Full-duplex Medium Access Control Protocol for Linear Underwater Chain Networks

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Abstract

This thesis investigates the performance improvements that can be realized with the application of full-duplex communication in Medium Access Control (MAC) schemes for linear underwater chain networks used for subsea pipeline monitoring. The study focuses specifically on the development of full-duplex MAC schemes in order to leverage full-duplex communication to significantly improve network performance in terms of throughput, latency, and monitoring rate while maintaining an acceptable Quality of service (QoS) for a reliable and efficient subsea pipeline monitoring system. The performance of the MAC schemes proposed in this thesis is evaluated using a BELLHOP-based simulated underwater channel model under best-case network scenarios (short pipelines deployed on a small scale, 2 to 20 km pipelines) and worst-case network scenarios (long pipelines large scale cases, 200 to 1000 km pipelines).

The thesis presents a new strategy for applying the LTDA-MAC (Linear Transmit Delay Allocation) MAC protocol to the full-duplex multi-hop underwater chain network scenarios by enabling in-band simultaneous transmissions in order to accomplish effective packet scheduling and thereby improve the network performance (higher throughput and lower latency). Furthermore, it proposes a new full-duplex linear transmit delay allocation MAC (FD-LTDA-MAC) protocol to further improve performance by redeveloping the traditional LTDA-MAC protocol to fully exploit full-duplex capabilities and to maximize spectrum reuse in order to achieve a higher monitoring rate, particularly for longer pipelines, by generating a more efficient packet scheduling in full-duplex underwater pipeline monitoring scenarios.

Contents

List of Figures

List of Tables

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Declaration

I declare that this thesis is a presentation of original work and I am the sole author. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References. The research presented in this thesis features in the author's publications listed below.

Journal Article

A. Ahmed, P. D. Mitchell, Y. Zakharov, and N. Morozs. "FD-LTDA-MAC: Full-Duplex Unsynchronised Scheduling in Linear Underwater Acoustic Chain Networks." *Applied Sciences* 11, no. 22 (2021): 10967.

Conference Paper

A. Ahmed, P. D. Mitchell, Y. Zakharov, and N. Morozs, "Performance of Linear TDA-MAC in Full-Duplex Underwater Acoustic Chain Networks," in *Proceedings of 7th IEEE World Forum on the Internet of Things*, (New Orleans, Louisiana, USA), June 14-July 31 June 14-July 31, 2021.

Chapter 1. Introduction

1.1. Overview

This thesis investigates Medium Access Control (MAC) protocols for full-duplex underwater acoustic networks (UANs). Numerous underwater activities have been made possible by recent advancements in acoustic communication and sensor technologies. Our capability to collect information from remote underwater locations is critical to our knowledge and understanding of the underwater environment. This opens up new possibilities in a variety of applications, including environmental monitoring, oceanographic data collection, marine archaeology, search and rescue missions, underwater oil and gas exploration, pipeline and infrastructure monitoring, marine life monitoring and control, border control, fish farming, freshwater reservoir management, and tsunami and seaquake early warning systems [11–13].

Establishing communication underwater effectively largely depends on acoustic communications as acoustics is critical for both long and short range scenarios. However, underwater acoustic communications are limited by underwater channel characteristics such as: very long propagation delay caused by low speed of acoustic signals (speed of sound is approximately 1500 m/s) [11, 13] low data rate (between 5-20 kb/s) due to limited channel bandwidth, high error rates, time-variability and high energy consumption (typical consumption between 50 to 100 W) [14, 15] which negatively impact the system's quality of service (QoS) and energy efficiency.

MAC protocol is important for a successful packet delivery in a network. The main aim is controlling and regulating access in order to provide effective utilisation and good quality of service. Success also depends a lot on the logical link layer. The current trends in the approaches to the design of MAC protocols for UANs are based on half-duplex communications. These protocols are based on Orthogonal access schemes such as Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA) and Space Division Multiple Access (SDMA) and involve the division of resources (time, frequency, code and space) into sub-resources to enable collision-free channel access for the network nodes [16]. Contention-free schemes have good potential for UANs, because of the likelihood of low collision.

Alternative approaches to sharing a single channel among a group of users are either scheduling or contention based. Contention based schemes utilise carrier sensing, handshaking or random access techniques [16] to access a shared channel. In the same vain, long propagation delays also create some uncertainty around channel idle/busy status prediction, which reduces the effectiveness of carrier sense protocols in UANs and this is amplified in multi-hop UANs. The persistent problems of low available bandwidth and long propagation delays have limited the design of MAC protocols for UANs. These have made the terrestrial radio networks approaches either unsuitable or provide poor network performance.

Recent breakthroughs in self-interference cancellation in full-duplex communication (a phenomena where network nodes can simultaneously transmit and receive data packets within the same frequency bandwidth) have opened up new possibilities for acoustic communication system throughput improvement and spectral usage. Some MAC layer issues may be resolved in this way, since it allows a node to concurrently detect the channel and receive a packet, which could lead to increased throughput, lower latency, and better overall network performance. The potential network improvement with full-duplex has motivated the development of a new MAC protocol for UANs. This thesis explores the network performance improvement that can be achieved with the application of full-duplex communication in MAC schemes for linear underwater acoustic chain networks. It focuses on the design, development and analysis of MAC protocols for full-duplex based linear underwater chain networks for subsea pipeline monitoring applications.

1.2. Hypothesis

The study presented in this thesis is guided by the hypothesis: *"Can new approaches to Medium Access Control exploit full-duplex communication to transform network performance in terms of throughput and delay for an underwater acoustic chain network?"* This hypothesis is tested by evaluation of the full-duplex MAC protocols developed with best case network scenarios (short pipelines) and worst case network scenarios (long pipelines). Pipeline monitoring is considered in this thesis, because the significance of underwater oil and gas pipeline monitoring cannot be overstated. Given that the majority of these pipelines transport petroleum products to very long distances, early detection of leaks and corrosion is vital to avoiding financial loss and, more significantly, preventing water body pollution that may be caused by oil spillage.

1.3. Scope

The aim of this thesis is to investigate the network performance improvement of full-duplex communication in underwater acoustic multi-hop communication in terms of delay reduction and improving monitoring efficiency. To achieve this, the following objectives are carried out: a thorough requirement study for the design of full-duplex based MAC protocol for UANs through an extensive literature review. The second objective is to design and develop a propagation and channel models which provide realisations of the underwater channel for evaluation of the MAC schedules. Thirdly, to analyse the LTDA-MAC's performance across various full-duplex underwater acoustic linear chain network scenarios. Lastly, to develop and evaluate full-duplex based MAC protocol that exploits the full capability of full-duplex communication for UANs. This thesis also examines the benefits of relay nodes in a multi-hop network topology by taking into account chain networks. The results presented throughout this thesis are based on the channel, propagation and network models described in Chapter 3.

