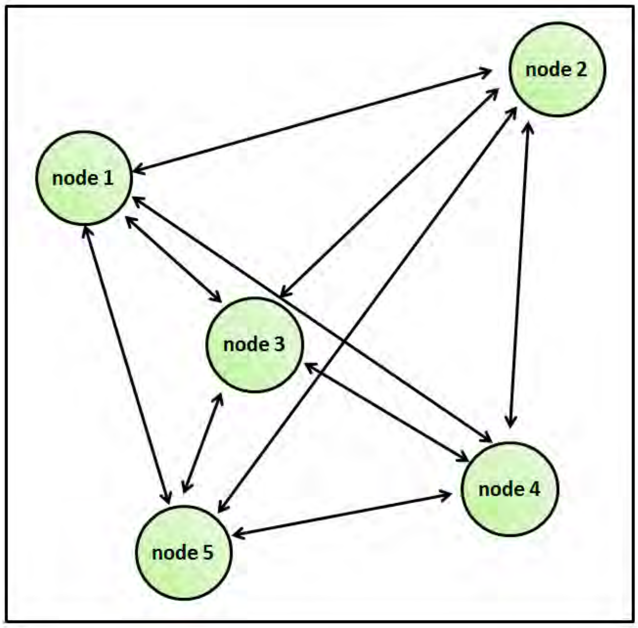

Fig. 3.1: Network Model.

3.2 Modeling Control and Data Channels

The protocol has a common control channel for all nodes to transmit control message and single channel for data packet transmission. The control channel is TDMA based having multiple slots. A TDMA frame consists of 'N' time slots given by

$$N = n_d + 1 \quad (3.1)$$

where n_d is the total number of nodes in the network. In a time frame with N time slots the first n_d time slots are dedicated to the each nodes respectively. This is shown in Fig. 3.2 for a four node network. When a node has data to transmit, it can call for reservation of the data channel through its corresponding time slot. Each of the time slots have a guard time, which ensures that the control signal transmitted does not collide with another control signal. Nodes will be allowed to use the data channel according to the sequence of reservation.

3.3 Operation Principle of the Proposed Protocol

To describe the whole operation principle of the system, a time diagram of the system is illustrated in Fig. 3.2. Two channels, the EM based control channel and acoustic based data channel are illustrated in the figure. For the ease of illustration, a four node system is considered. Therefore, one TDMA frame will consists of 5 time slots, where the first four are for the four nodes and the last one is for confirmation message of receiving a packet. It is assumed that at the activation of network the data channel is free and all the nodes know this. Every node maintains a data transmission table where they keep the information about the sender.

For the scenario depicted in Fig. 3.1, node 3 has the first data packet to transmit. Therefore it asks for reservation through the control channel. It is assumed that all the nodes will hear this reservation call. Consequently all the nodes will update their table of reservation sequence and node 3 will be written at the top of the table. Since the data channel is free, node 3 will start transmitting data immediately after the reservation call. As the other nodes knew that the channel was free they will assume that node 3 has started transmitting data just after the reservation call. Now they will put a label 'sending' on node 3 of their tables.

Now continuing through the time series diagram it can be observed that the next contender to transmit data is node 4, so it will make a reservation through its respective time slot (slot 4). All the nodes hearing it will update their table. Since the data channel is now occupied, node 4 will wait for the confirmation message before it can begin its transmission. Whereas in this waiting period node 1 makes a data sending request through the next time frame using time slot 1. Now this request will be queued up in the table of all the nodes.

It can be seen that the first data packet send from node 3 reaches its destination with its propagation delay and packet duration before time slot 5 of the time frame 3. Time slot 5 is the confirmation slot for sending confirmation packet indicating that the data packet has been received successfully. Thus when the respective receiver receives the packet it transmits a confirmation message through the timeslot 5. This in return ensures that all the nodes get the information that the data channel is now free to use for transmission. Now the first transmitter in the queue, which is node 4 starts transmitting its packet. In parallel the nodes update their table by labeling node 4 as 'sending' and removing the previous sender node 3 from the table. Now node 4 will be at the top of the transmission queue table and node 1 will be in queue. This process goes on for the whole time series.

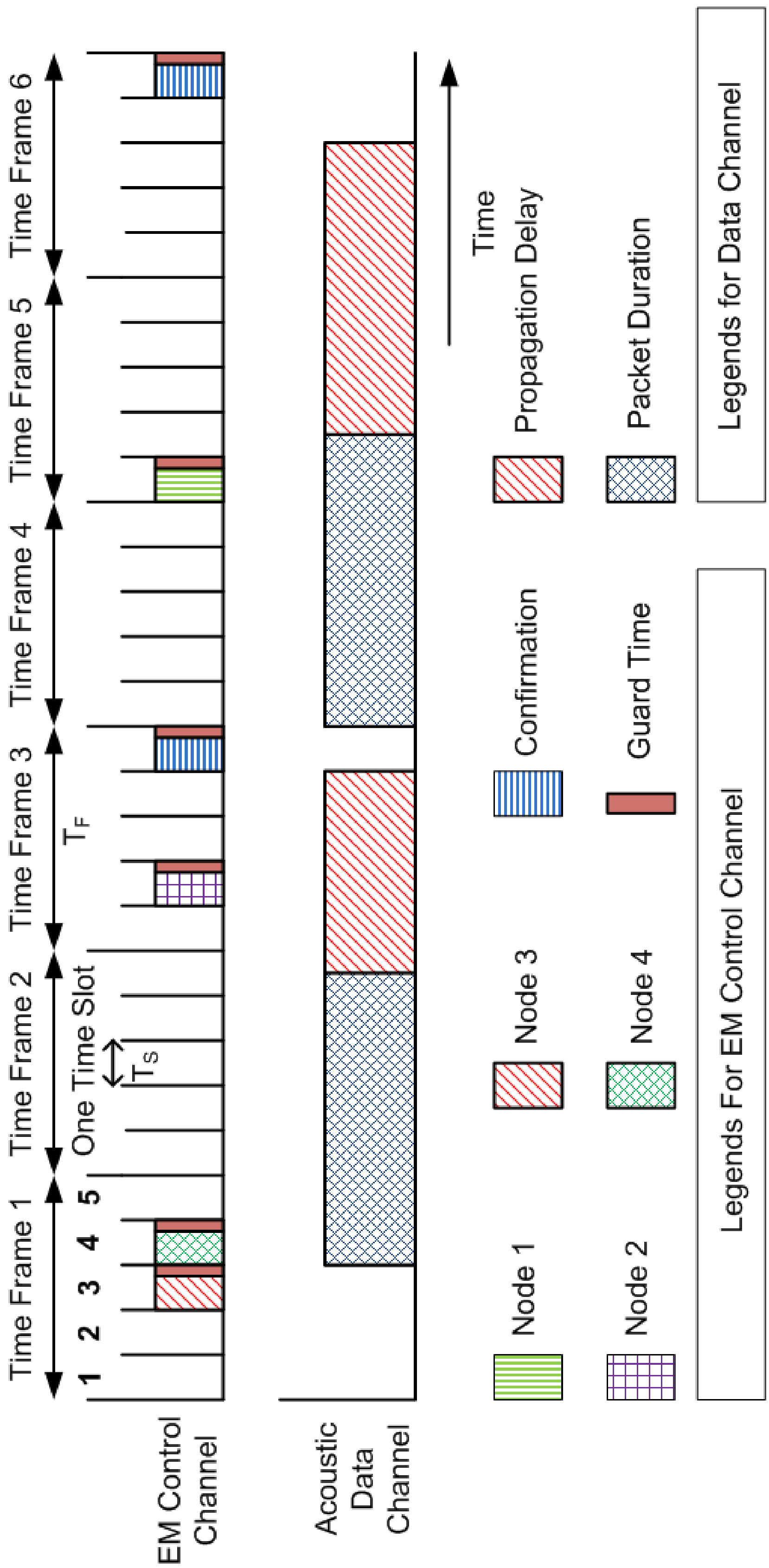

Fig. 3.2: Time series diagram of the proposed MAC protocol for single data channel.

3.4 Collision Scenario

The operation principle described above is for protocol interference model, where attenuation in the network is ignored. However in physical interference model, the control and data packets will face attenuation and nodes will face signal outage. Therefore all the nodes will not get the packets all the time. Some of the packets may get lost before reaching the nodes.

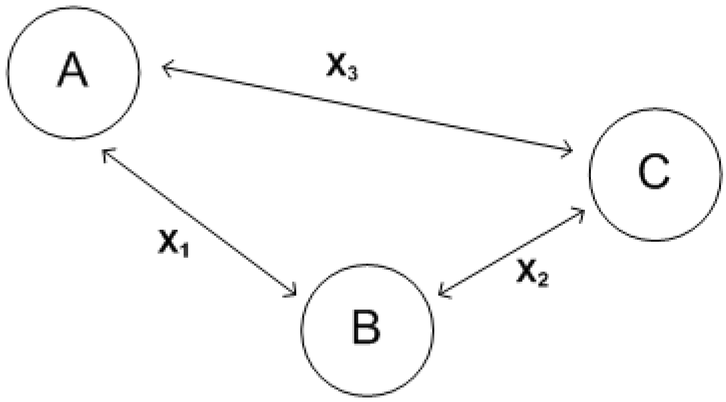

Fig. 3.3: Demonstrating data packet collision scenario.

To get a proper understanding of the situation of packet collision let us have a look at Fig. 3.3. There are 3 nodes - A, B and C. From node B, both A and C can hear control packets due to shorter distance. However due to increased distance between A and C, they sometimes misses the control packet. Also we will assume for now that data packets face less attenuation and can cover the whole network.

Now, if both nodes A and C has data packet to send to B at almost the same time, they will at first send control packet through their respective time slots to reserve the channel. Though node B will hear both these messages, however node A will not get the control packet of C and vice versa. Now both node A and C will start transmitting data packet to B, which will cause a collision of data packets on node B. Thus both the data packets will be lost.

The collision that happened increases the wastage of energy and missing of data. However that is not the only problem; other problems may arise. That is node B will not be able to send confirmation due to the packet collision. Also node A and C waiting for the confirmation will not update their table. This condition makes the network to get stuck and no transmission will take place afterwards. To make the protocol realistic, a channel occupation limit is thus used. When the channel seems occupied for a long time or a node is waiting for confirmation if the time crosses the channel occupation limit, then the node will assume that some miscommunication has happened and will make the channel status flag to free.

Proposed protocol also has the back off time feature. Due to heavy attenuation in larger network, there may arise a situation where the transmitter which is going for a transmission senses another data packet in the data channel. At this situation, the transmitter will back off from transmission for some specified time, which is the back off time for the system.

3.5 Pseudo Code of the Proposed MAC Protocol

```
Time Frame=0;
While (Total Number of Transmitter is greater than 1)

    Time frame = Time frame +1;

    For every node
        If generation time of the data is less than its allocated time slot for the current time frame
            Send control message and all nodes update their table
        End if
    End for

    For all nodes
        If the channel seems free and no other data is sensed
            If the nodes table suggests that it is the first transmitter
                it will send the packet and update its table
            else
                The first transmitter in the table is assumed to have sent its packet and node will update table
            End if
        End if
    End for

    If end of current frame
```

If any receiver receives the full data successfully

Send a confirmation message through the assigned time slot

End if

End if

For all nodes

If any confirmation is received

Make the status of the channel as available

End if

End for

End while

3.6 Performance Metrics

The proposed MAC protocol is analyzed in terms of throughput, collision rate, data packet missing rate, average waiting time, bandwidth efficiency and energy consumption. These performance metrics are defined as follows.

a) **Throughput:** It is the percentage of successful channel utilization. To measure this metric we used the following equation

$$\eta = \frac{T_G}{T_T} \times S_R \times G_R \tag{3.2}$$

where T_G is the total generation time, when the packet generation occurs. T_T is the total time needed to send all the packets generated within T_G. S_R is the success rate and G_R is the packet generation rate. Success rate S_R can be defined as below

$$S_R = \frac{N_S}{N_{Tr}} \tag{3.3}$$

where N_S is the total number of successful data packet transmission within T_T and N_{Tr} is the total data packet transmission within T_T.

b) **Collision rate:** The collision rate is the percentage of total packets which collided with each other at the reception and made unsuccessful transmission and can be given by

$$C_R = \frac{N_C}{N_{Tr}} \tag{3.4}$$

where N_C is the total number of collision at the receiver.

c) **Data packet missing rate:** It is the rate at which the data packets fail to reach the receiver due to the attenuation of the medium. It can be written as

$$M_R = \frac{N_M}{N_{Tr}} \tag{3.5}$$

where N_M is the total number of missing packets.

d) **Average Waiting Time:** Every node has to wait for some time to send its packet. The time between the generation of packet and the transmission is the waiting time. The average of all these waiting time is the average waiting time. Waiting time for a packet can be defined as

$$T_W = T_{tr} \sim T_{Gr} \tag{3.6}$$

where T_{tr} is the time of transmission and T_{Gr} is the time of generation of the same packet.

e) **Energy Consumption:** For the total simulation time if total N_{Ctrl} number of control packets and N_{Data} number of data packets are sent, then the total energy consumption for the simulation time is

$$E = E_c \times N_{Ctrl} + E_D \times N_{Data} \tag{3.7}$$

where E_C is the energy needed to transmit a control packet and E_D is the energy needed to transmit a data packet.

The above performance metrics are going to be evaluated in the simulation sections for understanding the functionality of the proposed protocol.

3.7 Simulation Settings

The proposed MAC protocol is first evaluated considering protocol interference model, i.e., ignoring the attenuation in the channel. Then the proposed protocol is investigated for more realistic case considering the impact of channel attenuation. Results presented in the following sections are generated through averaging the results from 500 iterations.

For simulating the proposed protocol, following system settings are considered.

i. Conductivity (σ) of water = 4.0 (sea) or 0.01 (fresh water) [9]
ii. Water permeability $\mu = 4\pi \times 10^{-7}$
iii. Water permittivity $\varepsilon = 81 \times 8.854 \times 10^{-12}$
iv. Speed of EM , $v_{EM} = \sqrt{f_{EM} \times 10^7 / \sigma}$, where f_{EM} is the frequency of EM [9]
v. Speed of Acoustic wave, v_{Ac} = 1500 ms^{-1} [9]
vi. Maximum network length, D_L = Distance between the two far most corners of the network.
vii. Maximum propagation delay for EM $T_{e,p} = \frac{D_L}{v_{EM}}$
viii. Maximum propagation delay for acoustic $T_{a,p} = \frac{D_L}{v_{Ac}}$
ix. Guard Time of the time slots, $T_{Gd} = \frac{D_L}{v_{EM}}$
x. Control packet duration, T_{ctrl}= Control packet size/(40% of carrier frequency of EM)
xi. One time slot duration = $T_{ctrl} + T_{Gd}$
xii. Total number of time slots = Total number of nodes + Total number of data channels
xiii. Frame Duration T_f = Total number of slot × Slot duration
xiv. Data Rate = 2400 bps (for Acoustic) or 40% of carrier frequency (for EM)
xv. Data packet duration, T_{Data} = Data packet length/Data Rate
xvi. Total Load = Generation rate of data packets of the whole network
xvii. Total Simulation time = T_T
xviii. Back off time = ceil($T_{e,p}/T_F$) × T_F, where T_F is the frame duration

Shadow fading is also considered for evaluating the system when channel attenuation is taken into account. It is modeled as a Gaussian random variable with zero mean and standard deviation ζ = 8dB. In addition, following simulation parameters as Tabulated in Table 3.1 and Table 3.2 are used, which have been taken in reference to various recent publications.

Table 3.1: Power and bandwidth parameters

Parameter	Value(s) Used (Typical)
Frequency of EM control channel	1kHz
Frequency of EM data channel	6kHz
Frequency of Acoustic wave	10kHz
Power of EM wave	1W, 10W, 10^6 W (30, 40, 90 dBm)
Power of Acoustic wave	1W (30 dBm)
Threshold of EM	-90dBm
Threshold of Acoustic wave	-90dBm

Table 3.2: Network parameters

Parameter	Value(s) Used (Typical)
Network area	100×100, 200×200, 300×300, 1000×1000, 3000×3000
Generation rate of the load (normalized to 2400 bits packet size)	0.1 to 1.6 (Poisson distribution)
Total packet generation time	50, 100 seconds
Control packet size	32 bits
Number of nodes	4 (uniformly distributed)
Data Packet size	2400, 4800, 9600 bits
Data Packet rate	2400 bps

3.7.1 Simulation Procedure

To simulate the proposed protocol, a MATLAB based simulation platform is developed. The following steps were followed to perform the simulations.

Step 1: The system parameters like frequency and speed of EM or acoustic, the transmission and threshold power etc. are specified.

Step 2: The network parameters, such as the size of the network, packet generation rate, data and control packet size, number of nodes in the network, etc. are specified.

Step 3: The coordinates of the nodes are determined using the *rand* function of MATLAB.

Step 4: The packet generation instances are then calculated using the defined packet generation rate for a fixed total simulation time. As the packet generation is modeled as Poisson process, packet inter-arrival time is generated using exponentially distribution.

Step 5: The transmitter and receiver are selected randomly with equal probability of every node to be the transmitter and receiver.

Step 6: While loop is initiated, the loop will continue until all the packets are transmitted successfully or not. The first frame starts from time 0.

Step 7: The generation times are checked if any of the transmitters is going to send a control packet through its time slot within the current time frame. If one or more transmitter sends packet and it was received with more power than threshold, then update it in the individual queue table of the nodes.

Step 8: If needed rearrange the table with respect to the time of reservation.

Step 9: For every nodes, check if the channel status register is free for the current time frame. If free then assume the sending of data packet by the first transmitter logged at the first line of the table of respective nodes.

Step 10: When the transmitter sends a signal update the information of receiver, transmitter and transmission time in a universal table to use it in the code later.