1.4. Thesis Outline

Chapter 2 firstly presents the overview of the fundamental concept of underwater acoustic communication paradigms with respect to applications and communication architectures; and then discusses the underwater acoustic channel highlighting impending challenges for designing MAC protocols for UANs. Furthermore, it presents an overview of full-duplex communication, highlighting different architectures, challenges and advantages associated with its application in relay chain underwater networks. Lastly, a critical review of the state-of-the-art MAC protocols for UANs highlights the need for network performance improvement in UANs is presented.

Chapter 3 discusses the experimental methodology for the development of propagation models used for the evaluation of the MAC protocol in underwater acoustic chain networks. It describes the methods and tools used to create underwater channel, and the network and simulation models used in evaluating the MAC algorithms in the thesis. Also, the traffic model, performance evaluation metrics are described in this chapter.

Chapter 4 investigates the performance of the LTDA-MAC (Linear Transmit Delay Allocation MAC) protocol in different full-duplex underwater chain network scenarios. It provides confidence on the viability of full-duplex to improve channel utilisation by the application of an established prior work in full-duplex scenarios. The network performance against the half-duplex counterparts is lastly presented in this chapter.

Chapter 5 presents the development of the FD-LTDA-MAC protocol which builds on earlier work to fully exploit the full-duplex capability in a linear full-duplex underwater chain network. This chapter presents the testing and evaluation of FD-LTDA-MAC on different underwater pipeline monitoring scenarios (best to worst cases) against LTDA-MAC with half-duplex and full-duplex nodes.

In conclusion, the findings drawn from the thesis, as well as a summary of the original contributions and recommendations for further research, are offered in Chapter 6.

Chapter 2. Literature Review

2.1. Introduction

There has been considerable research effort devoted to developing more reliable, efficient, and effective underwater operations using Underwater Acoustic Sensor Network (UASN) systems in order to explore the marine environment for economic and social purposes. This chapter provides an overview/review of the technologies involved, focusing on recent advancements in MAC protocol design for UASN and full-duplex communication from the following perspectives: fundamental concepts and background to Underwater Acoustic Networks (UANs) and full-duplex communication, application areas, and acoustic channel characteristics as they relate to data packet communication underwater. Similarly, MAC protocols for UANs are discussed, as well as their performance.

According to studies on the design of MAC protocols for UASNs, MAC protocols for UANs face numerous challenges that necessitate the use of alternative and more suitable solutions to ensure good Quality of Service (QoS) and energy efficiency. Due to the fact that the majority of radio frequency (RF) based MAC protocols do not account for long propagation delays, low data rates, and high power consumption [14], they cannot be directly applied to UANs. Additionally, while a few full-duplex MAC protocols have been developed for terrestrial WSN systems, additional research is needed to extend these protocols for underwater acoustic communication in order to fully exploit in-band full-duplex communication underwater.

2.2. Underwater Acoustic Communication Paradigms

The type of underwater system of interest system is made up of many sensors deployed underwater with capability to communicate via acoustic links. Converged underwater operations based on UASN paradigm is depicted in Figure 2.1.

The underwater system of interest is composed of numerous sensors that are deployed underwater and are capable of communicating via acoustic links. Figure 2.1 illustrates some underwater operations based on the UASN paradigm.

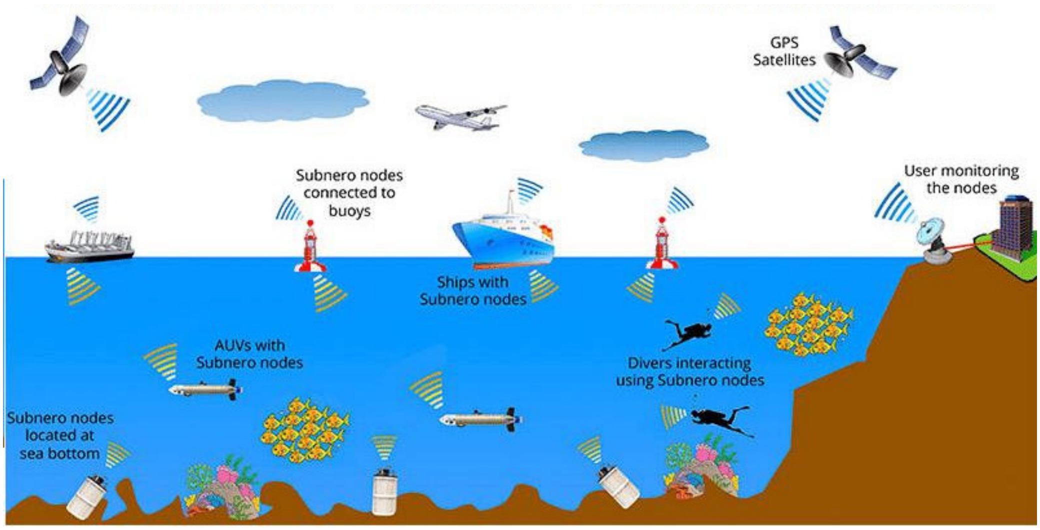


Figure 2.1: Some UASN based underwater operations (from [1]).

2.2.1. Justification for underwater operations

Conventional underwater operations have largely depended on cabled big machines such as Remotely Operated Vehicles (ROVs). Also, traditional monitoring approaches involve deploying underwater sensors to the ocean-bottom to record data of interests and the sensors are recovered at a later time to analyse the recorded data [14]. These traditional approaches have the following limitations.

Underwater operations in the past have relied heavily on cabled large machines, such as Remotely Operated Vehicles (ROVs) as shown in Figure 2.2.

Additionally, traditional monitoring approaches involve the deployment of underwater sensors to the ocean bottom to collect data of interest and then recovering the sensors to analyse the collected data [14]. These established methods have the following drawbacks.

i **No real-time monitoring:** Because the deployed instruments must be recovered before the data can be retrieved, there is no real-time monitoring. This may require several months to accomplish [14]. This impairs the reliability and effectiveness of underwater real-time operations.

ii **No online reconfiguration of the system:** Additionally, once the systems are deployed, configuration commands cannot be sent from onshore stations to the

Figure 2.2: ROV in Underwater operation (from [2]).

systems, such as ROVs. As a result, system tuning and reconfiguration become more difficult in the event of certain events requiring changes.

iii **Not impervious to failure:** Similarly, system failure is a frequent occurrence in underwater operations due to the environment's nature. Given the lack of onshore station-to-target system interactions with the traditional approaches, it will be impossible to detect instrument failure until they are recovered. As a result, this can have an effect on the outcome of the entire underwater operation [14].

iv **Cost:** Conventional underwater operations are prohibitively expensive and time-consuming.

v **Longer result period:** Moreover, conventional underwater operations may take longer to accomplish due to the time required for deployment, data gathering, and recovery. For instance, seismic imaging operation for oil exploration may take many years to complete.

On the other hand, UASN systems deployed in the sea, ocean, or shallow waters may be more efficient, and cost effective, as they support onshore-to-system interaction and configuration in real time, and are well suited for large-scale deployment.

2.2.2. Applications of UAC

UASNs have potential for more effective, reliable and smart underwater operations than the traditional methods. They can be applied to various fields of endeavour in underwater operations. Some important applications are:

i **Water Quality monitoring:** UASNs can be used to monitor water quality in a variety of applications, including ocean or canal monitoring and freshwater reservoir management systems, by measuring parameters such as dissolved oxygen, pH value, and electrical conductivity (EC) [6, 17, 18].

ii **Marine habitat monitoring:** Effective monitoring of the marine environment for a variety of species of underwater living organisms can be accomplished through the use of UASN systems for studying ecosystems and predicting ecological change [19, 20].

iii **Fish Farming:** Additionally, UASNs can be used to monitor fish farm parameters such as pH, temperature, and ammonium to ensure that precise fish farm conditions are maintained for optimal production [21, 22].

iv **Natural resources exploration:**UASNs can also be used to explore underwater natural resources such as oil and gas, manganese crust detection, and so forth. It is a more cost-effective alternative solution for offshore oil and gas exploration in the modern era, given the dwindling global crude oil prices [23, 24].

v **Underwater Pipeline Monitoring:** Due to the widespread deployment of underwater pipelines across continents for the transportation of crude oil and other essential products, UASNs are the only feasible solution for monitoring such a large scale of infrastructure. With the possibility of a real-time data gathering, underwater crude oil-related disasters such as an oil spill can be detected early enough to prevent significant water pollution.

vi **Flood disaster monitoring:**UASNs can be deployed underwater to measure and calculate aquatic parameters that can be used to determine flood warnings [25–27].

vii **Monitoring of the ocean's seismic activity:** Similarly, by deploying UASN systems, ocean conditions that can result in Volcano, Earthquake, and Tsunami can be monitored more precisely and in real time in order to provide early warning in the event of such occurrences [4,28]. Additionally, they can be used to monitor ocean climate.

viii **Military Applications:** Naval network-centric warfare, mine reconnaissance, submarine localization and surveillance, and border control can all be accomplished more effectively through the use of UASN systems, [29,30].

ix **Sports and Assisted Navigation:** UASN systems are capable of performing navigational tasks for ships, vessels, and boats. This can also be extended to swimming sports in order to improve swimmers' performance monitoring [31,32].

A surveillance application of a UASN system is shown in Figure 2.3.

As a result of the preceding discussions, it is critical to emphasize that UASN systems provide a superior alternative and a broader range of applications for underwater operations than conventional approaches.

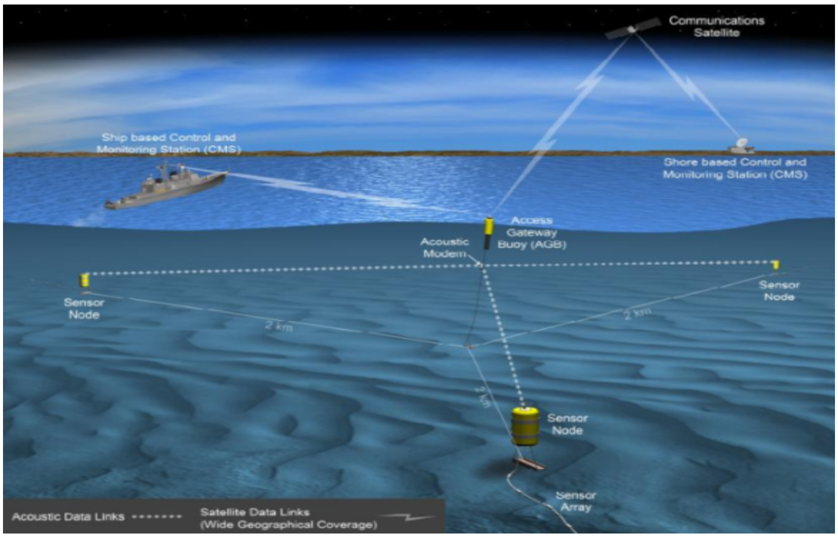
2.2.3. Challenges of UAC

Despite the UASN systems' promising applications in a variety of underwater operations, there are some design challenges in this domain. Notable challenges are:

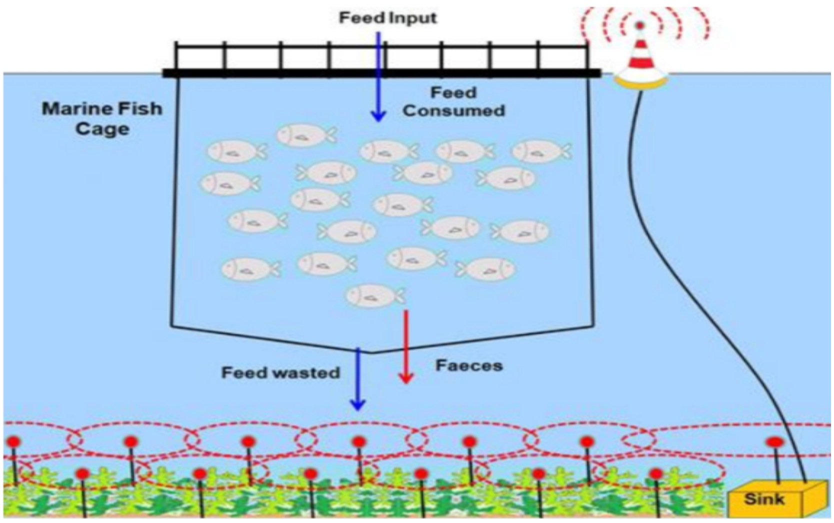
i **Cost of deployment:** The cost of deploying UASNs in terms of expenses is higher than that of terrestrial WSNs. This is due to the higher cost of acoustic modems in comparison to the smaller motes used in terrestrial WSNs. Additional factors contributing to the high cost of deployment of UASNs are the protective shields used to protect underwater hardware from the harsh underwater environment and the high pressure housing [5,16].

ii **Deployment topology:** Due to the high cost of deployment, UASN are deployed sparingly in comparison to terrestrial WSN, which are typically densely deployed. Sparse deployment imposes additional challenges on protocol designers [5, 16], as explained in Section 2.5.5.1 (on Challenges for designing MAC protocol in UASNs).

iii **Power consumption:** UASN consumes more energy than the terrestrial WSNs,



(a)



(b)

Figure 2.3: UASN applications: (a) Surveillance network system (b) Fish farming scenario (directly copied from [3] and [4] respectively.)

because, the acoustic modems consume high energy due to more complex signal processing and greater communication distances as a result of sparse deployment [5, 16]. However, battery power cannot be recharged and solar energy cannot be exploited in underwater environment. Thus, high battery capacity and/or energy efficient network protocols are essential.

iv **Inbuilt Data memory:** UASNs require more data memory than terrestrial WSNs, owing to the requirement for data caching in the irregular underwater channel [5, 16].

v **Hardware failure:** Underwater sensors are prone to frequent failures because of fouling and corrosion.

vi **Lack of standardization:** Because less research has been conducted on UASNs, there are currently very few comprehensive standard models.

vii **Difficult to experiment:** Experimentation with UASNs is also challenging due to expensive and abrasive nature of the underwater environment, such as the sea or ocean.