Step 11: Check if any data is successfully received within the current time frame. To do so, check with the universal table if any other data packet can interfere with the current data packet or not, if not then the data packet is assumed to be received successfully if it passes the threshold. Then update the universal table with the information of successful data reception and store the data reception time in the universal table.

Step 12: Check if the confirmation reaches all the nodes in the network. If confirmation reaches the nodes with power larger than threshold, then update their respective queue tables by deleting the first line of the table and thus making the second transmitter the first contender.

Step 13: If confirmation is not found, then check if the channel occupation limit has exceeded for that node. If exceeded, then set the channel register to free and update the queue table.

Step 14: check if all the data packets have been transmitted or not. If not then go to the next time frame, otherwise end the while loop.

Step 15: From the universal table check the total successful transmission and the total time needed to transmit these data. From these data calculate the performance metrics.

Step 16: Go through Step 3 to step 15 many times to get better and accurate results of the performance metrics.

By doing all the above steps for minimum 500 iterations, the average values of the performance metrics are evaluated and presented in the following sections.

3.8 Performance with Protocol Interference Model

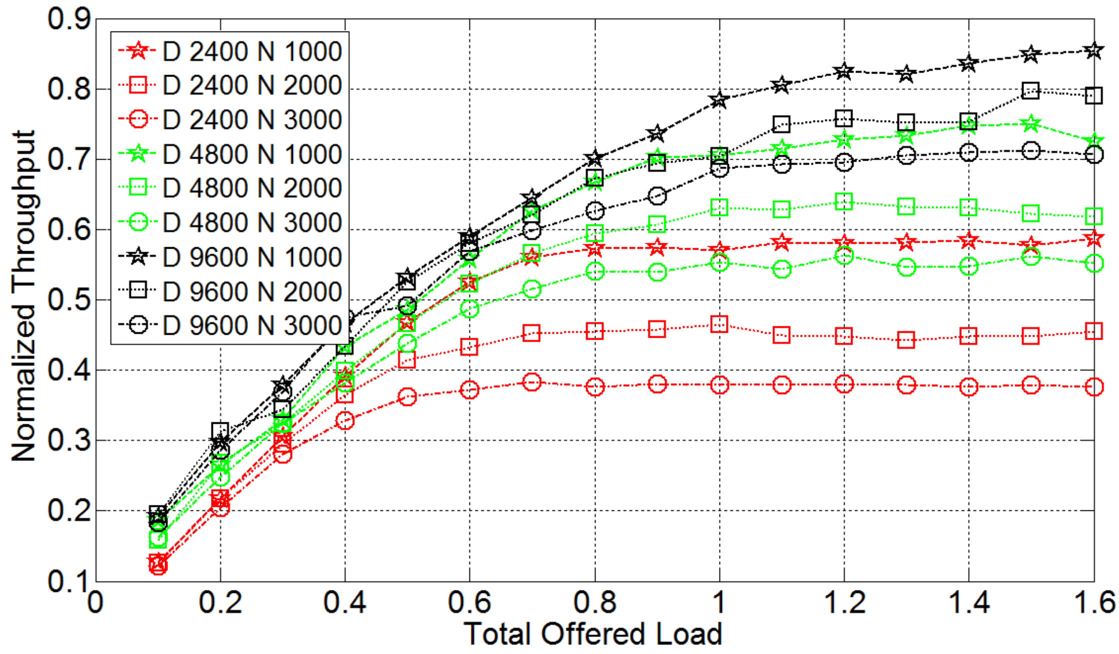

Fig. 3.3: Effect of network load on throughput.

Fig. 3.3 demonstrates an increasing trend of the network throughput with the increase of offered load. However, after certain network load, throughput becomes almost independent of the offered load. Due to the data channel reservation through the TDMA based control channel, after certain load, there are always some packets in the queue waiting for transmission. That is why throughput becomes almost flat after this traffic load. It can also be observed that with the increment of network size, throughput decreases. This is because, with the increase of network size, propagation delay decreases leading to reduced throughput. This can be visualized more clearly by observing Fig. 3.4, where throughput is presented for a generation rate of 1.6 data packets/sec. Network size equal to zero implies the theoretical ideal case such that all the nodes are located at the same place indicating zero propagation delay. In such a case, throughput depends only on the time frame duration. Therefore irrespective of the data packet size, the throughput is quite close for the zero network size. However with the increment of network size, the adverse impact of propagation delay on throughput seems to affect more on the single data packet of 2400 bits, rather than the four stacked data packets aggregating 9600 bits. The 4800 bits data packet is affected more than the 9600 bits, though not as bad as the 2400 bits, which is also evident from Fig. 3.3.

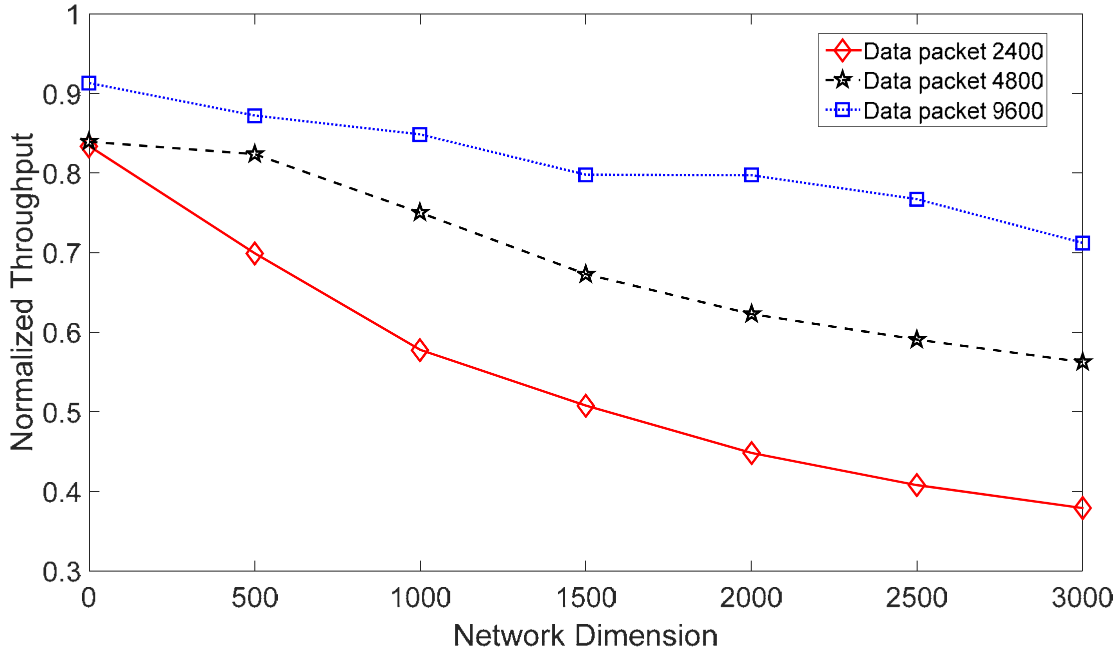

Fig. 3.4: Effect of network size on throughput.

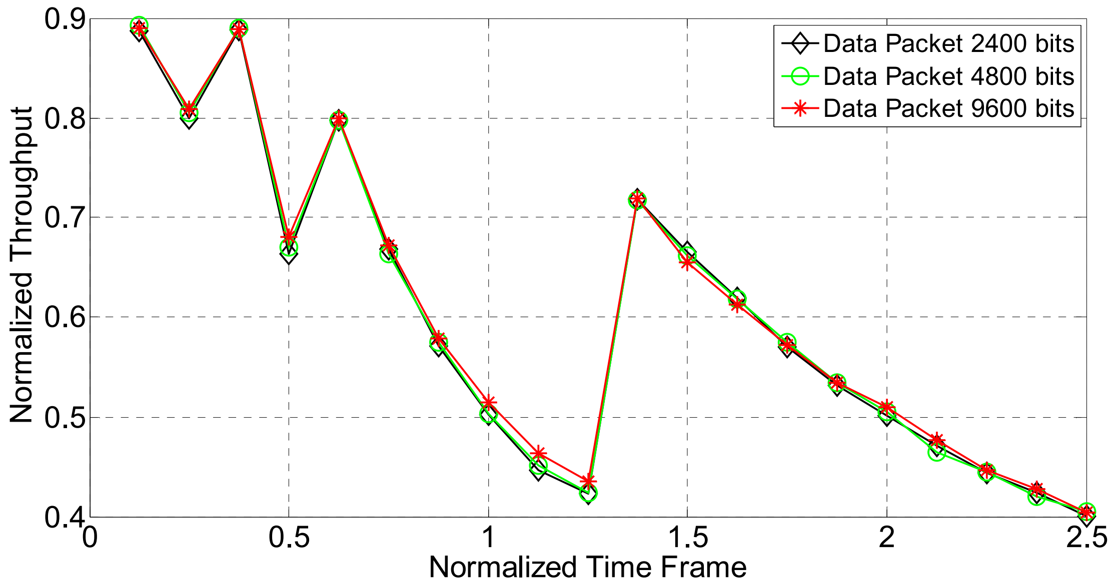

Fig. 3.5: Effect of normalized TDMA frame duration on throughput.

To check the effect of TDMA frame duration on the throughput of the proposed MAC protocol, the network is simulated for a generation rate of 1.6 data packets/sec and the results are presented in Fig. 3.5. Here normalized frame duration is the ratio of control channel frame duration to the data packet duration. It can be observed that when the time frame is relatively smaller than the data packet duration, throughput is quite high.

However with increase of time frame duration, fluctuation is observed in the normalized throughput. For instance, when the normalized frame size is around 1, throughput nearly becomes the lowest. It is because, if a data packet is received at a node in such a case, the node has to wait almost a full one frame to send the confirmation message. Thus, it is very important to set the time frame according to the data packet duration. From the figure, we can also say with certainty that for ideal channel having no attenuation effect, different packet size has no significant impact on throughput. This is demonstrated as the throughput for all three different packet sizes (namely 2400, 4800, 9600 bits) follows the same pattern alongside with each other.

3.9 Performance with Physical Interference Model

For all the simulation results presented in Section 3.8, channel attenuation is ignored, which is widely practiced in literature for evaluating MAC protocols. However, such analysis is not realistic and evaluates over-estimated results. This section presents the results for physical interference model by taking the effect of attenuation into account.

3.9.1 EM-based Control and Acoustic-based Data Channel

In the EM-Acoustic based, the EM wave is used for the control channel, whereas the acoustic wave is used for the data channel. The control channel uses 1kHz EM carrier, while the data channel uses 10kHz acoustic carrier in this simulation platform. The power used for the acoustic data channel is 30dBm.

3.9.1.1 Throughput

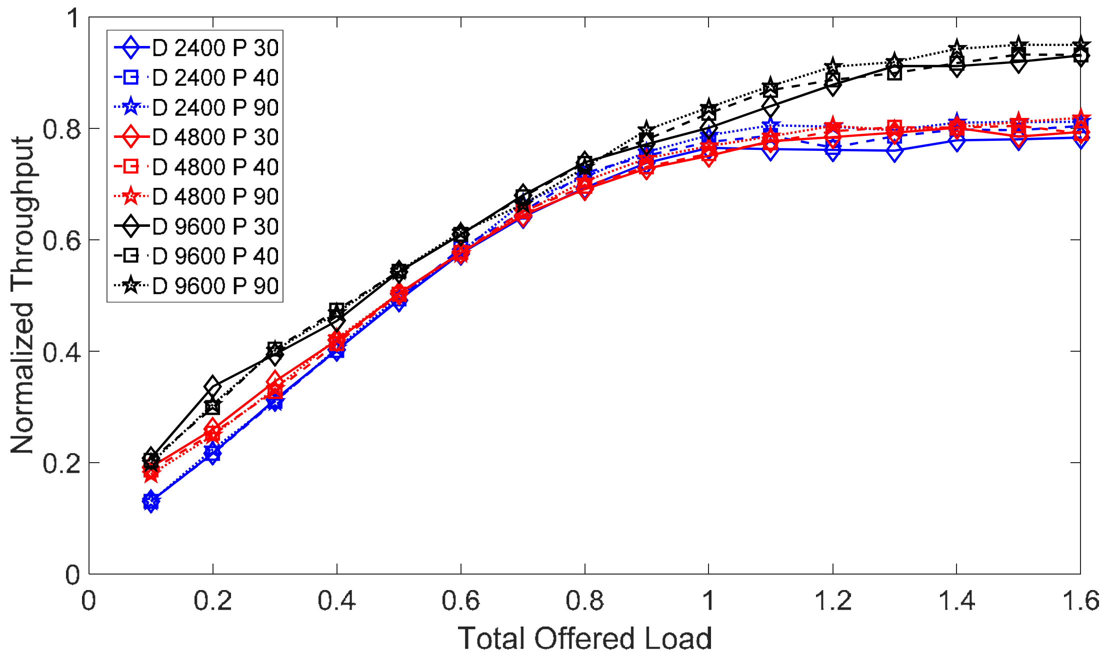

Fig. 3.6(a): Throughput with offered load (network size 100m).

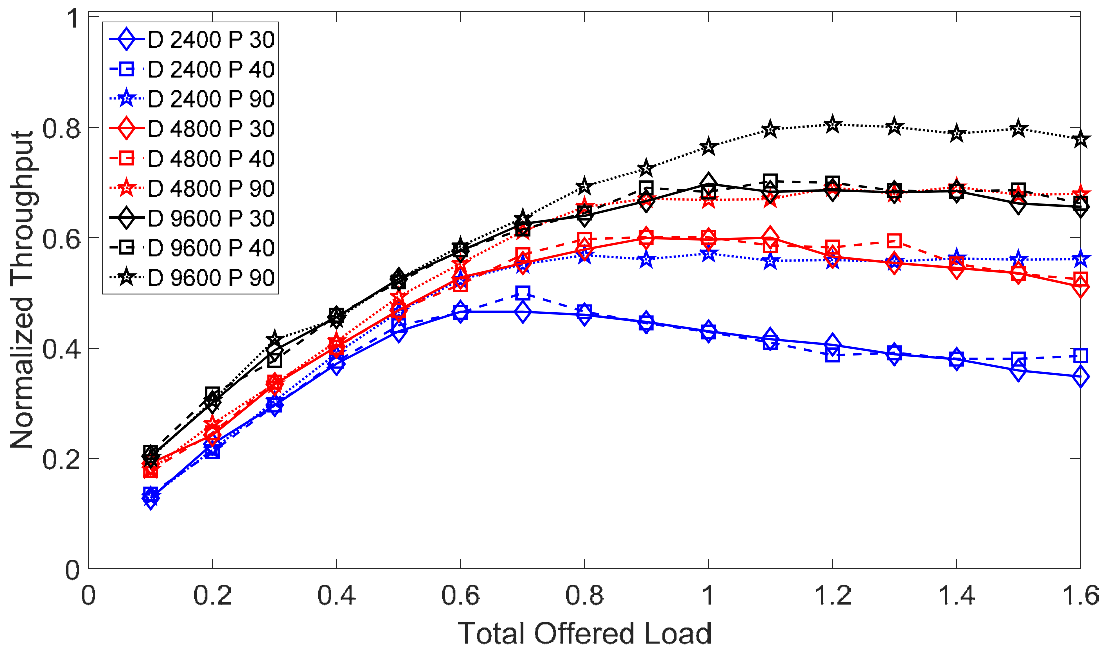

Fig. 3.6(b): Throughput with offered load (network size 200m).

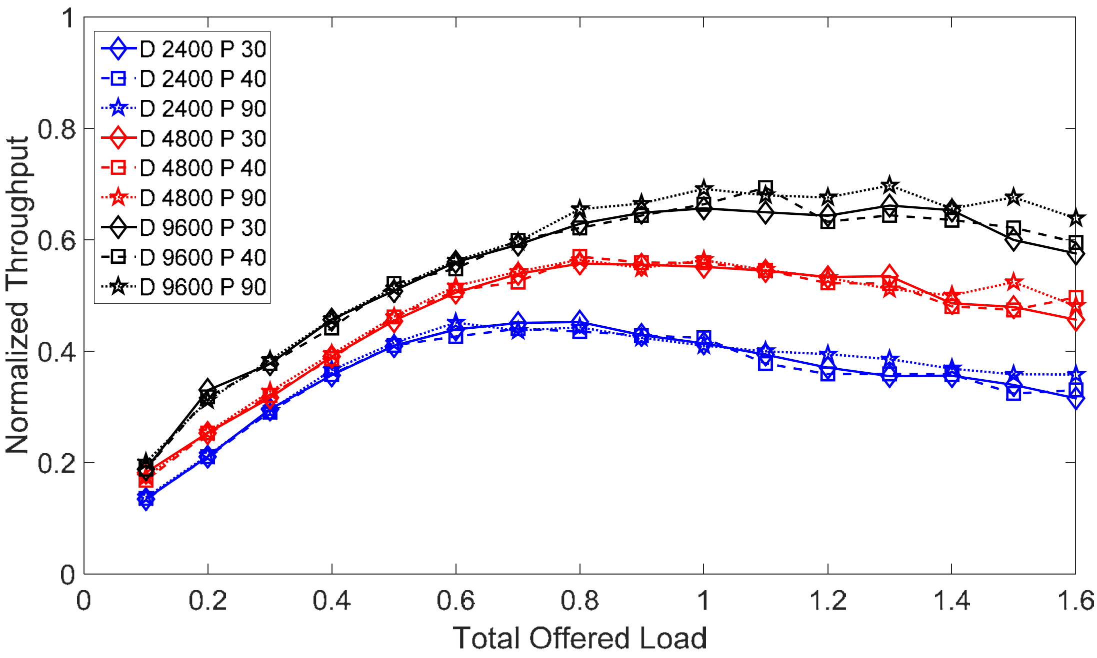

Fig. 3.6(c): Throughput with offered load (network size 300m).

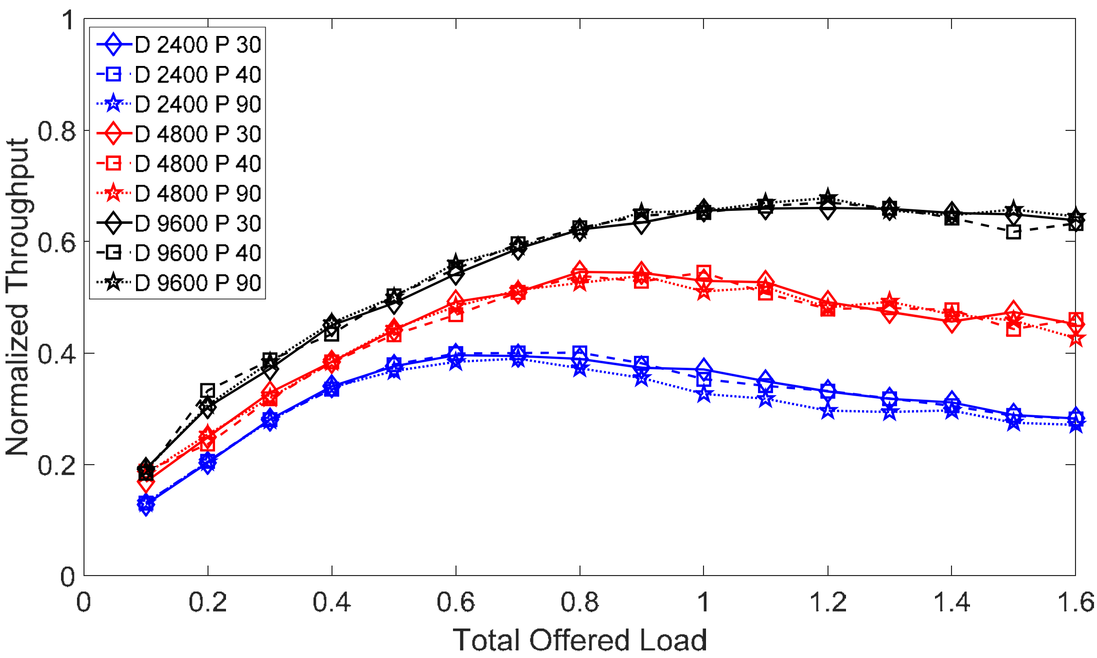

Fig. 3.6(d): Throughput with offered load (network size 500m).

Figures 3.6(a)-(d) demonstrates the variation of system throughput with the offered load for different network sizes, namely, 100m, 200m, 300m and 500m. The dimensions given are length of one of the edges. The meaning of the legend 'D 2400 P 30' is that the data packet size is 2400 bits and the control packet is transmitted with a power of 30dBm.

For all the figures, initially throughput increases with the increase of the offered load. Also for higher network size, increasing pattern changes and for higher network size, throughput tends to decrease in the higher traffic region. The reason for this is the increase of collisions with the increase of load. Also for the same reason as explained in Fig. 3.3, with the increase of packet size, network throughput increases.

Now, it can be seen from the four figures that when the network size is 100m, the throughput for all types of data packet is quite high and nearly close to each other. This is because, the control packets are being received by all the nodes in the network. However, with the increase of network size, throughput decreases because of the increased propagation delay, potential loss of control packets and collisions of data packets.

On the other hand, as can be seen that except the case of network size 200m, increase in the energy of control packets from 30dBm to 40dBm and then to 90dBm shows nearly no change in throughput. It is due to the reason that 30 dBm is enough for the control packets to reach all the nodes of the network for the network size of 100m. In contrast, for network size of 300m and 500m, it is large enough for heavy attenuation of control channel EM signal and thus increasing the power from 30dBm 90dBm has virtually no impact on the throughput performance. If the power could have been increased to a much higher value, throughput would have increased.

Thus we can come to a decision that proper communication in the control channel is mandatory for this protocol and partial communication may deteriorate the performance.

3.9.1.2 Collision Rate

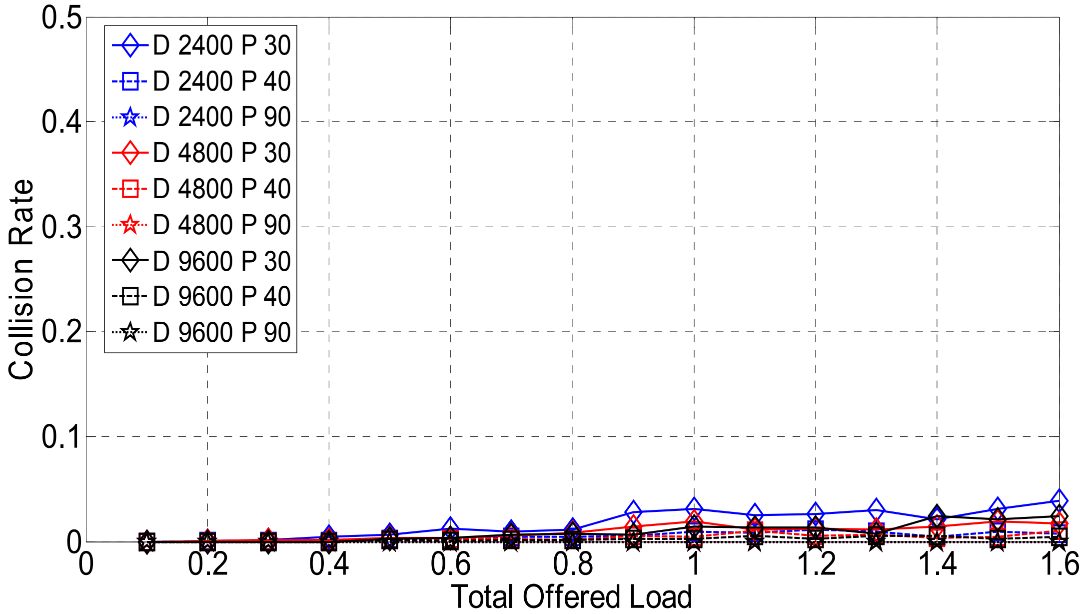

Fig. 3.7(a): Collision rate with offered load (network size 100m).

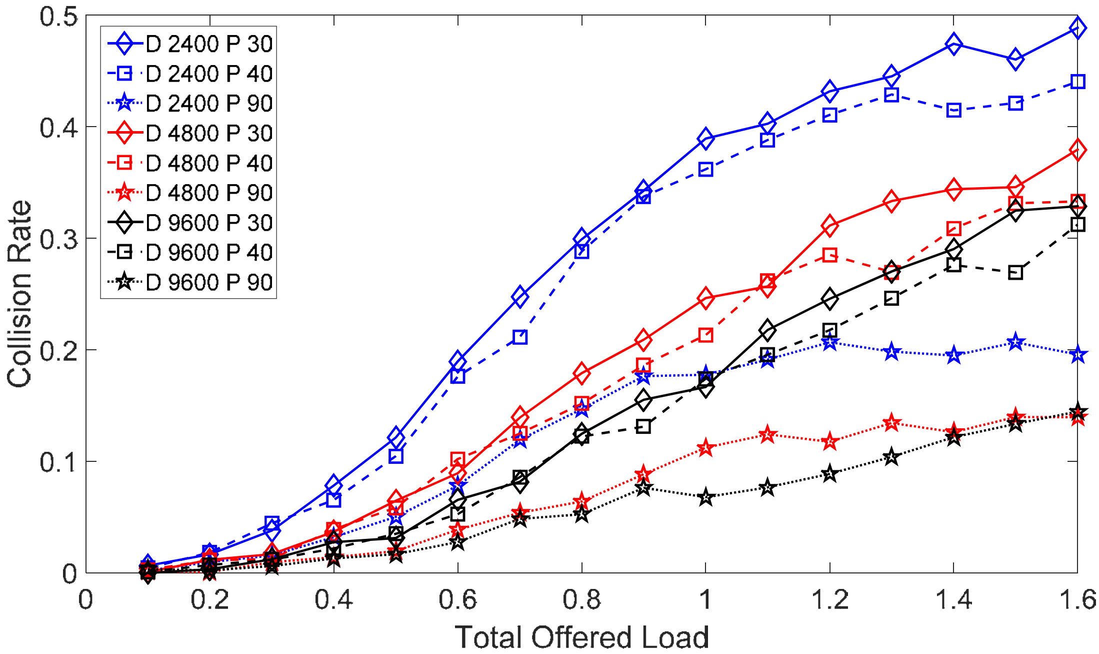

Fig. 3.7(b): Collision rate with offered load (network size 200m).

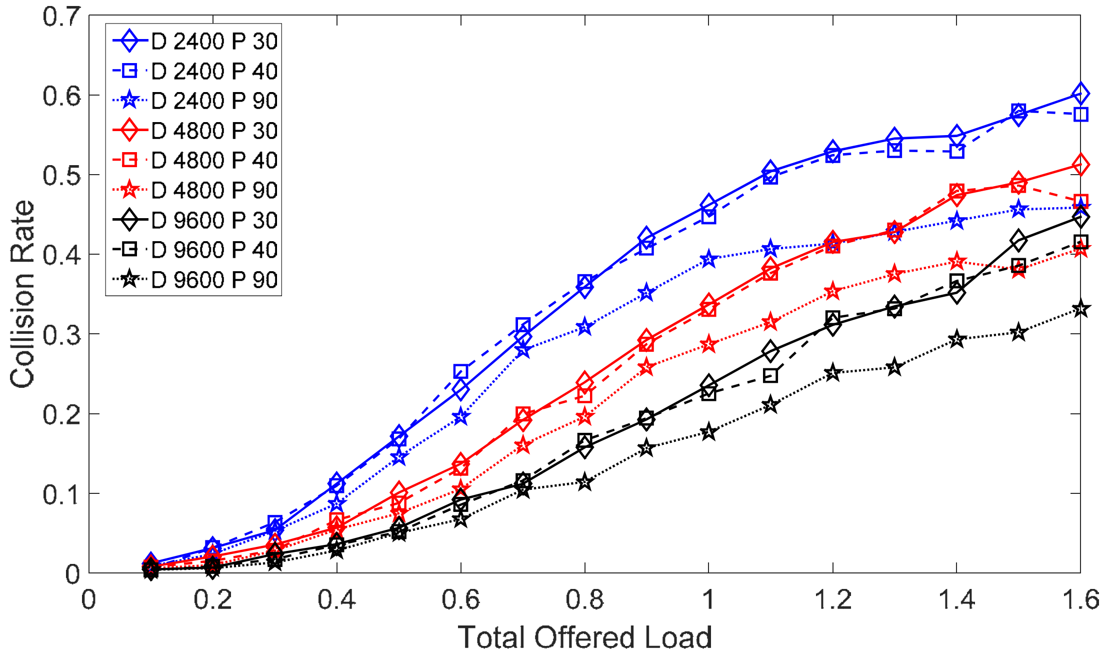

Fig. 3.7(c): Collision rate with offered load (network size 300m).

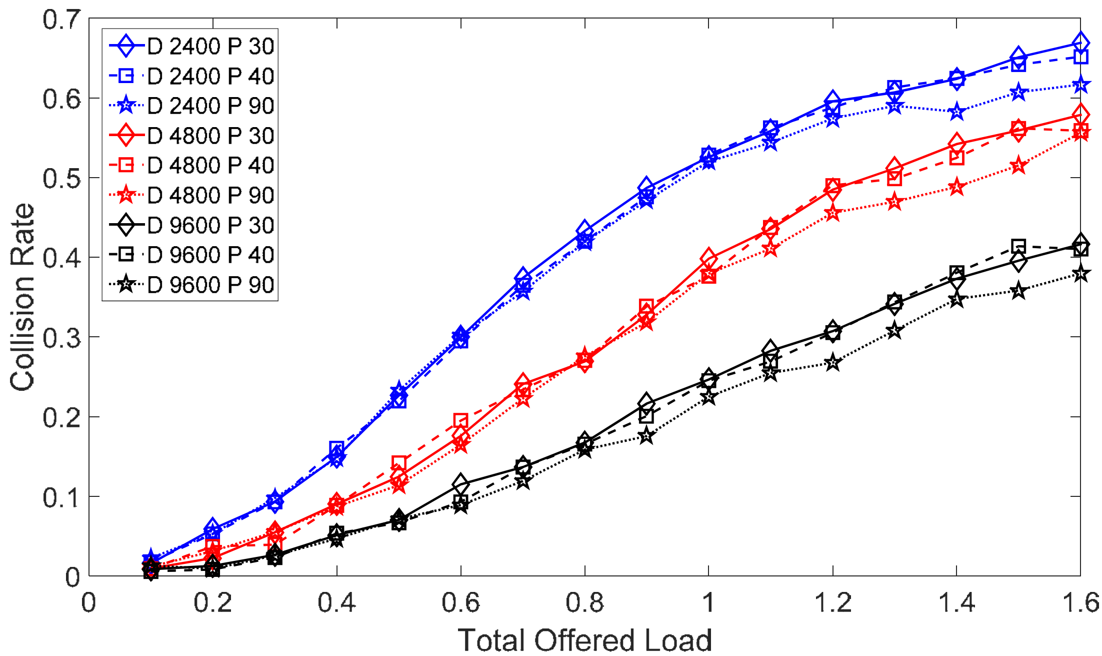

Fig. 3.7(d): Collision rate with offered load (network size 500m).

Collision rate determines the percentage of data packets wastage due to collision. The data packets while being received if interfered by any other packet in that channel is counted as collision. Figures 3.7(a)-(d) present the data packet collision rate for the proposed protocol for different network sizes. Fig 3.7(a) shows the collision rate for network size 100m. As we can see that the collision rate of data is negligible which indicates the high success rate of control packets. This is because for smaller network, the protocol can perform well with its control packet being heard by all the nodes. Therefore the collision rate is nearly zero. However with the increment of network size, the control packets start to attenuate more and cannot reach every node. As the network size increases, many control packets cannot reach the nodes and therefore the collision rate increases, and the protocol becomes more contention based. Increasing the power of transmission for the control packets from 30dBm to 50dBm doesn't seem to have any effect on the collision rate, as still it is not enough to overcome the attenuation. However, with the increase of power to 90 dBm, collision rate decreases as it is high enough for reaching some additional control packets to reach the nodes. Another thing worth noticing is that the collision rate also depends on the packet size; the larger the packet size the smaller is the collision rate.

3.9.1.3 Waiting Time

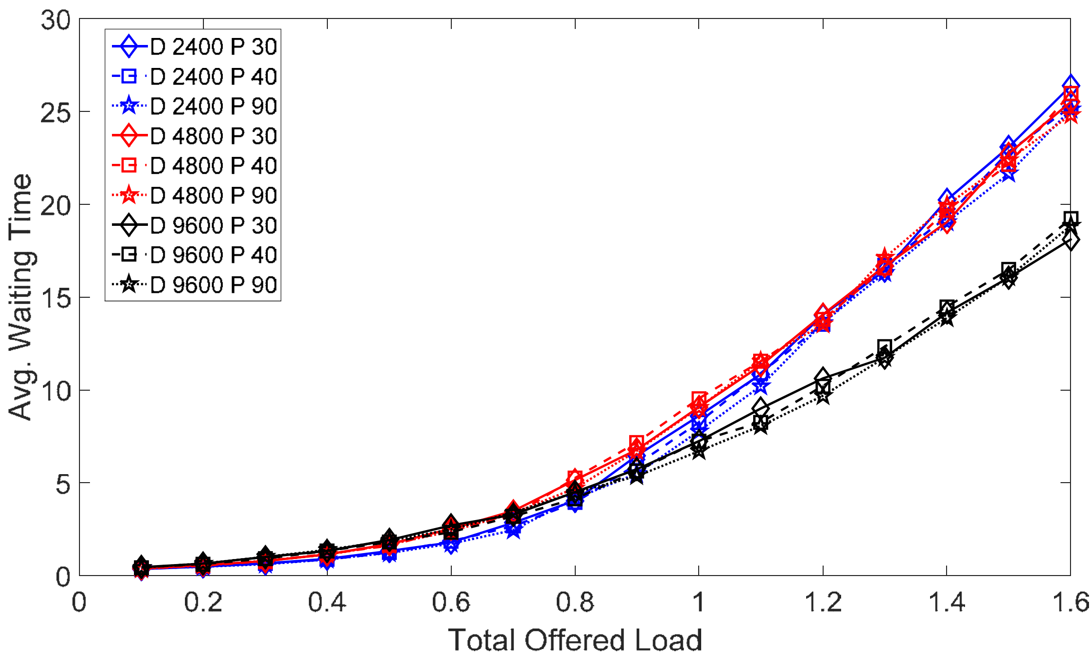

Fig. 3.8(a): Waiting time with offered load (network size 100m).