2.2.4. Architecture of UANs and topology

UASNs are composed of a variety of components (sensor nodes and vehicles) that are deployed underwater to perform useful tasks such as data collection, monitoring, and so on, as well as military tasks. Due to the difficulties associated with underwater channels, these devices differ from those used in terrestrial WSNs. The following subsections summarize the major components:

2.2.4.1 Underwater Sensors

These consist of sensor tips and acoustic modems. The sensor tip measures underwater physical quantities (data) of interest, such as salinity, temperature, pressure, and flow rate, while the acoustic modem transmits the sensed data between sensor nodes and to the surface station [5]. Underwater sensor and acoustic modem diagrams are shown in Figure 2.4.

As noted in [33], most modern underwater acoustic modems are non-reconfigurable,

(a) (b)

Figure 2.4: Examples of underwater sensor nodes: (a) LinkQuest underwater sensor nodes and (b) EvoLogics Acoustic modem (from [5]).

owing to hard-coded algorithms in their firmware, including those for the physical layer and bit stream formats. The protocols for communication between modems are also typically not modifiable by the user, which is another disadvantage. The issues listed above are some of the difficulties that real world testing faces, and they serve as compelling arguments in favour of simulation.

2.2.4.2 Unmanned or Autonomous Underwater Vehicles (UUVs, AUVs)

Unlike remotely operated vehicles (ROVs), they are mobile nodes that are outfitted with numerous sensors and can move autonomously, eliminating the need for tethers or cables to transmit remote control signals. In comparison to conventional underwater sensor nodes, they have greater power and can smartly and more effectively replicate the functions of miniature submarines. They communicate with the shore directly through a surface station and satellites, according to [33].

2.2.4.3 Underwater Sink

Underwater sinks are in charge of relaying data acquired by sensor nodes from the bottom of the ocean to the surface of the water column. According to [5, 34], they are equipped with both horizontal communication capabilities for delivering configuration commands and data to and from sensor nodes, and vertical communication capabilities for relaying collected data to the surface.

2.2.4.4 Surface Buoy/Station

In comparison to the other components already covered, this one is more complex because it is equipped with an acoustic transceiver, a radio frequency transceiver, and satellite transmitters for communication between underwater sinks and over the air [34, 35].

2.2.4.5 Surface Sinks

Surface sinks are often housed on ships, and they can be either stationary or moveable in nature. They act as a gateway between various surface stations and the underwater network, and they transfer data packets with other surface components via radio or satellite links [33].

2.2.4.6 Onshore Sinks

In contrast to surface sinks, onshore sinks are placed on the shore and have the capability of communicating with surface sinks and other independent networks, as [33] points out.

2.2.4.7 Satellites

Satellites are critical components that enable data packet transmission between ships operating on the sea surface and the shore. They also give critical information for the network, such as node positioning [33].

The schematic in Figure 2.5 illustrates the interactions between the components of the UASN.

2.2.5. Communication Architecture of UASN

The network architectures of UASN systems differ from one another. The nature of the application determines how this classification is applied. The following subsections provide an overview of the various communication architectures that have been implemented for UASN systems.

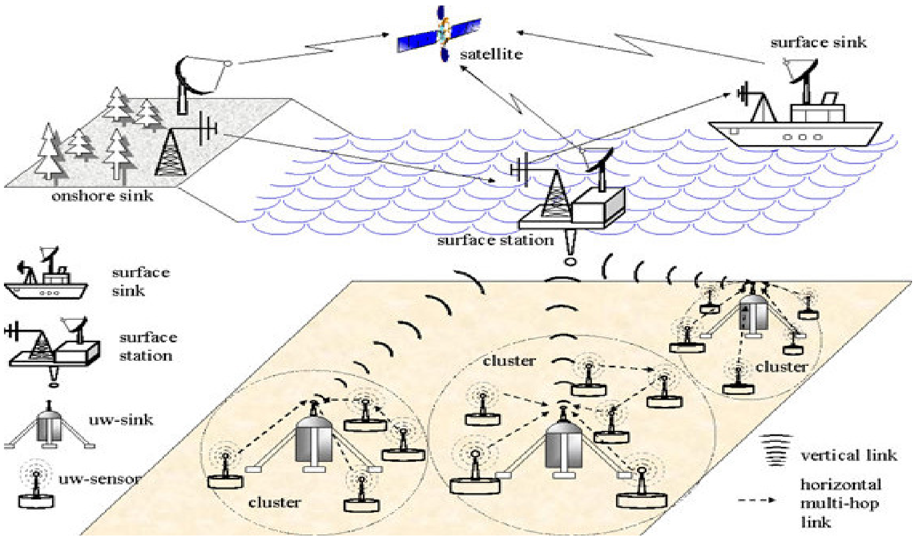


Figure 2.5: UASN Components and interactions (from [5]).

2.2.5.1 One-Dimensional (1-D)-UASN Architecture

This is the type of UASN communication architecture in which each sensor node (floating buoy or autonomous underwater vehicle (AUV)) functions as a self-contained network capable of sensing, processing, and transmitting data to the remote station via a single-hop star network topology. In 1-D UASNs, nodes communicate by acoustic, radio, and/or optical means [5, 36].

2.2.5.2 Two-Dimensional (2-D)-UASN Architecture

UASNs in 2-D are made up of anchored underwater sensor nodes, underwater sinks, and surface stations that are arranged in clusters with the anchored sensor nodes serving as the cluster heads. The anchor node communicates with other cluster member nodes on a horizontal level and with the surface buoyant nodes on a vertical level (surface stations). The cluster nodes in this sort of network are fixed, and data transmission is accomplished through either direct links or multi-hop pathways to the UW-Sinks. Depending on the nature of the application scenario stated in [37], other topologies such as star, mesh, or ring could be used. Multi-hop networks, on the other hand, are preferred over direct lines, which have lower energy efficiency and lower network throughput, but need the use of complicated routing functionality. Consequently, signalling cost should be minimized when using a multi-hop connection for a 2-D architectural configuration.

2.2.5.3 Three-Dimensional (3-D)-UASN Architecture

A 3-D UASN is a form of architecture that describes the groups of sensors that are deployed underwater as multi-level anchored clusters of nodes. This employs three different communication structures that involve inter-cluster communication between depth separated nodes (horizontal communication), intra-cluster communication between the anchor nodes of different clusters (diagonal communication) and the communication between the anchor to buoyant node or surface station (vertical communication). It is also multi-hop and may use star, ring, and mesh network topologies with acoustic, optical, and RF links for data packet communications. [6]. This architecture is commonly used for 3D ocean sampling. The challenges associated with this architecture are sensing and communication coverage [16].