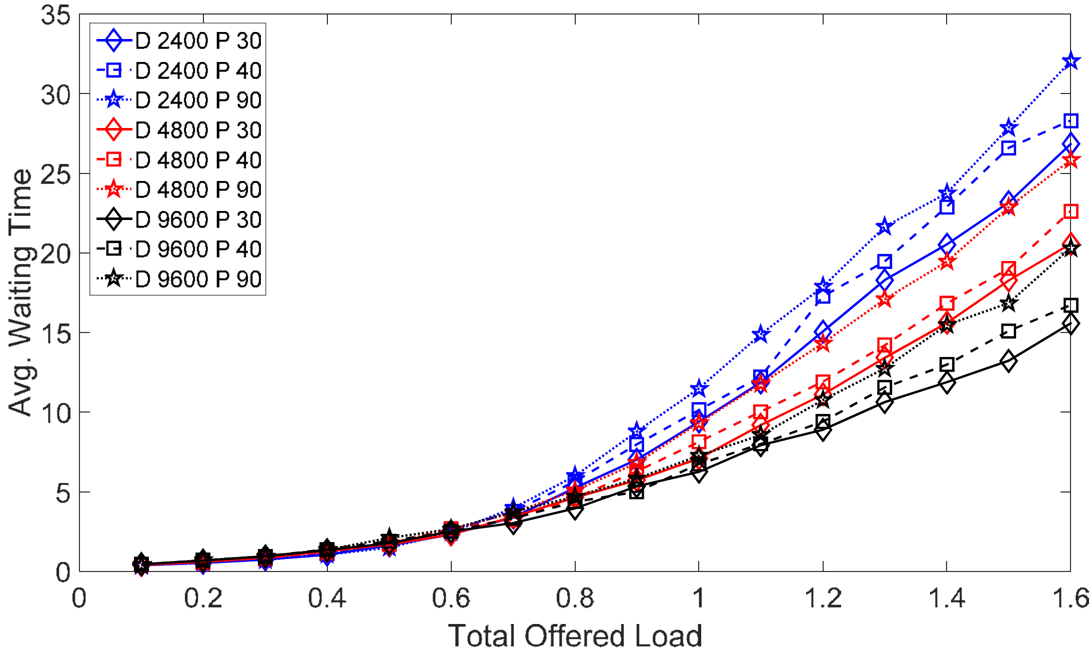

Fig. 3.8(b): Waiting time with offered load (network size 200m).

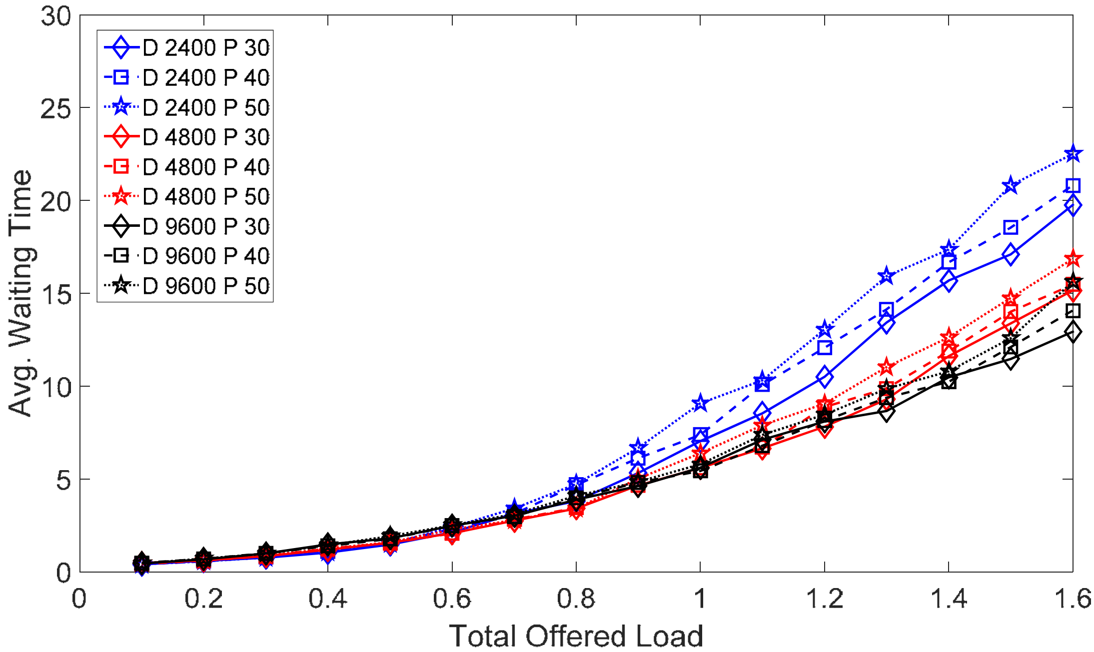

Fig. 3.8(c): Waiting time with offered load (network size 300m).

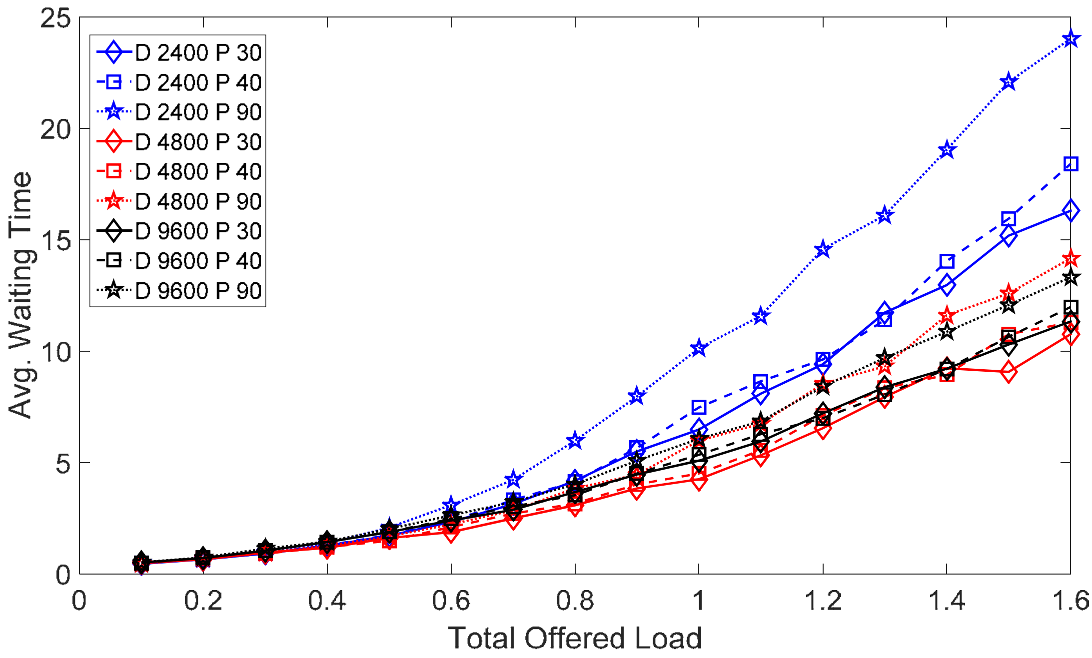

Fig. 3.8(d): Waiting time with offered load (network size 500m).

Average waiting time for a packet is the average time that a packet has to wait before it can be transmitted. Thus waiting time is one of the major metrics which affects the performance of a MAC protocol. From Figs. 3.8(a)-(d), average waiting time with the offered load for different network size is depicted. With the increase of load, the network becomes more and more congested leading to increased waiting time for the packets as seen in all the four figures.

On the other hand, when the network size is 100m, the efficiency of control packet is almost 100% for all of the power used for control packets. Therefore, average waiting time is same for different power ratings. When the network size increases from 100m to 200m, the control packet loss issue enlarges and waiting time increases as the nodes cannot update their table properly. Also the confirmation message success rate falls, therefore the nodes have to wait for some back off time to be sure of the channels status. As discussed above for Fig. 3.7, when the network size increases significantly, the protocol becomes more carrier sense based and therefore contention based. As the carrier sense contention based protocols have lower waiting time, therefore the waiting time for larger network size and lower control packet power decreases as observed in Fig. 3.8(c) and (d).

Furthermore, average waiting time also depends on the packet size. As more and more packets are bunched together to form a large packet, the average waiting time decreases. It is because the waiting time counting starts after the formation of the larger packet. Thus it can be noticed that the average waiting time for 9600 bits data packet is the smallest for all the cases.

3.9.1.4 Energy Requirement

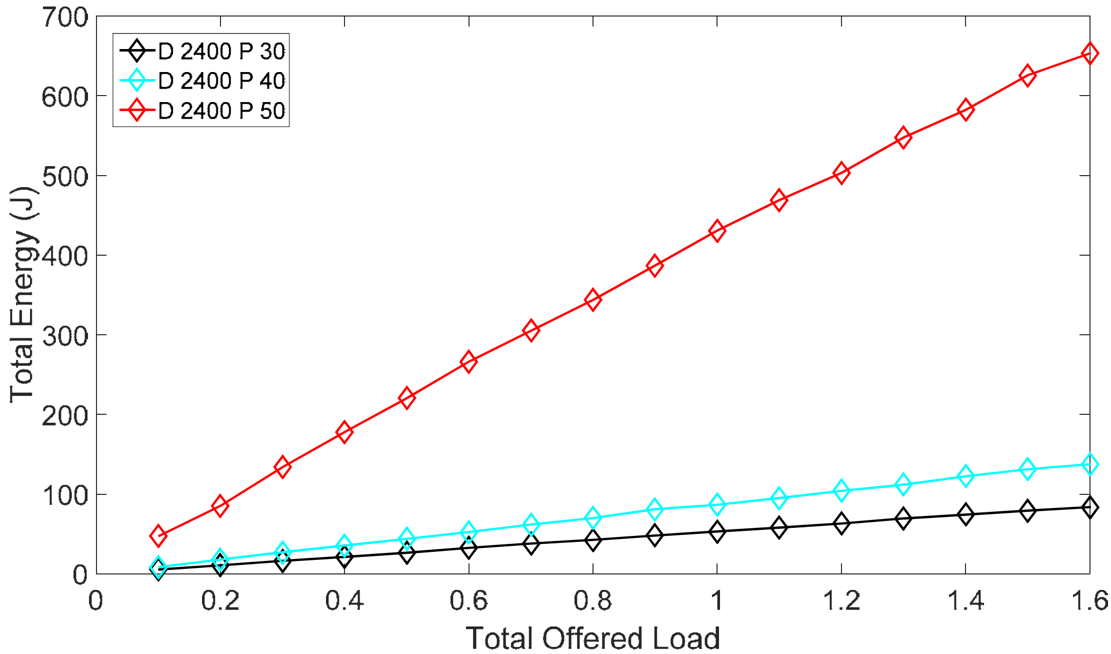

Fig. 3.9: Total energy with the offered load.

The Total energy needed to send the data packets generated within a specific time (results for 50 sec is shown) is plotted in Fig 3.9. The total energy consists of the energy needed for the control packets and the data packets. Here in the simulation three different power is used for the control packet transmission - 30dBm, 40dBm and 50dBm. The power of data packets was not changed because 1W power was enough to cover the network area for acoustic channel. As the data packets are always assumed to use 1W power, the change of energy occurs due to the change in control packets power only. From the figure, it can be observed that increasing the power to 50W for the control packet consumes a lot of energy. However as we have seen in Figs. 3.6-3.8, it doesn't provide any noticeable improvement in the performance of the protocol.

3.9.2 EM-based Control and Data Channels

The following simulation results are for the EM-EM based protocol, where both the control and data channels are EM based. The main difference between the control channel and data channel EM wave is the carrier frequency. The control channel uses 1kHz, while the data channel uses 6kHz in this simulation platform. The power used for the control and data channel is fixed at 30dBm (1W). As the EM wave attenuation increases with the frequency, the network size is constrained within 120m.

3.9.2.1 Throughput

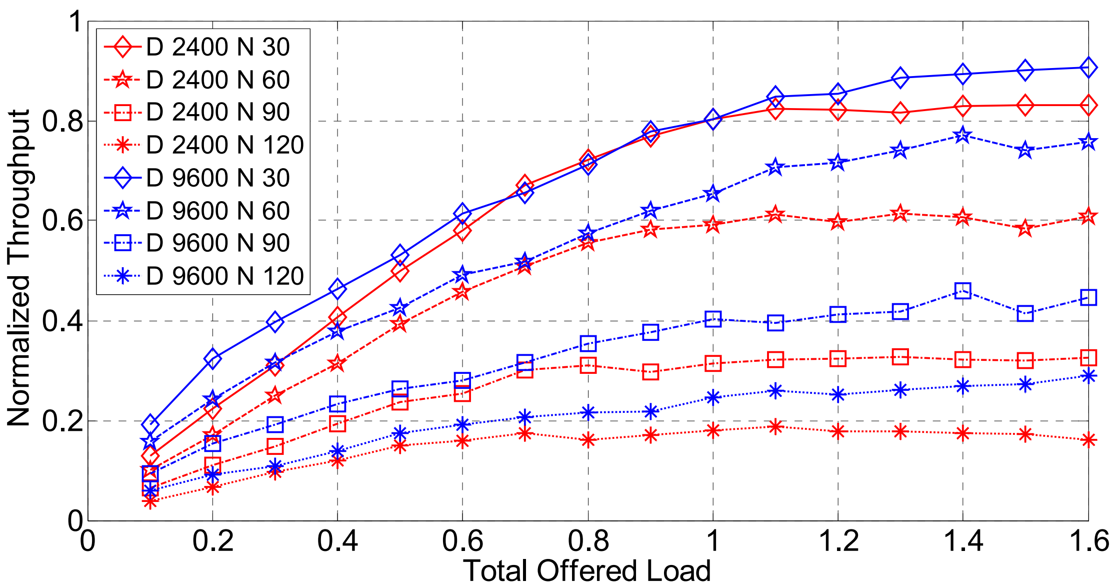

Fig.3.10: Throughput with the offered load for different network size.

Throughput of the proposed EM-EM based MAC protocol for varying offered load with the impact of network size is depicted in Fig. 3.10. The legends are explaining the network size and packet size, thus 'D 2400 N 30' means that the data packet size is 2400 bits, while network size is 30m. Most noticeable part of the plot is that with the increment of network size the throughput falls no matter what the data packet size is. The second finding is that larger data packets always give better performances. The reasons behind these behaviors of the throughput curves are same as those explained in Fig. 3.6.

3.9.2.2 Collision Rate

Collision occurs when the control packets cannot reach the nodes due to attenuation. As explained before, this figure also demonstrates that collision rate increases with the increase of offered load and the reduction of packet size. As the control channel uses 1 kHz as carrier frequency, attenuation for 120m is not that much. Therefore it can be seen in Fig. 3.11 that collision rate is quite negligible for network size from 30m to 120m. Few collisions of data packet occur for network size 120m, which is still within 1% and 2% for 9600 bits and 2400 bits data packet respectively.

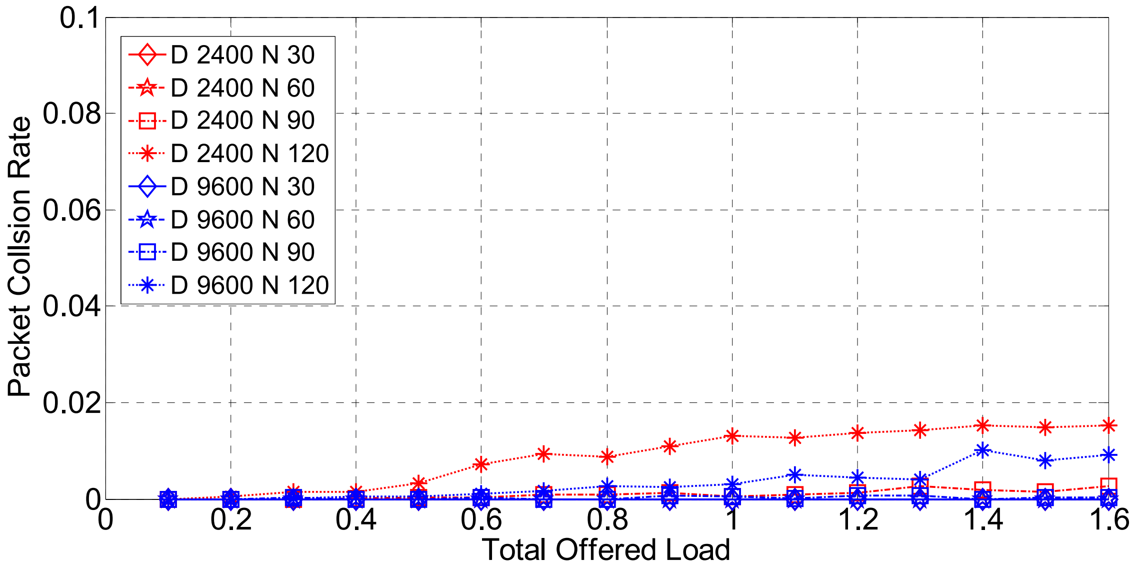

Fig. 3.11: Collision rate with the offered load for different network size.

3.9.2.3 Packet Missing Rate

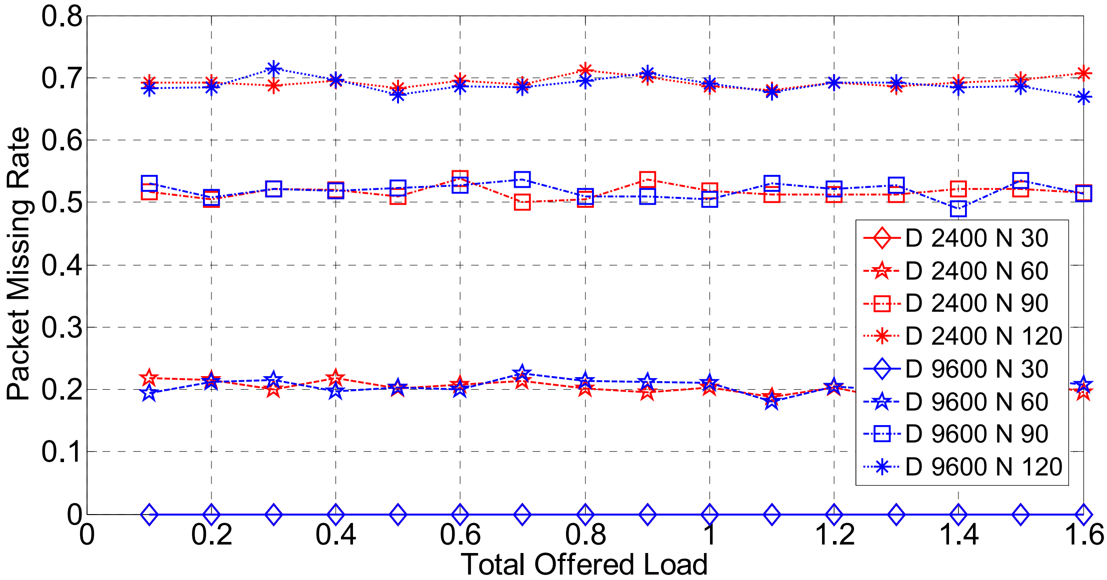

Fig. 3.12: Packet missing rate with the offered load for different network size.