2.2.5.4 Four-Dimensional (4-D)-UASN Architecture

A hybrid architecture consisting of fixed UASNs, mobile UASNs, and 3D-UASNs is referred to as a 4-D UASN architecture. The mobile network communicates between anchor nodes and remote stations through Remotely Operated Vehicles (ROVs). In this case, sensor nodes can communicate directly with ROVs, and the communication links used are determined by the distance between the sensor nodes, the ROVs, and the remote station. For very close nodes, radio frequency links are employed, whereas for longer distances, acoustic links are used for data packet transfers [38]. The various architectures are illustrated in Figure 2.6.

2.2.6. UAN stack architecture

UASNs employ a comparable Underwater Acoustic Network (UAN) stack design to terrestrial WSN systems, which consists of application, transport, network, data link, and physical layers. The following sections provide an overview of these network layers.

2.2.6.1 Physical Layer

The physical (PHY) layer is in charge of signal modulation and demodulation, channel equalization, and data encryption. It establishes the specifications for the transmis-

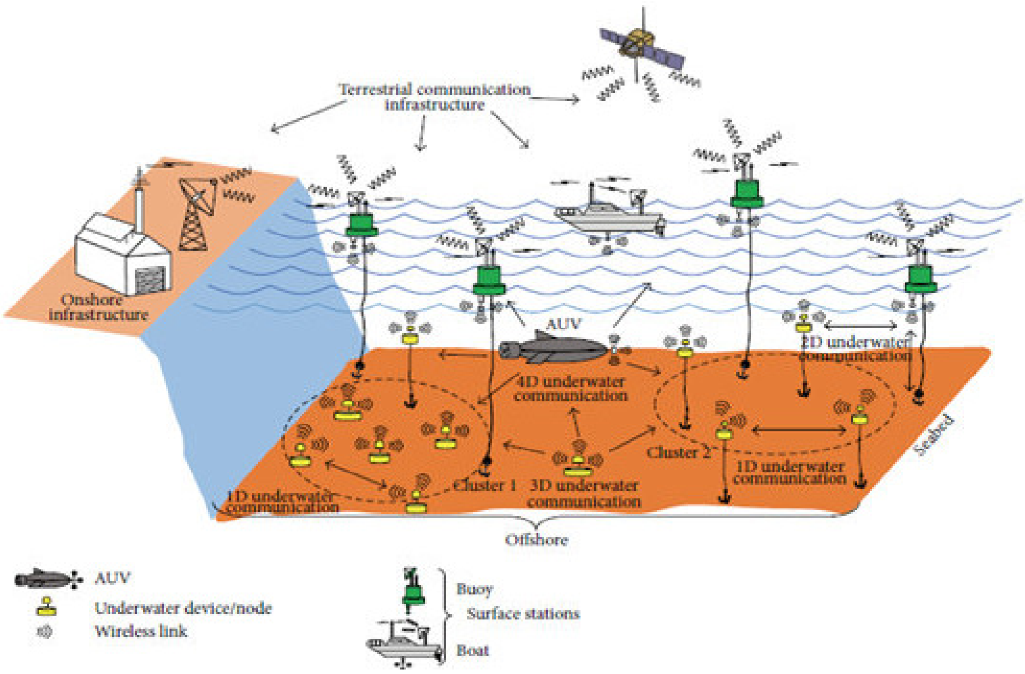


Figure 2.6: Communication architecture of UASN systems (from [6]).

sion of bits through a physical channel connecting network nodes (transceivers). The transmitter does modulation or encoding, while the receiver performs demodulation or decoding. Modulation techniques can be categorized into two types: non-coherent and coherent. Another important process that takes place at physical layer is channel equalization which is the process of filtering the received signal to cancel any ISI. Although guard times can be inserted between successive symbols to avoid the problem of ISI but at the expense of bandwidth. The block diagram of a physical layer implementation of underwater acoustic communication is shown in Figure 2.7.

Figure 2.7 illustrates how the underwater acoustic communication PHY layer and radio communication PHY layer are quite different from one another. Acoustic hydrophones are used at the PHY layer of underwater communication as transducers for analogue to digital and digital to analogue conversion. Additionally, a block that inserted guard durations between subsequent symbols was necessary to circumvent the ISI issue, however, this comes at the cost of bandwidth. Modulation schemes such as On-Off keying (OOK), Frequency-Shift Keying (FSK), Phase-Shift Keying (PSK), Quadrature Amplitude Modulation (QAM), Direct-Sequence Spread-Spectrum (DSSS), and Orthogonal Frequency Division Multiplexing (OFDM) among others can be employed [39,40]. Also, channel equalization takes place at the physical layer. This involves filtering the

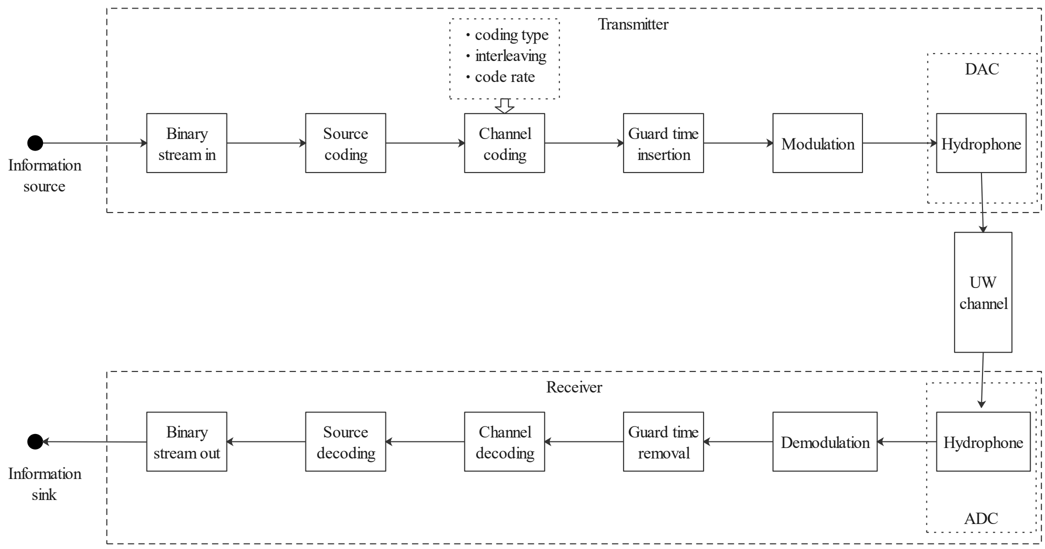


Figure 2.7: Block diagram of UW communication PHY layer.

incoming signal to eliminate any Inter Symbol Interference (ISI).

2.2.6.2 Data Link Layer

The data link layer defines the protocol for data transmission over the underwater acoustic channel (common medium). The optimal operation of this layer is constrained by limited bandwidth and a significant and variable delay. This layer contains the Medium Access Control (MAC) and Logical Link Control (LLC) protocols.

Logical Link Control layer describes ways for delivering data reliably to higher levels at the sink(s) while minimizing overhead, retransmissions, and discarded data. The most common method is Automatic Repeat Request (ARQ), however there are many variations and alternative approaches [14].

Forward error correction (FEC), although considered to be a part of physical layer helps ensure low error rates. FEC reduces physical layer error rates, allowing link layer protocols to function better.

Some MAC protocols rely on ARQ. This is especially true for MAC systems that use RTS/CTS to reserve channels. The DATA/ACK in RTS/CTS/DATA/ACK exchange is the ARQ mechanism [16].

Due to the fact that this is the primary objective of this research, the Section 2.5 presents a thorough evaluation of the technology and state-of-the-art approaches.

2.2.6.3 Network Layer

The network layer takes care of forwarding packets between nodes to their intended destinations. This layer's protocol is referred to as the routing protocol. It is not required for single-hop network topologies, but is critical when considering multi-hop network topologies. Routing protocols can be classified into three categories: reactive, proactive, and geographical routing protocols [51].

Route discovery is used by proactive routing techniques to create a path between network nodes for message routing to the destination [16]. DSDV, OLSR, and others are examples. In contrast to proactive routing protocols, reactive routing protocols establish paths by flooding control packets from sources [16]. They rely heavily on overhead signals and have a high delay, which may be increased by an underwater channel. Also, it is necessary to keep in mind that the dynamic topology of underwater networks may hinder the suitability of reactive routing protocols for underwater acoustic communication. AODV, DSR, and others are examples. Geographic routing protocols, similarly, establish routes between sources and destinations using localization information [16].

2.2.6.4 Transport Layer

The transport layer is responsible for flow control and congestion control, according to [16]. It is essential, among other things, for the reliability of event transport in underwater acoustic communication systems.

2.3. Underwater Acoustic Channel

Apart from radio and light, it has been established that acoustic communication is the cheapest and most viable link capable of efficiently transmitting data underwater over a significant range [5]. The next subsection explains why radio and optical communication are less suitable for use in the underwater scenarios considered in this thesis.

2.3.1. Justification for acoustic communication in UANs:

Due to the fact that radio waves are susceptible to attenuation in underwater water channels due to their low frequencies (30-300 Hz) [16], RF communication in underwater environments has a limited propagation range (approximately 10 m in seawater) [52], necessitating the use of large antennas with high power to cover large distances, which is not only costly but also impractical. Additionally, the low propagation rate associated with underwater channels is accentuated by limited-bandwidth modems.

On the other hand, optical signals are highly susceptible to scattering and absorption in some underwater channels, resulting in a significant reduction in communication range [16, 52]. However, seawater presents reduced absorption, thus Underwater optical communication may be suitable for some under applications especially in clear waters (with a range of around 100 m), and would require the use of high bandwidth modems to achieve any substantial data rate [52]. Similarly, optical transmissions require transceiver alignment which may limit communication range [23, 52]. As a result, acoustic communication appears to be the most effective method of communication for the scenarios explored in this thesis especially, the cases with long pipelines. It can provide efficient data transmission over long appreciable range in clear, shallow, unclear and deeper water bodies. It is the de facto communication method by the aquatic lives to communicate over long range.

Underwater acoustic channels, on the other hand, have distinctive properties that impede effective communication in underwater environments. Some of these characteristics are discussed briefly in the next subsection.

2.3.2. Underwater acoustic channel characteristics and challenges

The following are some of the unique characteristics that are associated with an underwater acoustic channel.

(I) **Very long and variable propagation delay:** The propagation delay in an underwater acoustic channel is extremely long, roughly 0.67 s/km [16], which is caused by the low sound speed in the channel (around 1500 m/s). This may result in a decrease in network performance metrics such as throughput. Additionally, because sound speed is temperature, salinity, and pressure dependant, it varies across the depth between 1450 to 1540 m/s [52, 53]. High delay variance might impair the estimation of Round Trip Time (RTT), a critical statistic for evaluating the performance of communication protocols. The speed of underwater acoustic propagation is empirically calculated as follows in [51]:

$$\begin{aligned} c(z,S,t) &= 1449.05 + 45.7t - 5.21t^2 + 0.23t^3 \\ &+ (1.333 - o.126t + 0.0009t^2)\times \\ &(S-35) + 16.3z + 0.18z^2 \end{aligned} \tag{2.1}$$

where z, S and t are depth, salinity and temperature respectively. Equation (2.1) is an important factor when determining Round Trip Time (RTT), slot allocations, active and idle scheduling models of MAC protocols.

(II) **Low Bandwidth:** Attenuation and interactions between the water body's bottom and surface significantly diminish the available bandwidth in an underwater channel. This results in distance-dependent transmission at a low data rate (about 100 kbps) [53].

(III) **Multi-path arrivals/propagation:** The geometry of underwater channels results in multiple path arrivals and propagations, leading to significant Inter Symbol Interference (ISI) delay. This result to a high Bit Error Rate (BER) and signal deterioration [5, 53]. In this case, signals propagate via reflections from the surface and bottom of the water body in addition to the direct path, resulting in a multipath effect with significantly greater time dispersion than wireless propagation in air [54]. The size of the ISI spread is determined by the link configuration (horizontal links have a greater spread than vertical links), the depth, and the internode distances. According to [55], the impulse response of a multipath based time-variant underwater channel is as follows:

$$c(\tau, t) = \sum_p A_p(t)\delta(\tau - \tau_p(t)), \tag{2.2}$$

where $A_p(t)$ and $\tau_p(t)$ represent the amplitude and the delay of time-variant path. Equation (2.2) would be relevant for setting up simulation parameters. Signal also varies randomly due to surface waves, internal turbulence and speed of sound fluctuations [56].

(IV) **Doppler spread:** Doppler spread is defined as the frequency range over which a channel has a non-zero Doppler power spectrum. It happens as a result of Doppler shifts caused by relative or perceived motions of the transceivers and channel boundaries, which degrades acoustic transmissions as well [51]. Again, horizontal links are more susceptible to Doppler spread than vertical links [16]. The delay spread can be up to tens or hundreds of milliseconds, which can cause signal distortion at certain frequency levels [56].

(V) **Doppler-shift:** The underwater channel's Doppler shift is also substantially bigger than that of the RF channel (approximately several orders higher), which complicates symbol synchronization for CDMA-based MAC schemes [5, 53].