The most important feature for EM-EM based protocol is the packet missing rate, which happens due to the severe attenuation in the data channel for using a higher frequency. From Fig. 3.12, it can be observed that for network size of 30m, data packets were not missing due to attenuation. For 60m network size, the missing rate increase to 20%. If the network size is increased further, missing rate jumps to 50% at 90m and 70% for a network size of 120m. So the detrimental effect of attenuation can be easily understood from the above discussion. Another point worth noting is that the offered load and the data packet length doesn't have any impact on the packet missing rate as the attenuation does not depend on these two parameters.

3.9.2.4 Waiting Time

The last performance metric for the EM-EM based protocol is the average waiting time. Figure 3.13 shows the impact of network size, data packet size and the offered load on the average waiting. The observations that were made in the EM-Ac scenario are applicable in this case also. However, comparison of the curves of data packets of 9600 bits and 2400 bits, it can be inferred that the network size has lesser impact on the waiting time for larger data packets.

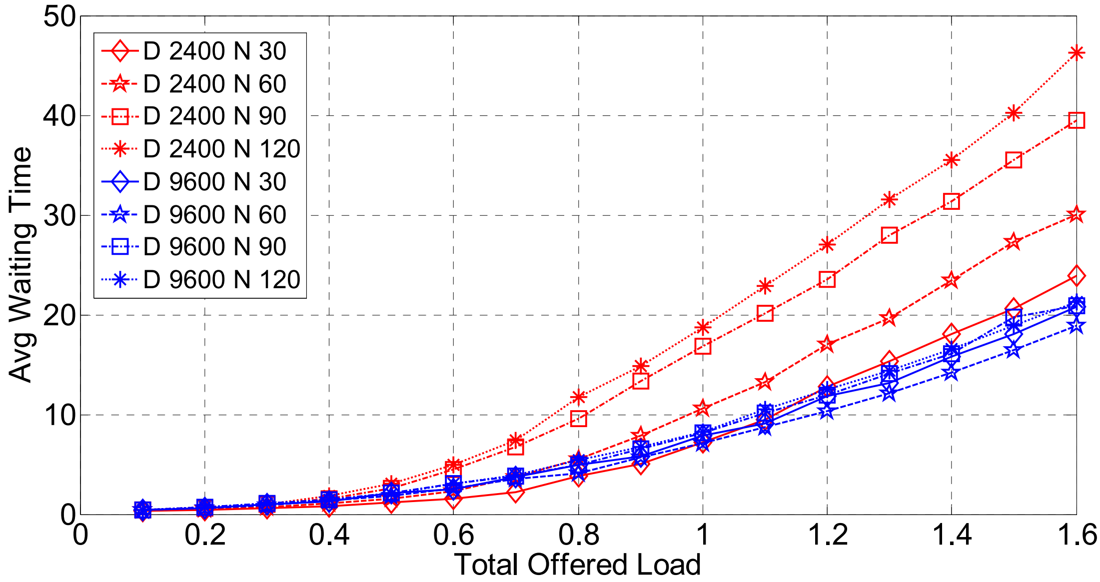

Fig. 3.13: Average waiting time with the offered load for different network size.

3.10 Chapter Summary

This chapter have presented single data channel based MAC protocols by integrating EM wave communication. A control channel is also proposed for signaling purpose. Extensive simulations under various network settings have been carried out. From the analysis, we can conclude that network size plays the major role in underwater protocol performance. The propagation delay which depends solely on network size diminishes network throughput with its increment. Also the EM suffers a lot of attenuation and so larger network sizes tend to limit the coverage of the proposed protocol. One solution might be to use lower carrier frequency for EM. Also substantial increase in the EM channel power doesn't seem to affect the network performance much.

Chapter 4

MAC Protocol for Multiple Data Channels

Following the protocol that is described in the previous chapter, this chapter extends the proposed protocol for multiple data channels. The major change is the addition of multiple data channels in the physical network and extra time slots in the control channel for confirmation of packet reception through different data channels resulting in a much more complex scenario. Extensive simulations are carried out to gain insight about the multiple data channel scenario.

4.1 Control Channel and Data Channel

The control channel for multiple data channel is quite similar to the control channel of single data channel. However one big difference is that now the total number of time slot in a TDMA frame of the control channel will be changed by the following equation

$$N = n_d + n_c \tag{4.1}$$

where n_c is the number of data channels used by the protocol. It is because each data channel has one time slot in the control channel TDMA frame dedicated for it. This slot is used by the node to send the confirmation packet and thus indicating the availability of that data channel. Now when any node has data to send, it sends the reservation request control packets through its time slot. Now if there are 3 data channels and the first one is busy while other two are free, then the node will send its data through the second data channel. Within some short period if any other node wants to send its data packet, it may then use the third data channel.

After some time when a data packet has been successfully received by the receiver, the receiver will then send confirmation through the dedicated time slot of that data channel. In this way, it is informing other nodes about the availability of that particular data channel.

4.2 Operation Principle of the Proposed Protocol

The operation principle of the proposed MAC protocol with multi-channel is somewhat similar to the single data channel based protocol. However, the scenario is much more complex. The major difference is now that the nodes will have to use more flags to trace the status of all the data channels. To explain the operation principal properly, a time series diagram is presented in Fig. 4.1 for a network having two data channels and four nodes.

As discussed before, when a node requires channel for data transmission, it first requests for reservation of data channel using its assigned time slot in the EM wave based TDMA frame. Data channels are allocated to the requested nodes as per the request message received sequence. We assume that in the TDMA frame, time-slot 1 to 4 are assigned for sending reservation request of nodes 1 to 4 respectively, while slot 5 and 6 are for sending confirmation message of releasing data channels 1 and 2 respectively. Duration of each of these slots is equal to the control packet duration plus the guard time duration.

For instance, let Fig. 4.1 depicts the beginning of the system. At first, node 2 wants to send data packet and therefore requests for reservation through slot 2 of the EM channel TDMA frame. The data transmission tables which are maintained by nodes will now be updated, as discussed in the single channel operation principle. Now as both the data channels are free as found in its own table, node 2 starts transmitting data using acoustic data channel 1. Now if another node wants to transmit data, it can start transmitting data through data channel 2.

For example, we can see in the figure that node 4 wants to transmit data after a while. As the data channel 1 is now occupied by node 2, node 4 transmits the request message for reserving a data channel and then starts transmitting its data through the data channel 2. Once again the tables maintained by the nodes will be updated, and this time both node 2 and node 4 will be labeled as 'sending'. Also the flags maintained to keep track of the channel status will now indicate both channels as busy.

Now as all the data channels are booked, the other nodes intended to transmit data will maintain the reservation process through their respective time slots and wait for data channel to be freed. These reservation calls will also be updated on the tables maintained by the nodes.

We see from the diagram that the next transmitter in the list is node 3. It will send its reservation for data channel through its given time slot and all the nodes are assumed to have heard it. Now every node will update their table once again. Then after a while, we see that the data transmitted through data channel 1 by node 2 is completed. However, the channel 1 remains busy for the duration of data packet plus the time required to propagate the data signal from node 2 to the desired destination, which is also shown in Fig. 4.1. After this time period, the channel 1 can be freed. Therefore, upon receiving the complete data packet, the receiver now transmits a receive confirmation message using slot 5 of TDMA frame. Through this confirmation message, all the nodes are now notified that data channel 1 is free and then node 3 starts its transmission through data channel 1.

Now if we look at the time series of data channel 2, we see that upon the reception of the data packet, the receiver sends a confirmation message using slot 6 of TDMA frame to let others nodes to know that channel 2 is now free. As we can see from the time series that the data packet of channel 2 was received during time slot 6, therefore the confirmation message is sent during the 6^{th} slot of the next time frame (T_F). This process of transmission and reception of data will go on for the rest of the time series.

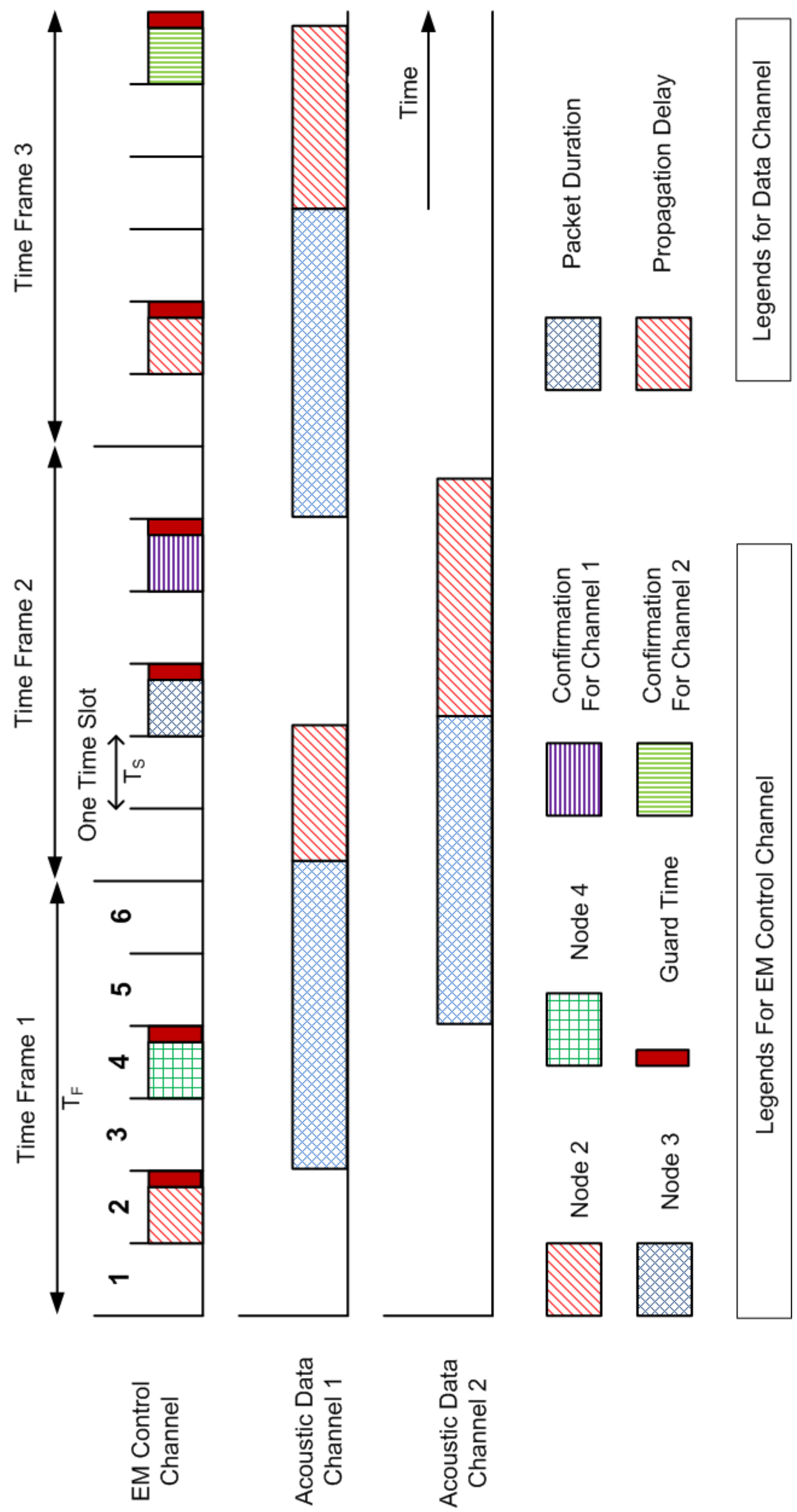

Fig. 4.1: Time series diagram for the proposed protocol with multiple data channels.

4.3 Collision Scenario

The collision scenario discussed in the previous chapter is also applicable for multiple data channel scenario. However, for multi-channel case, collisions occurring in one data channel do not affect the data packet transmission of the other data channels. The channel occupation limit and back off time is same as discussed in the previous chapter.

4.4 Performance Metrics

All the performance metrics defined in Chapter 3 will be used in this chapter as well. However along with those, a new metric is defined. Also the throughput is modified to be used in the multi-channel scenario as discussed below.

a) **Bandwidth Efficiency:** The Bandwidth efficiency is the normalized throughput for current BW with respect to some default BW or data rate as defined below.

$$\eta_{BWn} = \left(\frac{\eta_C}{R_C}\right) \div \left(\frac{\eta_D}{R_D}\right) \tag{4.2}$$

where η_c is the throughput for the current BW allocation, R_c is the data rate for the current BW, η_D is the throughput with default BW and R_D is the data rate of the default channel.

b) **Apparent Throughput:** Apparaent throughput is the total throughput achieved from all the data channels and thus it can be greater than 100%. The apparent throughput can be calculated by the equation of throughput (3.3) used in the previous chapter. However apparent throughput will not express the channel utilization, if multiple channels are used with a total BW different than the single channel BW.

c) **Normalized Throughput:** The significance of normalized throughput is same as stated in the previous chapter. However the equation needs some modification. If all the channels use the same BW as the single channel was using, then normalized throughput η is the apparent throughput η_a divided by the number of channels as given below.

$$\eta = \frac{\eta_a}{n_c} \tag{4.3}$$

Another important point is that if the BW of the single channel is divided among the channels then apparent throughput and normalized throughput are same.

4.5 Simulation Settings

Unless otherwise specified, all the simulations parameters used in the previous chapter will be used in this chapter as well. In addition, following parameters presented in Table 4.1 are used for the following simulation results. Two cases of multiple data channels considered. In the first case, the bandwidth of the single data channel is divided among the multiple data channels. For the second case, each data channel has a bandwidth equal to that of single channel case resulting an increase in total system bandwidth. Control packet power is always used equal to30 dBm.

Table 4.1: Network parameters

Parameter	Value(s) Used (Typical)
Number of data channel	1-4
Data Packet size	2400 bits
Data rate	600, 1200, 2400 bps

4.6 Performance with Protocol Interference Model

This section presents the impact of various parameters on the network throughput under varying number of data channels and other system parameters ignoring the impact of channel attenuation. Presented results are evaluated for EM-Acoustic MAC protocol.

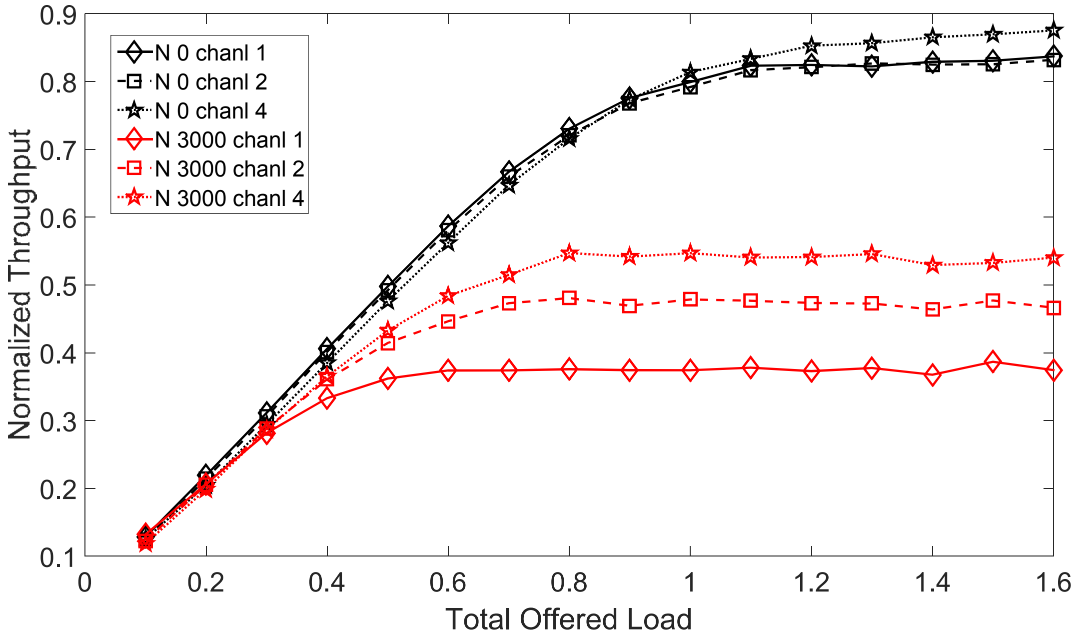

Fig. 4.2: Normalized throughput with total offered load for different number of channels and network size.

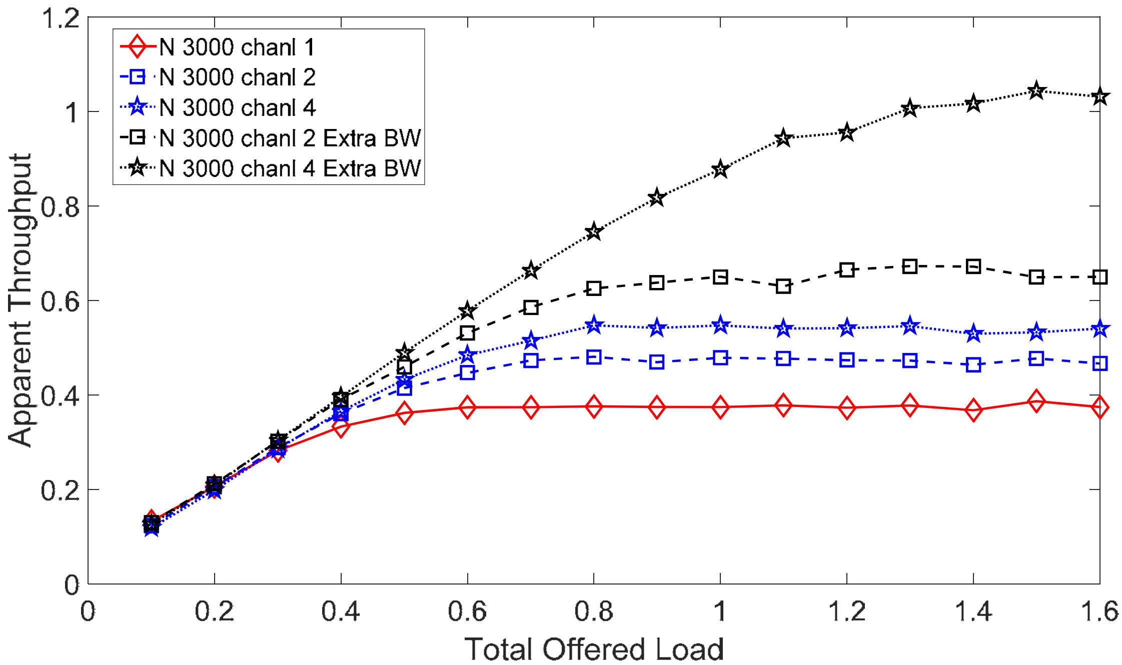

Fig. 4.3: Apparent throughput with total offered load for different number of channels (two different BWs).

The legend in Fig 4.2 with 'N 3000 chanl 4' means that the network size is 3000m and 4 parallel data channels have been used. Also, multiple channels do not use extra BW, i.e., the BW of single channel is divided equally between the channels. From the figure, it can be noticed that the throughput for single channel and multi-channels for zero network size is almost same. Therefore for zero network size with no propagation delay, the normalized throughput is almost same for single and multi-channels. However when the network size increases, the benefit of using multi-channel becomes realizable. With large network size having high propagation delay, multiple channels are useful to overcome the effect. Still increasing the number of channel doesn't increase the throughput linearly. The effect seems to saturate with increasing number of channels.

In Fig 4.3, the apparent throughput with the offered load for different number of data channels are shown. The legends with 'Extra BW' mean that in those cases the channels have same BW of the single channel, thus having larger system BW. That's why when the channel number is increased, the apparent throughput even soars above unity. It is because, though the parallel channels are not being used properly, however the summation of their utilization can be well above unity. It means that the data transmission rate is above the maximum limit of one single channel. Another thing worth noticing is that the throughput increases quite linearly with the increase of multiple channels with larger BW.

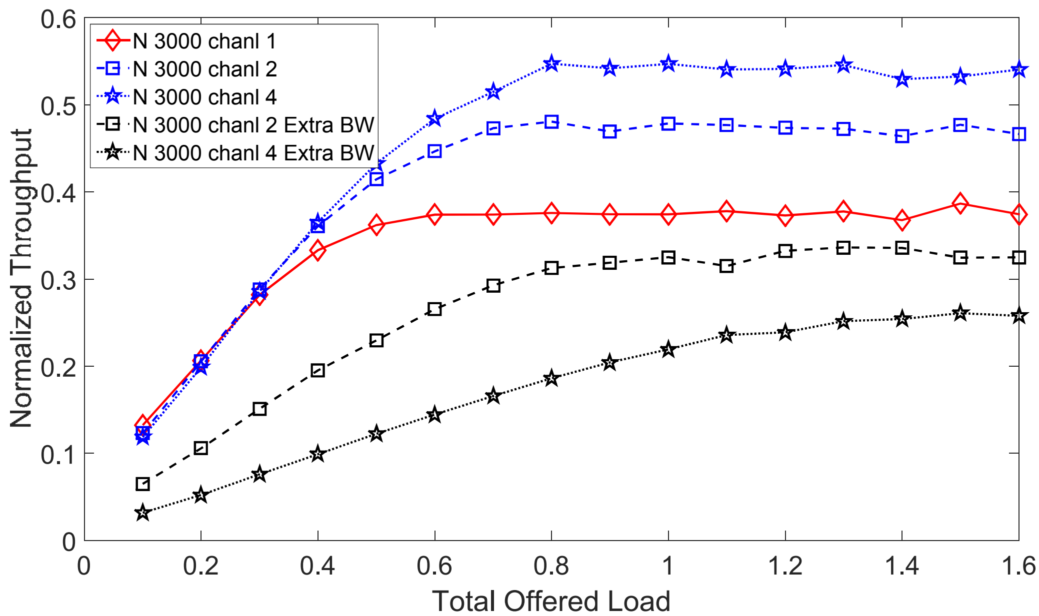

Fig. 4.4: Normalized throughput with total offered load for different number of channels (two different BWs)

At last in Fig 4.4, the normalized throughput graph is plotted. From the figure it is obvious that the channels using higher BW cannot utilize their channels to the full capacity. Though the packets are being sent quicker, most of the time the channel is being wasted. Also the more the number of channel, the more is the wastage. We can see that for 4 data channels with extra BW, the channel utilization is only around 25% for high data traffic.

4.7 Performance with Physical Interference Model

This section presents the results considering the channel attenuation as well as propagation delay.

4.7.1 EM-Acoustic Based Control and Data channel

The following results are for multiple acoustic data channels and single EM based control channel. The EM carrier frequency for the simulation is still 1 kHz and acoustic wave has 10 kHz as its carrier. As EM and acoustic attenuation models are used, therefore the network sizes used are smaller. Also, for proper comparison, multiple data channel cases, total bandwidth of single-channel case is equally divided among the multiple data channels.

4.7.1.1 Throughput

Fig. 4.5 shows the change in throughput for different number of channels with different network sizes. When the network size is 100m, proposed protocol with different number of data channel gives close performance. Also, 2 and 4 parallel channels cases give close performance for network size from 200m to 500m. However, for single case network with the increase of network size from 200m to 500m, throughput degrades rapidly and the gaps with the multi-channel cases increases.

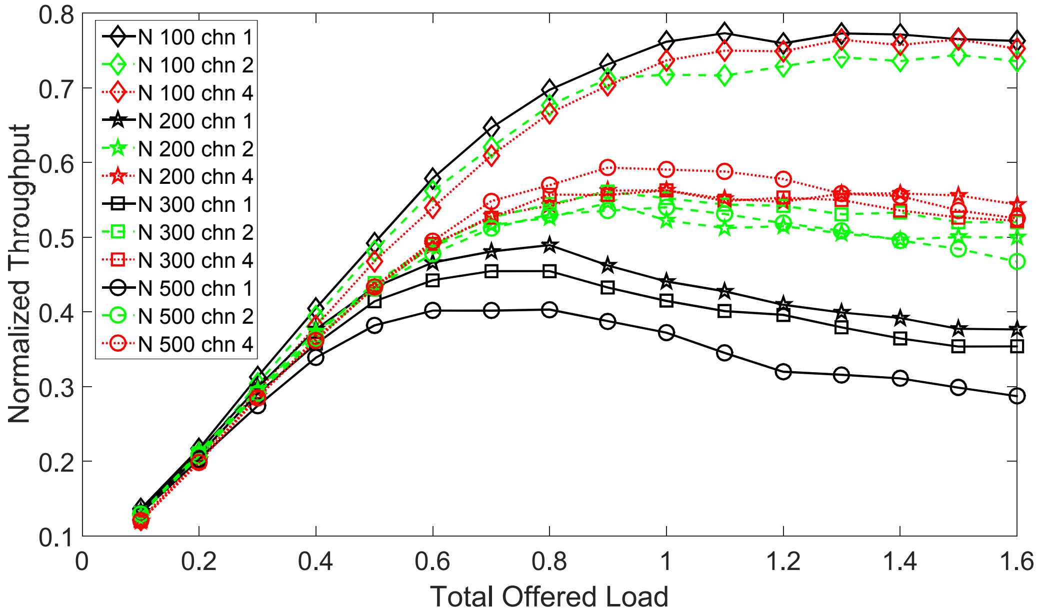

Fig.4.5: Normalized throughput with total offered load for different number of channels and network size.

4.7.1.2 Collision Rate

The effect of network size on collision rate for different number of channels is depicted in Fig. 4.6. As expected, the collision rate gives a jump when the network size is expanded to 200m from 100m. It supports the graph of throughput discussed in Fig. 4.5. With closer observation, close correlation can be found with this plot with the previous plot of throughput. The throughput and collision rate has just the opposite relationship. Another thing worth noticing is that collision rate always increases with the increment of network size for both single and multiple channels. However the effect is quite severe for single channel.

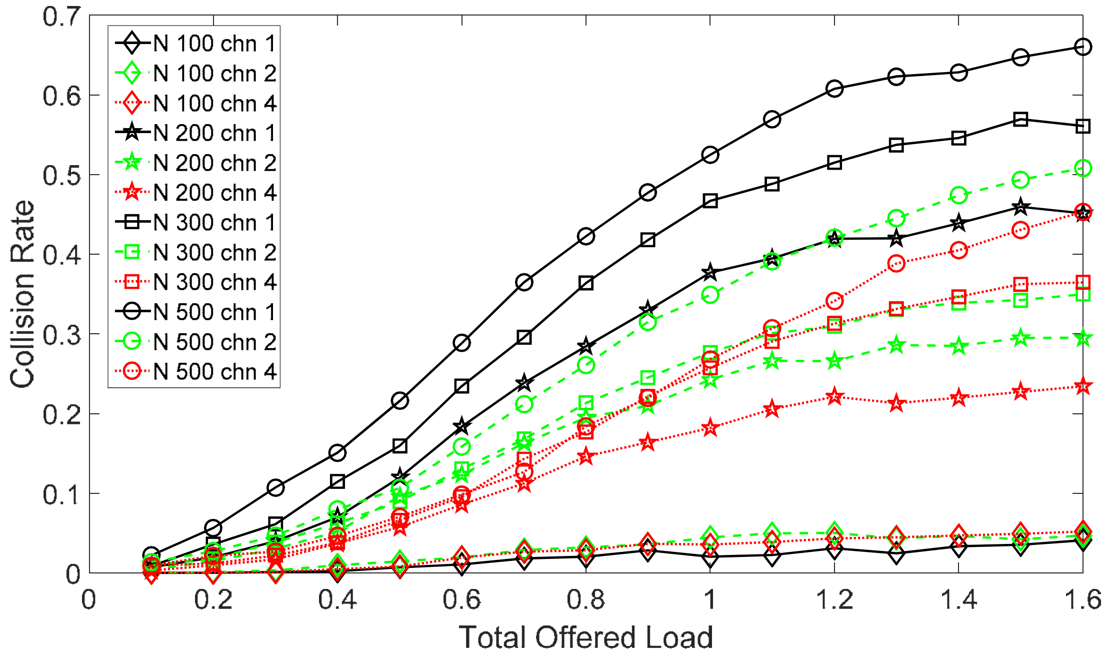

Fig.4.6: Collision rate with total offered load for different number of channels and network size.

4.7.1.3 Waiting Time

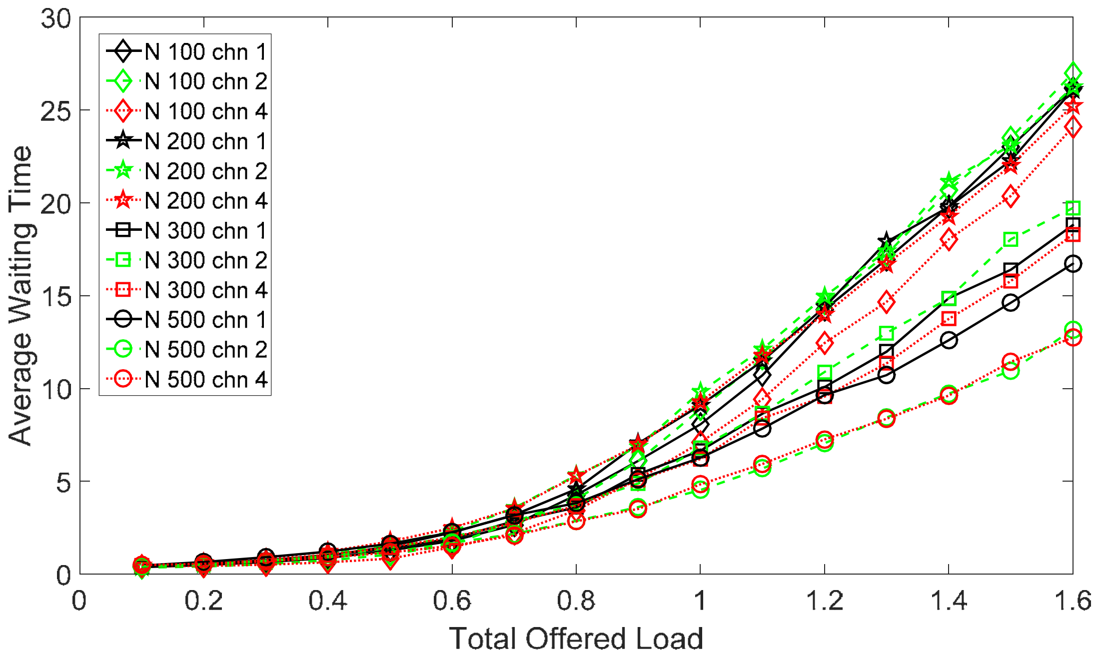

Fig. 4.7: Waiting time with the total offered load for different number of channels and network size.

For different number of data channels, it is expected to have lower waiting time with higher number of parallel channel. Fig. 4.7 illustrates the average waiting time for different loads with different number of data channels. From the figure, it can be verified that increasing the number of channel always decreases the average waiting time for the network. Also as the network size gets bigger, the propagation delays become bigger and uncertainty of control packet reception increases the waiting time.

4.7.2 EM-EM Based Control and Data channel

This section presents the results for the case of EM communications for both the control channel and the data channel.

4.7.2.1 Throughput

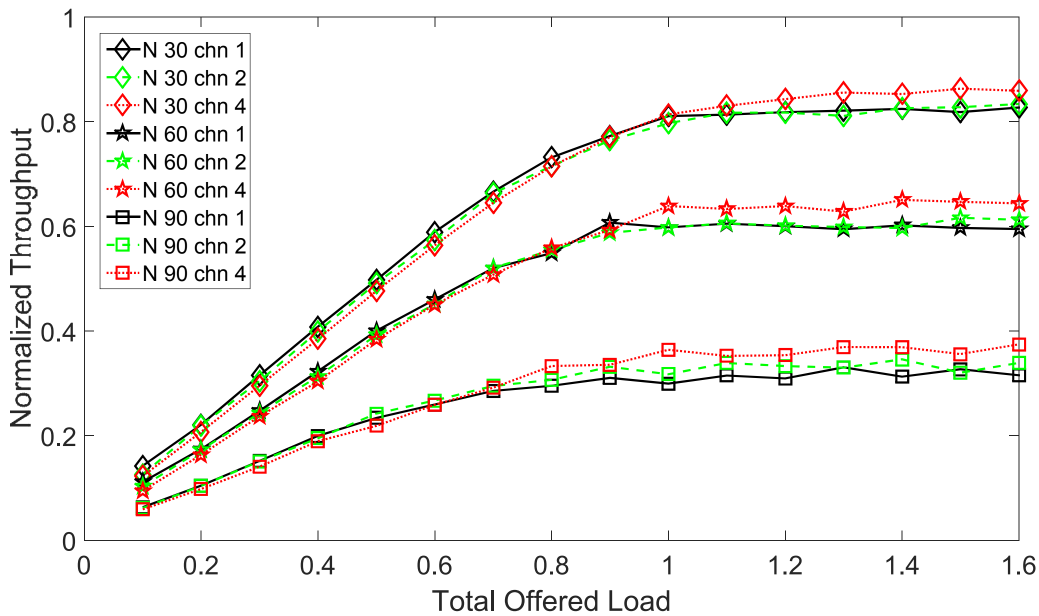

Fig. 4.8: Normalized throughput with total offered load for different number of channels and network size.

In Fig 4.8, the effect on throughput for different network sizes with different number of data channels is shown. The protocol here is EM-EM based. As can be seen, the throughput decreases with the increment of network size and no improvement is achievable by increasing the number of data channels. This is due to the fact that with high carrier frequency in the data channel, the EM channel data packets are not reaching their destination most of the time decreasing the throughput of the system drastically.

4.7.2.2 Waiting Time

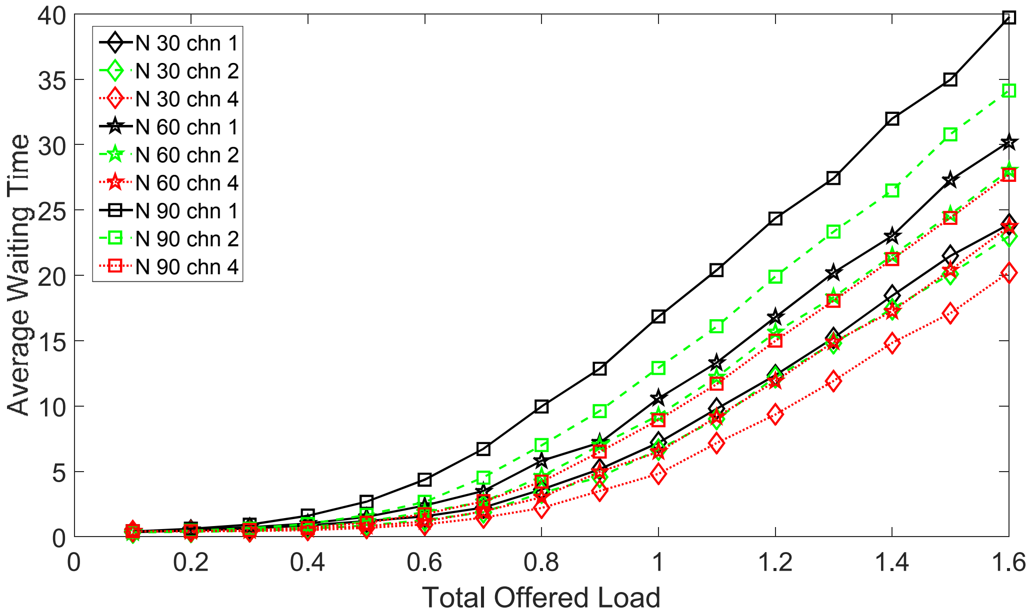

Fig. 4.9: Waiting time with the total offered load for different number of channels and network size.