(VI) **Attenuation and Noise:** Attenuation, a distance- and frequency-dependent factor, is responsible for path loss in underwater acoustic channels and is caused by absorption (the conversion of acoustic wave energy to heat energy) [55]. As a result, attenuation is a function of absorption, scattering, reverberation, refraction, dispersion, and depth. It is stated as follows [57]:

$$A(x, f) \approx x^k \sigma^x(f), \tag{2.3}$$

where x, f, k and σ are the distance, frequency, the geometric spreading factor and absorption coefficient respectively. For cylindrical spread (horizontal radiations only), k is equal to 1, while k is 2 for spherical spreads (omnidirectional point source).

Underwater channels are associated with non-white Gaussian background noise that exhibits a declining power spectral density [56]. The two primary sources of noise in an underwater channel are ambient noise and other noises. The ambient noise in an underwater channel is caused by turbulence, shipping, surface disturbances, and thermal, while other sources of noise include man-made, biological, ice, rain, and seismic. In an underwater environment, noise can be expressed as follows:

$$\sum N(f, w, s, \tau) = N_{ambiant} + N_{others}. \tag{2.4}$$

The resultant effects of the major noise sources which provide power spectral densities of each source relative to frequency, f (kHz) in (dB re μ Pa per Hz) in underwater acoustic channel is empirically expressed as [51, 58, 59]:

$$\begin{aligned} N_{ambiant}(f, w, s) = 10(logN_t(f) + logN_s(f, s) + \\ logN_w(f, w) + logN_{th}(f)), \end{aligned} \tag{2.5}$$

where N_t, N_s, N_w and N_{th} are the noise components due to turbulence, shipping, wind and thermal respectively. While the noise components according to [51] are given as:

$$10logN_t(f) = 17 - 30logf \tag{2.6}$$

$$\begin{aligned} 10logN_s(f) = 40 + 20(s - 5) + 26logf - \\ 60log(f + 0.03) \end{aligned} \tag{2.7}$$

$$\begin{aligned} 10logN_w(f) = 50 + 7.5w^{1/2} + 20logf - \\ 40log(f + 0.4) \end{aligned} \tag{2.8}$$

$$10logN_{th}(f) = -15 + 20logf \tag{2.9}$$

(VII) **Propagation loss:** Attenuation results from a decrease in the sound intensity along the path from the transmitter to the receiver as a result of sound signal absorption. Attenuation increases as distance and frequency increase. The Transmission Loss (TL) of an acoustic channel is calculated as follows:

$$
\begin{aligned}
TL(r, f, D, T) &= TL_{spreading} + TL_{absorption} \\
&= 10klog(r) + 10log\alpha(f)\times \\
r \times 10^{-3}, \qquad (2.10)
\end{aligned}
$$

The attenuation caused by absorption (conversion of acoustic energy to heat) is given by:

$$TL_{absorption} = ss + \alpha \times 10^{-3}, \qquad (2.11)$$

where ss represents the spherical spreading factor expressed as:

$$ss = 20logr \qquad (2.12)$$

and r represent the transmission range and the attenuating factor, α given empirically by Thorp's formula [35] as:

$$\alpha = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75 \times 10^{-4} f^2 + 0.003. \qquad (2.13)$$

It is critical to consider the implications of link classifications such as range, communication direction (vertical or horizontal), and depth (shallow water $<$ 100 meters, deep water, oceans) when designing MAC protocols for UASNs and to make reasonable trade-offs in order to maximize network performance. This decision is made based on the application area of the UASNs. Table 2.1 summarizes the various application ranges and corresponding underwater channel bandwidth [14, 51, 60].

2.3.3. Pipeline monitoring applications

Parallel to the global increase in energy consumption, there has been a rapid expansion in oil output. Pipelines are commonly used to distribute and transport petroleum, nat-

Table 2.1: Application Ranges and Bandwidth for Acoustic channel

Application range	Range (km)	Bandwidth (kHz)
Very long	1000	< 1
Long	10 - 100	2 - 5
Medium	1 - 10	≈ 10
Short	0.1 - 1	20 - 50
Very short	< 0.1	> 100

ural gas, and other crude products. These pipeline infrastructures are prone to leaks, ruptures, and breakdowns due to aging, degradation, and deliberate vandalism. Leaks and ruptures caused by aging and rapidly deteriorating pipeline infrastructure alone cost millions of dollars every year to repair [61].

As a result, it has become imperative to protect these resources and facilities in order to sustain these countries' economies and meet global energy demand. Thus, it will be unwise to continue using traditional methods of securing and maintaining pipeline facilities. Physical surveillance is one of these approaches, however it is labour intensive, expensive, temporary, and ineffective. In the event of underwater activities, another technique involves the employment of remotely operated submersibles, which are also enormous, extremely expensive, and only deployed temporarily [11].

Thus, it is necessary to have a system such as Underwater Acoustic Sensor Networks (UASNs) that is less expensive, more efficient, and more reliable, and capable of providing continuous, real-time monitoring of underwater pipeline infrastructure to detect and warn of pipeline defects such as corrosion, leaks, and intentional vandalism before they reach the magnitude of a major disaster [61].

Corrosion has also been identified as a major cause of pipeline collapse, which can result in serious harm to human health and property, as well as supply disruption. A recent example is a 267, 000 gallon oil leak on Alaska's North slope that was discovered after five days [61]. British Petroleum (BP) was forced to close a large portion of the facility later that year because of serious corrosion of the pipe walls [61].

Long pipelines are utilized for a variety of purposes in a number of countries. In Nigeria, for example, the oil and gas sectors rely heavily on pipelines to transport and distribute petroleum, natural gas, and other crude oil products between shipping ports, refineries, and oil and gas wells. According to [62], many kilometres of pipelines have been laid in Nigeria, including 4,315 kilometres of multi-product pipelines, 1037 km of gas pipelines, and 666 km of crude oil pipelines. Another example is the world's longest pipeline, which runs for around 1200 km under the North Sea from Norway's Ormen Langeled field to England's Easington Gas Terminal, carrying approximately 25.5 billion cubic meters per year [63]. Pipeline incidents are primarily associated with damage caused by inadvertent or intentional digging near existing pipelines [61].

Pipelines can be monitored and protected using a variety of technologies and procedures. As proposed by [64], conventional leak detection methods were utilized. This strategy is mostly based on routine inspections performed by maintenance employees. As a result, it requires significant human participation, lacks real-time monitoring of the pipeline, and may reveal a defect only after it is too late. As a result, it has the potential to result in significant economic losses and environmental pollution. Additionally, [65–67] presented real-time pipeline monitoring systems based on wired or wireless sensors. Wired-based monitoring systems, on the other hand, are susceptible to damage in any section of the network. Unauthorized individuals can easily deactivate the monitoring system by cutting the network wires, and it is also difficult to pinpoint the location of a failure in a wire. This issue becomes more complicated when it comes to underwater and subsurface pipelines. Similarly, [68] established a system for monitoring pipeline infrastructure via WSNs and developed a routing protocol for delivering data from sensor nodes to the sink. However, because this technology did not solve the issue of sensor node energy constraints, it has a low reliability and a high energy consumption.