Average waiting time with respect to the network size is of less significance if the throughput of the system is constantly decreasing with the increment of network size. In Fig 4.9, it is obvious that increasing the network size increases the waiting time and increasing the number of channel always decreases waiting time. Decrease in waiting time is due to the availability of multiple data channels for data transmission. However, all these have very subtle effect on the throughput performance of the protocol because of the missing of data packets.

4.8 Impact of the Number of Data Channels

In light of the simulation results found so far for multiple channels, we would like to compare the throughput, collision rate, waiting time and energy consumption for different number of channels for a fixed network size of 200m with some fixed packet generation rate. To keep the comparison easy to understand only EM-Acoustic based protocol is used. It is also assumed that for multiple data channel cases, total bandwidth of a single data channel is equally divided among the multiple data channels.

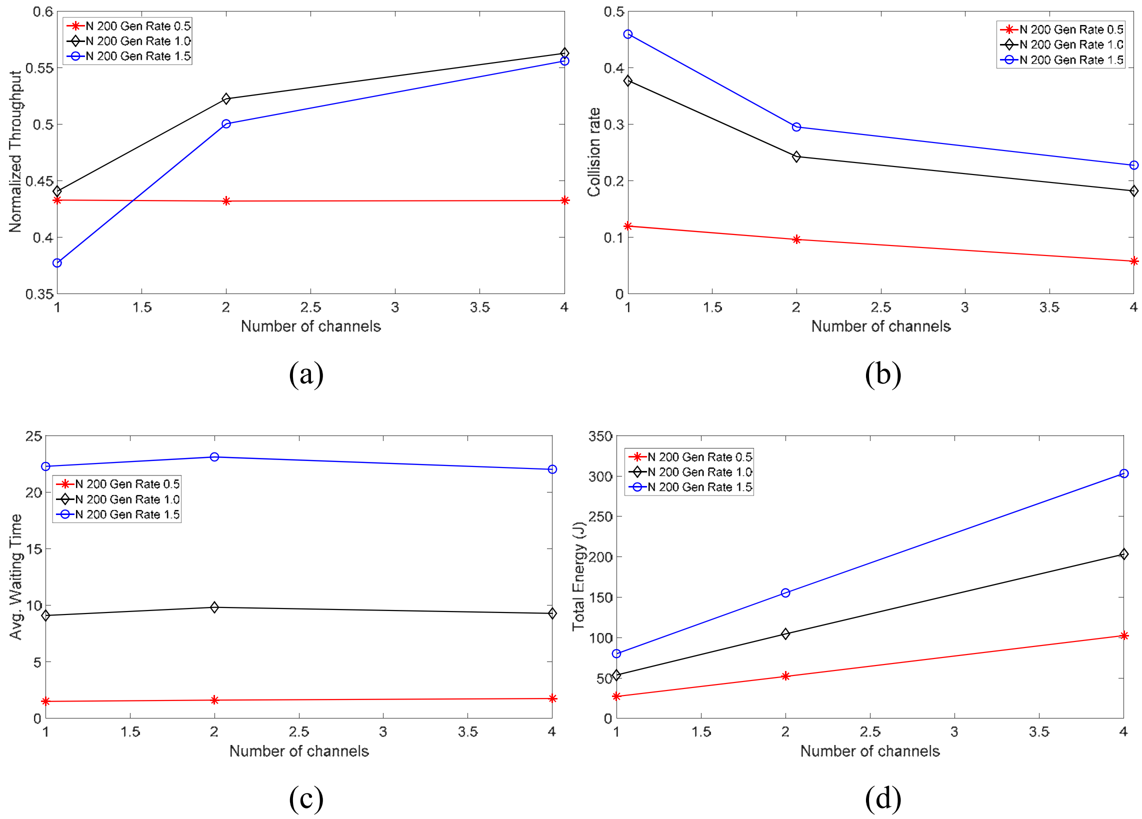

Fig. 4.10: Comparison of throughput, total energy, collision rate and waiting time for different number of channels.

Fig. 4.10 gives the complete overview about the performance of the multiple data channels. Fig. 4.10(a) shows the improvement in throughput that can be achieved by using multiple data channels. In Fig. 4.10(b), we can see that the improvement in collision rate using multi-channel based protocol. However up to 4 data channels, average waiting time has not that much improved as evident from Fig. 4.10(c). On the other hand, using multiple data channels means that the protocol needs more energy to run, which is depicted in Fig. 4.10(d). Therefore, it can be concluded that multiple data channel performs well for higher offered load consuming more energy with the increase in the number data channels.

4.9 Chapter Summary

The chapter presents a multiple channel data channel based MAC protocol by incorporating EM wave for communications. In addition to other system parameters, the impact of the number of multiple data channels on the performance of the protocol is thoroughly investigated. Use of multiple data channels can improve the performance of the proposed protocol to a great extent. However the attenuation of signals deals a great amount of damage in that improvement. The effect of attenuation on the proposed protocol is severe when the data packets gets affected. It is the reason for which EM-Acoustic based case has higher throughputs. Therefore it is crucial to check the issue of attenuation to properly get the advantages of multiple channels.

Chapter 5

Comparison and Feasibility Study

Comparison of a protocol with the existing counterparts is the most crucial part for any new protocol. Also the feasibility of a protocol depends on the physical environment. This chapter presents a comparison of the proposed protocols with others as well as conduct a feasibility study for determining the appropriate application area of the proposed EM based MAC protocols.

5.1 Comparison with other MAC Protocols

Performance of the proposed single data channel based MAC protocol is compared with that of CSMA, ALOHA-CS and ALOHA-AN [46] with respect to the throughput of the network as shown in Fig. 5.1. The comparison is done assuming protocol interference model for a network size of 3000m and using EM-Acoustic scheme. As we can see from the figure, proposed protocol outperforms the other protocols by a great extent for all types of loads. It also offers great performance for different types of data packet sizes. For higher loads, the proposed protocol shows consistent throughput like ALOHA-AN, whereas the performance of other protocols degrades.

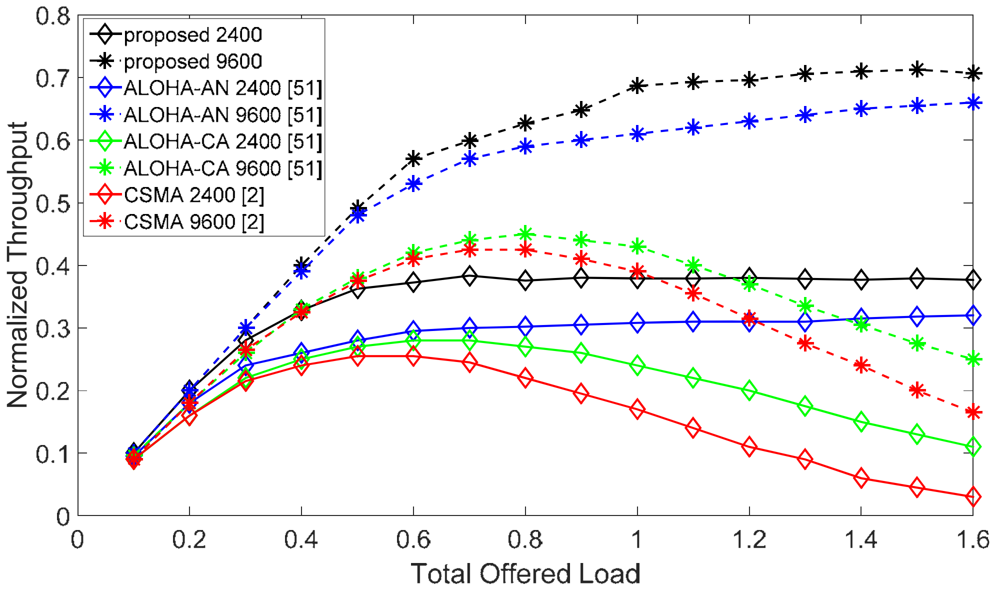

Fig. 5.1: Comparison of the proposed single data channel based MAC protocol with CSMA, ALOHA-CS and ALOHA-AN.

5.2 Comparison of Throughput

A comparison between the three types of channel cases possible for the proposed single data channel based MAC protocol in terms of throughput is depicted in Fig. 5.2. For this figure, EM carrier frequencies 1 kHz and 6 kHz are used for the control channel and the data channel respectively, whereas 10 kHz is used for the acoustic data channel. Control packet power and data packet size used for the simulations are 30 dBm and 2400bits respectively. The throughput performance of EM-EM, EM-Acoustic and Acoustic-Acoustic based cases are plotted. The ideal case is where no attenuation is involved. It can be clearly seen that for the ideal case, the EM-EM and EM-Acoustic based protocol outperforms the Acoustic-Acoustic based one. However with attenuation and for a network size of 100m, the EM-EM offers very poor performance, whereas the performance of the other two is still unaffected. This is because the attenuation of EM with high frequency is huge for 100m, whereas EM with low frequency used in control channel has comparatively lower attenuation.

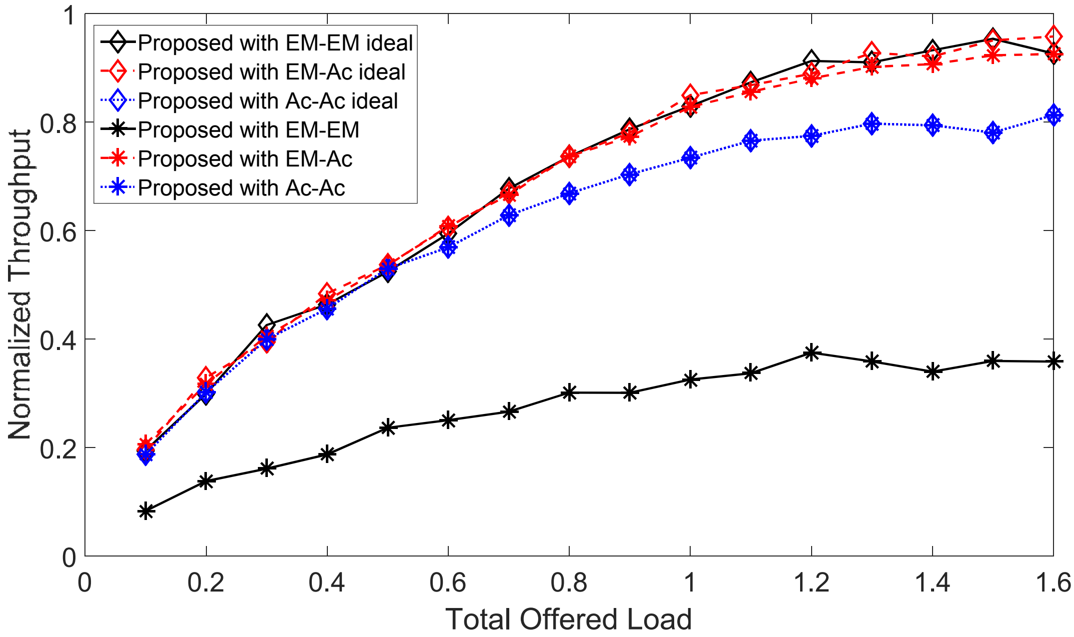

Fig. 5.2: Comparison of different cases of the proposed protocols (network size 100m).

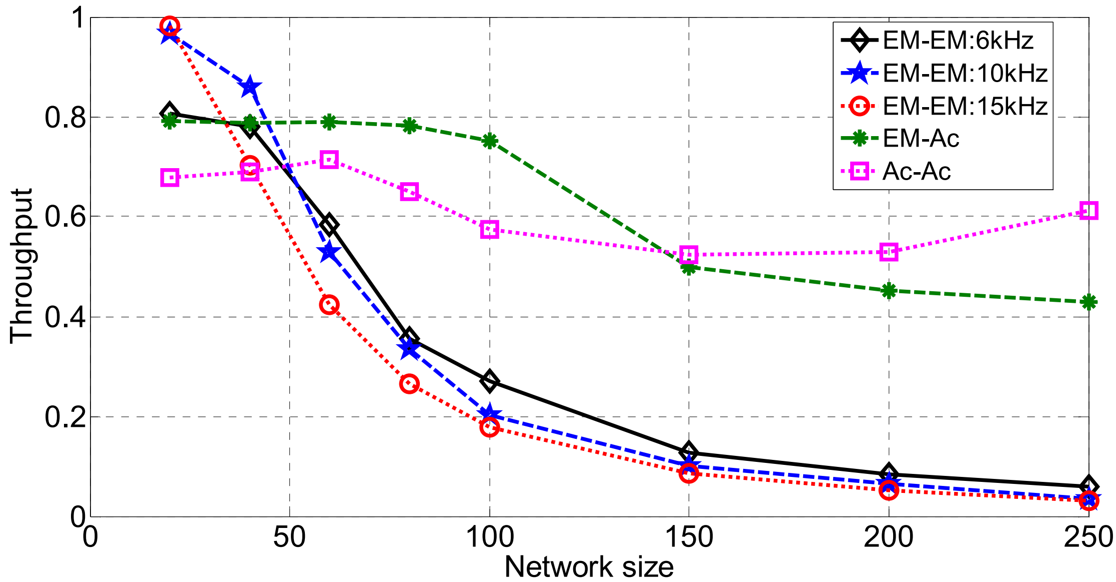

Fig. 5.3: Normalized throughput with different network size.

It has already been accepted that EM waves with high frequency attenuates rapidly in underwater. However with high frequency, higher data rates can be achieved. To check the feasibility of EM for different network size, simulation was done to create Fig. 5.3. For this figure, 1 kHz is used as the carrier for the EM control channel, whereas 10 kHz is used for the acoustic data channel. Control packet power and data packet size used for the simulations are 30 dBm and 2400bits respectively. From the figure, it is obvious that for small sized network, EM can give quite high normalized throughput and can beat EM-Acoustic or Acoustic-Acoustic counterparts. For network size below 40m, EM with 10 kHz frequency has the highest throughput. The jump in throughput at high frequencies is due to the higher bit rates.

5.3 Comparison of Waiting Time

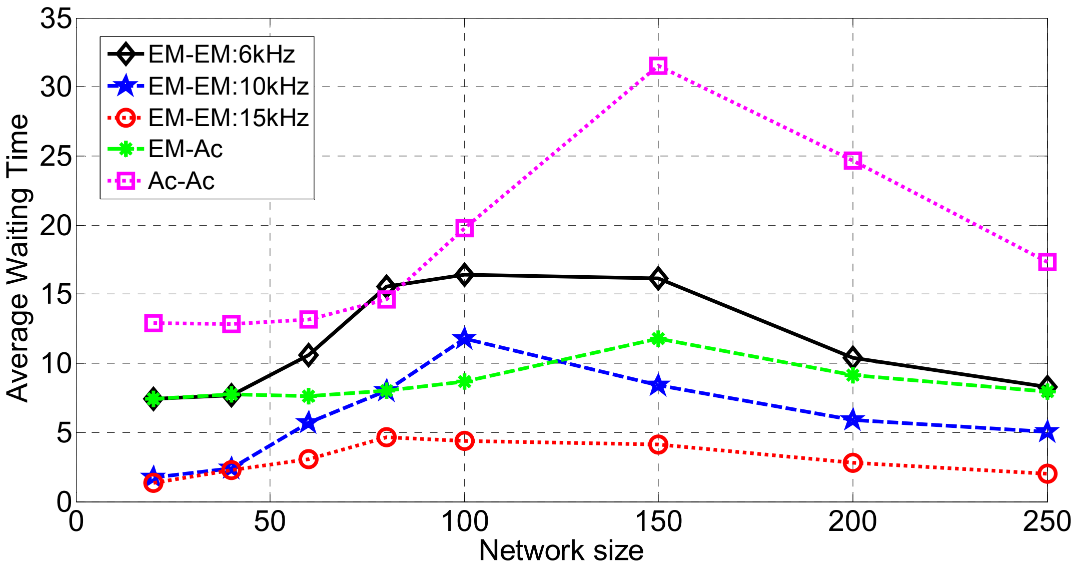

Fig. 5.4: Normalized throughput with different network size.

Waiting time performance of the proposed protocols for the cases presented in Fig. 5.3 is presented in Fig. 5.4. Simulation settings are same as those for Fig. 5.3. Similar to throughput, once again it can be identified that for smaller network size, EM-EM based MAC protocols outperform the others. Waiting time in EM-EM protocols gets even better with the increase of carrier frequency, (i.e., channel bandwidth). It can also be seen even if we make the control channel EM based and keep the data channel acoustic based, waiting time remains always much lower than that of completely acoustic based system demonstrating the advantage of EM wave based communications for UWSNs.

5.4 Comparison of Success Rate

Up to this point the most problematic parameter that hinders the performance of the proposed protocol is the attenuation of EM. To cope up and mitigate the effect, some steps can be taken. As shown is Fig. 5.5, the success rate of data packet can be boosted up by using multiple data channels. These multiple channels use the same total bandwidth of the single channel. However with parallel communications, the data packet collision rate subsides a lot. For instance, success rate of single channel with total load of 0.5 packets/sec can be boosted to 93% from 77% by using 4 parallel channels for a network size of 500m. This increment of success rate is clearly visible for other higher loads also.

Another thing worth trying is to send larger data packets instead of sending smaller ones which has been discussed in Chapter 3. As identified before, use of larger data packets decreases the probability of collision and increases the success rate.

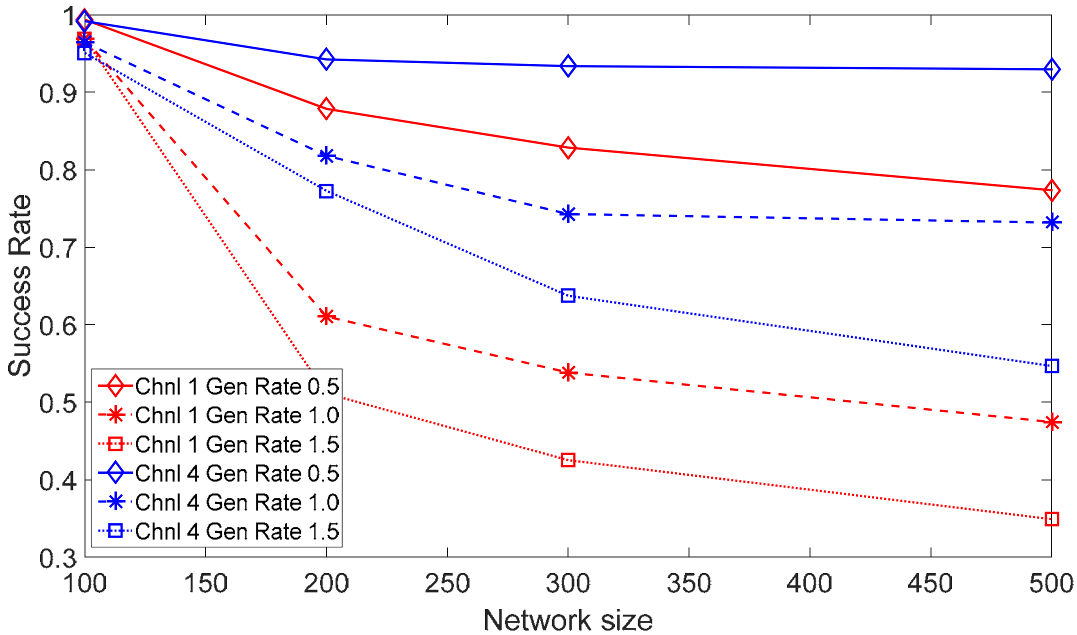

Fig. 5.5: Success rate of the protocol for different network size with single and multiple channels for the proposed EM-Acoustic MAC protocols.

Success rate of a MAC protocol is important not only as it increases the throughput, but also it decreases the wastage of energy. Previously (Fig. 5.5), success rate has been checked for the proposed EM-Acoustic based MAC protocols for different network size with multiple channels. Fig. 5.6 compares success rate for different combinations of channels with the network size. It is evident from Fig. 5.6 that including EM in both channels of the protocols results nearly 100% success rate up to a network size 40m and thereafter, success rate decreases drastically. The EM-Acoustic gives better success rate than EM-EM, while Acoustic-Acoustic has 100% success rate for all network sizes up to

250m. Thus, the performance of the proposed EM based MAC protocols is comparable with that of the only acoustic based protocol.

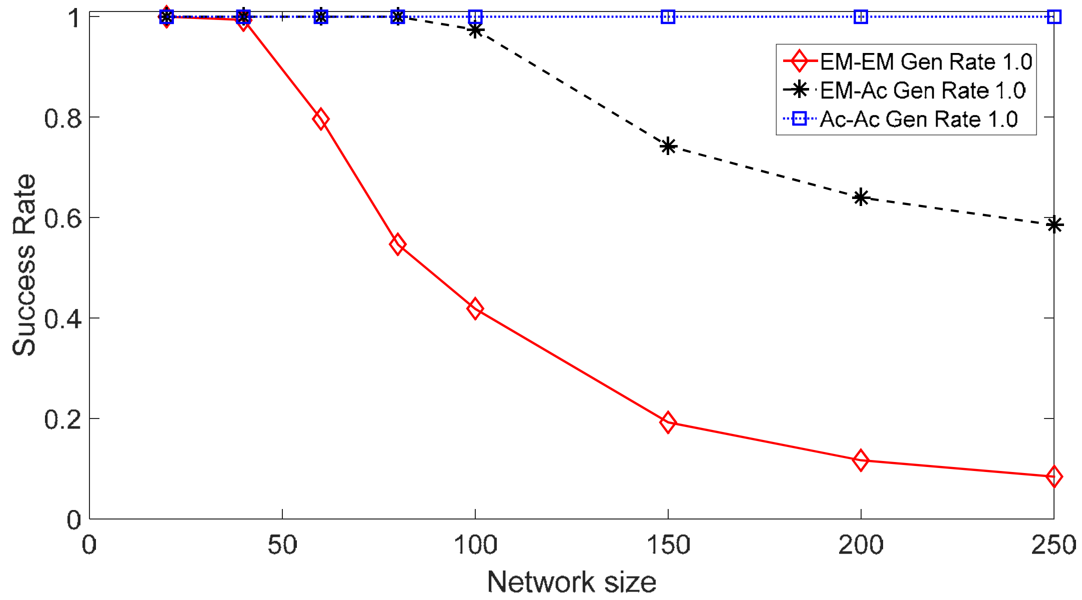

Fig. 5.6: Success rate of the proposed MAC protocols for different network size with different channel types.

5.5 Comparison of Energy

Energy consumption is one of the major performance metric for UWSNs. Here in Fig. 5.7, energy consumption curve is presented for transmission energy only. This is the energy needed to transmit the packets generated within 50 seconds with packet generation rate of 1 data packets/sec.

From the figure it is quite easy to notice that Acoustic-Acoustic, EM-Acoustic and EM-EM with 6 kHz data channel carrier consume almost same energy. Whereas higher EM carrier frequency with its high bit rate consumes a much lower energy. The reason behind is that with higher bit rate, the transmitter can transmit the data in lesser time than before. Therefore EM with carrier frequency 10 and 15 kHz needs a lot lower energy than the EM with 6kHz carrier frequency.

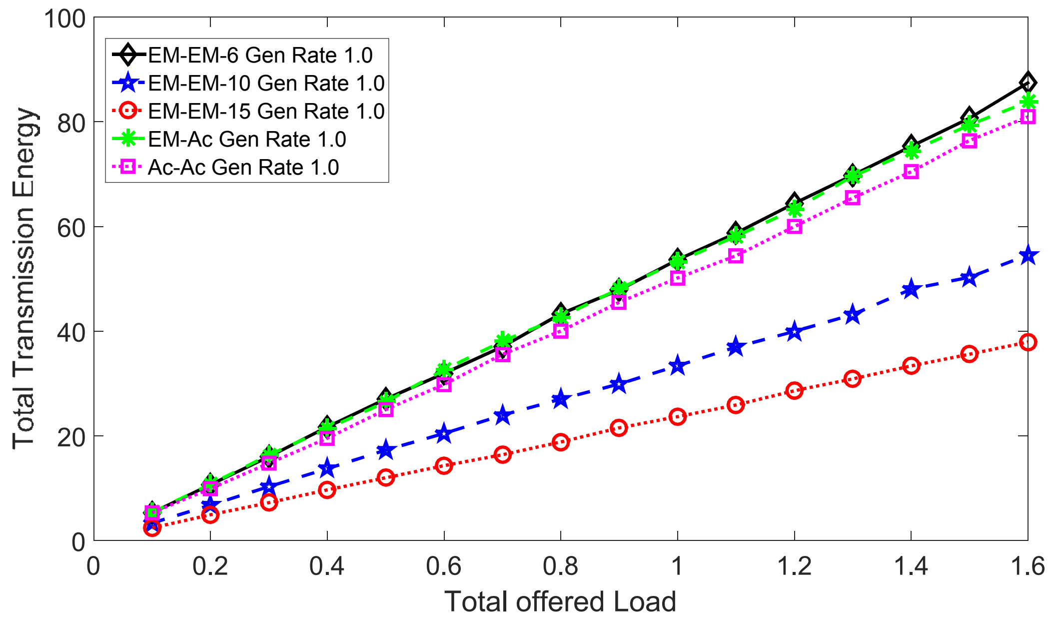

Fig. 5.7: Total energy requirement with the offered load for varying EM channel bandwidth.

5.6 Comparison of Network Coverage with Water Conductivity

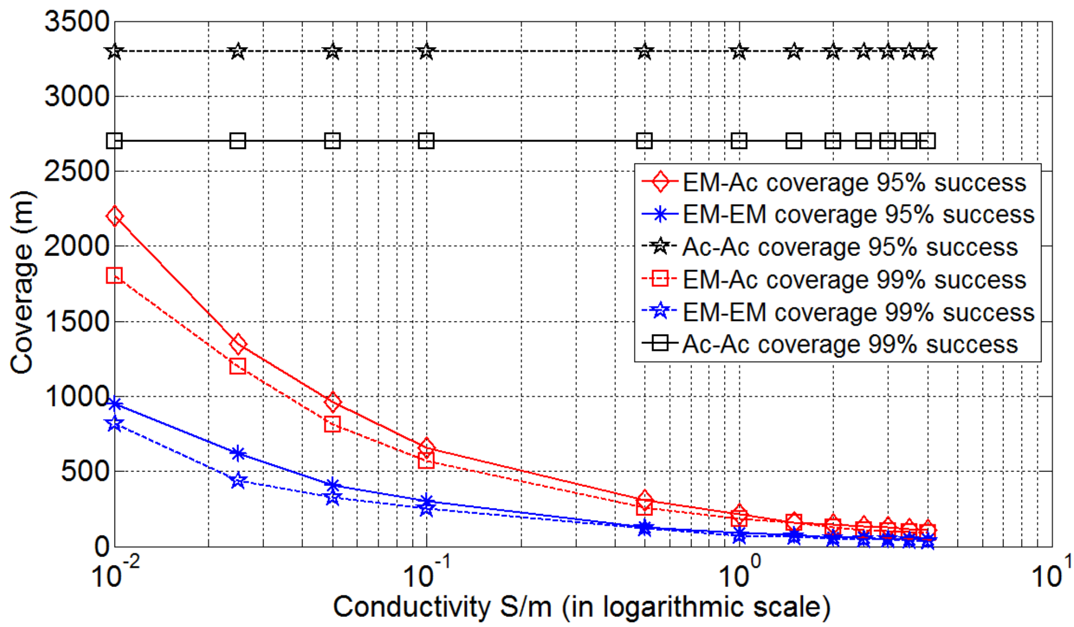

Fig. 5.8: Network coverage with respect to the conductivity of water.

With all the results and discussions presented so far, it can be said without any hesitation that the network coverage of any protocol has great significance in its performance. Especially for the case of EM-EM based protocol which suffers a lot with its high frequency data channel. Now if we look at Fig. 5.8, the network coverage is determined by the successful packet transmission of the proposed protocol for 95% and 99% success rate. The figure tells us that water with low conductivity (fresh water with very low salinity) can provide huge coverage for the proposed EM wave based MAC protocols. In fresh water (conductivity 0.01) with the EM-EM topology, coverage can be achieved as far as 1000 meter, whereas for EM-Acoustic case the coverage is around 2200 meter with 95% success rate. On the other hand the coverage of acoustic wave does not depend much on salinity and it shows a consistent coverage of 3300 meter with 95% success rate.

5.7 Chapter Summary

This chapter has compared the proposed MAC protocols with other works and presented an overview about the feasibility of the proposed protocols. Proposed protocols have very high throughput outperforming all the compared protocols when the network is assumed with protocol interference model. With the consideration of channel attenuation, proposed MAC protocol with its EM-EM based channels can be used for small networks, while EM-Acoustic based one can perform well for moderate size networks. The EM-EM based protocol can beat its EM-Acoustic and Acoustic-Acoustic counterparts by achieving higher throughput, lower waiting time, lower energy consumption and nearly 100% success rate for network sizes below 40 meters. On the other hand the proposed protocol with EM-EM and EM-Acoustic can be used in freshwater environment with a broader network area.

Chapter 6

Conclusions and Future Works

This chapter summarizes the findings of this research. Possible extensions of this research works are also outlined.

6.1 Conclusions

This thesis have proposed MAC protocols for single-hop mesh topology based UWSNs employing EM wave for communications. Proposed MAC protocols use a TDMA based control channel for signaling purpose and can have multiple data channels for data packet transmission. The control channel always use EM wave as its carrier, while the data channels can be of EM or acoustic based. For performance evaluation of the proposed protocols, both protocol interference model and physical interference model have been analyzed.

Chapter 3 discusses about the proposed protocol with single data channel. It was observed that the proposed protocols with single data channel has high throughput, which is very susceptible to propagation delay, that means the network size. However use of larger data packets by combining smaller data packets can lower the susceptibility. The time frame duration of the control channel also has significant impact on the performance of the protocols. Smaller time frames tend to give higher throughput, however time frame duration comparable to the data packet duration can affect the throughput greatly.

When physical interference model has been considered for EM-Acoustic based single data channel protocol, the effect of network size and packet size were observed. For larger packets, almost always the throughput has increased, while the collision rate and average waiting time have decreased. However with the increment of network size the control packets have faced the signal outage issue. When the network size changed from 300m to 500m, the protocol has lost its originality due to the attenuation and become alike a simple carrier sensing protocol. Thus a decrease of average waiting time has been seen for network size of 300m and 500m. On the other hand collision rate always have increased with the increment of network size and increasing the total transmission energy of the nodes had not have much impact on the performance of the protocol.

Afterwards in Chapter 3, EM-EM based single channel protocol has been analyzed. The terrible effect of path loss has been found prominent in that scenario. The simulation has been done for network sizes up to 120 meters only, after that the throughput decreases rapidly with the increment of network size and increasing the data packet size have not seem to work that much. Also the packet missing rate due to signal outage is huge and same for both types of packet sizes (2400 bits and 9600 bits). The packet missing rate while increasing with the network size has gone above 50% for a network size of 90 meters only.

In Chapter 4, MAC protocol for multiple data channels has been proposed. Using multiple channels, the effect of propagation delay has been diminished to some extent. Also by using extra total BW, the throughput can be increased as a whole. However the overall channel utilization has reduced with the increment of total BW. It has also been observed that the throughput of the proposed protocol increases with the increment of data channels for EM-Acoustic based channels. Also the average waiting time and collision rate have been found to decrease with the increment of channel number. On the other hand, EM-EM based topology has not shown noticeable improvement in throughput with the increment of data channels due to high attenuation.

The feasibility of the proposed MAC protocol has been investigated by comparing the proposed protocols with some other MAC protocols as presented in Chapter 5. It has been found that the proposed MAC protocol outperforms CSMA, ALOHA-CA and ALOHA-AN for different offered loads. It has also been observed that the protocol has consistent throughput for heavy loads. The proposed protocol has three variants with respect to the type of channels used - EM-EM, EM-Acoustic and Acoustic-Acoustic. When comparing along them, it has been observed that EM-EM works quite well for short range communication, while EM-Ac is suitable for moderate size networks and for long range communication, acoustic based protocol prevails. The success rates of these three schemes have been simulated for different network sizes and it has been observed that EM-EM has the worst performance with increased network size, EM-Acoustic has relatively better, and Acoustic-Acoustic is the best. While using the EM-EM, it has been identified that it uses low energy than its acoustic counterpart for higher carrier frequency. Therefore using EM wave for short range communications with high carrier frequency can be beneficial. Using multiple data channels can increase the probability of successful data packet reception and thus can lead to better performance. Our simulations have also found that when using the protocol with EM channels, the network coverage increase a great deal with the decrease of salinity (thus conductivity) of water.

6.2 Future Works

From the current stage of the research work presented in this thesis, it can be extended in several directions. Some of the potential open issues are outlined below.

- **Multi-Hop UWSNs:** The proposed MAC protocols are developed assuming single hop communications. However, for underwater applications, multi-hop communication is of extreme importance. This is even more critical for EM communication based UWSNs as the communication range for this technology in deep water is much lower than that of acoustic systems. For covering a larger area using EM based UWSNs, higher number of nodes are to be deployed implying the importance of multi-hop communications. Therefore, extending the proposed MAC protocols for multi-hop scenarios can be considered a potential research opening.

- **Current and Mobility Impact**: Unlike the terrestrial sensor networks, UWSNs suffers from the inherent slow to medium mobility due to water current and the movement of other marine lives. The research in this thesis has not considered the mobility effect in designing the protocols. Therefore, in future research, the proposed MAC protocols can be modified to make them robust to overcome the impact of both water current dynamics and mobility due to other reasons. Mobility models of the nodes in underwater can also be integrated in such protocols.

- **Duty Cycling of MAC Protocol**: In the proposed MAC protocols, no duty cycling mechanism to sleep and wake-up the nodes has been used. In UWSNs, recharging the node batteries or replacing the batteries is a difficult task as they are usually submerged in water. Therefore, duty cycling is of great importance for saving energy and increasing the life time of nodes. Future research can explore this area and design some sleep-wake scheduling for the nodes to make the networks energy efficient.

- **Compensation Techniques**: In this research, guard time is used as a mechanism for reducing the number of collisions among the data packets from various nodes. On the other hand, under physical interference model, collision can happen as the confirmation control packet might not reach all the nodes due to signal outage. Thus, future research can explore to develop novel mechanisms, for example, adaptive power control, capture effect, etc., for minimizing collisions.

- **High Packet-loss Rate Issue:** As the underwater channel is less reliable than terrestrial networks for various additional phenomena, packet-loss rate is higher in UWSNs. Therefore some measures should be taken for handling such situations leading to reliable operations of the proposed MAC protocols. For instance, dense deployment of nodes, parallel transmission of the same data packet, etc. can be focused in future works. For facilitating these features, proposed MAC protocols have to be improved.

- **Synchronization:** Although TDMA based MAC protocol reduces collisions resulting in more energy efficient networks, synchronization can be a critical issue. This research assumed that all the nodes are synchronized to each other. Future research can extend the proposed TDMA based MAC protocols such that they become less sensitive to loss of synchronization.

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