Moreover, [69] described a system named PipeNet for detecting and localizing leaks and failures in water transmission pipelines. While this technology is promising, it suffers from limitations in terms of flexibility, large scale deployment, and interoperability. [70] offered an in-network information processing paradigm for pipeline monitoring based on WSNs, but did not include any concrete methods for implementing the proposed technique. This is mostly due to the fact that monitoring information reveals ambiguity and variation in expressive form, as well as massive amounts of data and sophisticated relationships. An example underwater monitoring scenario is shown in Figure 2.8.

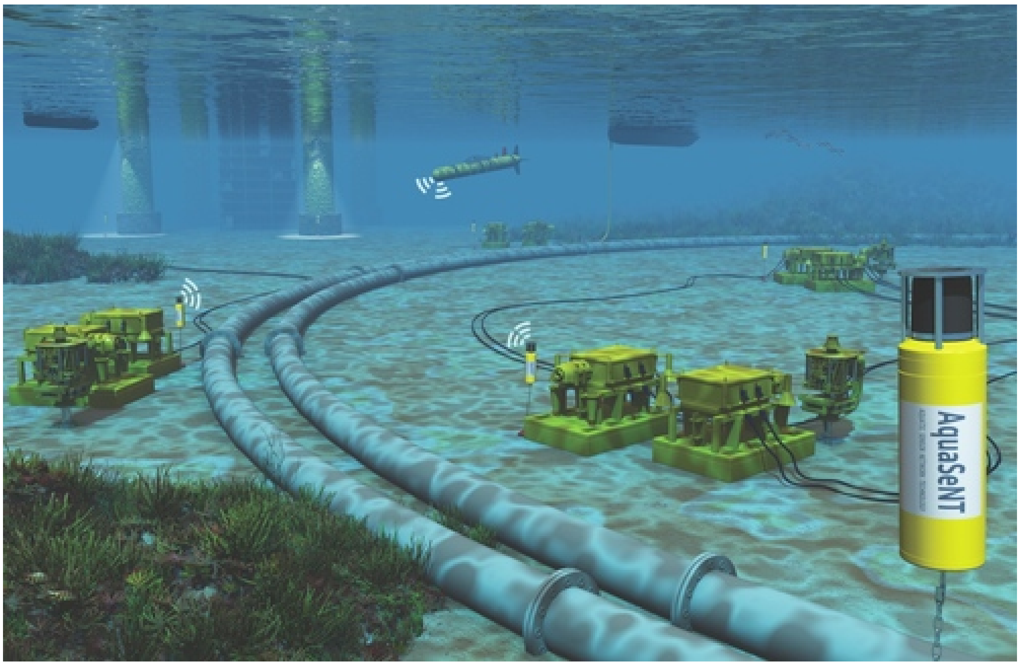


Figure 2.8: Underwater pipeline monitoring example (directly copied from [7]).

In conclusion, it is critical to monitor underwater pipelines in real time to avert calamities that could impact the water body and result in economic loss. Although there are a few techniques to monitoring based on UANs, as described previously, such systems are based on half-duplex communication, which has low network performance and thus low monitoring efficiency. Thus, it is expected that a full-duplex-based pipeline monitoring system can be used to improve network performance, thereby increasing the efficiency of monitoring underwater pipelines.

2.4. Full-duplex communication

2.4.1. Overview of Full-duplex communication

Full-Duplex (FD) communication refers to a phenomenon whereby network nodes can transmit and receive data packets simultaneously within the same band (In-band) [71]. It is theoretically expected that FD communication can double the channel capacity (spectral efficiency) achieved by half-duplex communication given the same resources.

Because of the low data rate associated with underwater acoustic communications, it may be possible to investigate the use of FD technology to efficiently double the theoretical bandwidth and, consequently, potentially double the transmission data rate, as opined in [71]. The efficiency of links, the user experience, and the usage of available resources could all be significantly improved as a result. As a result, the monitoring efficiency (a measure of the effectiveness of the monitored data with respect to the rate of data retrieval) with respect to underwater pipeline can be improved. However, half-duplex transmission has lower network performance and in turn lower monitoring efficiency because, it cannot simultaneously transmit and receive in band, thus, less effectively reuse spectrum as compared to full-duplex.

The FD transmission scenario is depicted in the Figure 2.9 diagram.

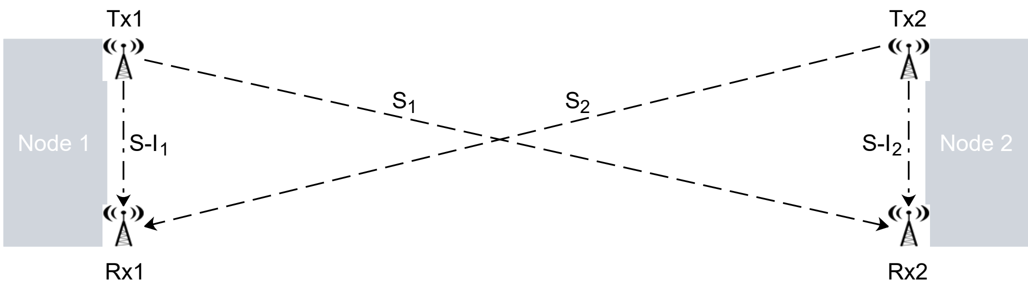


Figure 2.9: Full-Duplex Transmission scenario.

Node1 transmits a signal (S_1) via transmitter, Tx1 to Node2 to be received by receiver Rx2, while Node2 transmits signal (S_2) via Tx2 Node1's receiver, Rx1. Node1 and Node2 receivers both receive $SI_1$and SI_2 respectively. $SI_1$and SI_2 are referred to as self-interference signals. The intensity of the S-I felt at respective receivers depends on the distance between Node1 and Node2. For any meaningful signal reception at Rx1 and Rx2, $SI_1$and SI_2 must be appropriately cancelled to make S_1 and S_2 larger than $SI_1$and SI_2. Thus,

$$S_1 = Rcvd_2 - SI_2 \tag{2.14}$$

and

$$S_2 = Rcvd_1 - SI_1, \tag{2.15}$$

where $Rcvd_1$ and $Rcvd_2$ are the total received signals at Node1 and Node2 respectively.

2.4.2. Full-Duplex Communication Architectures

Basically, full-duplex communication can be achieved using two basic forms of links, the unidirectional and bidirectional links.

2.4.2.1 Unidirectional communication

A unidirectional FD communication mode involves a multi-hop network scenario where only relay nodes are equipped with full-duplex capabilities. The node with the full-duplex capability is able to transmit and receive from the other two half-duplex nodes (source and sink nodes) at the same time and in-band [72]. In this case, communication between the full duplex nodes and the half duplex source or sink is in one direction at a given instance.

2.4.2.2 Bidirectional Communication

On the contrary, bidirectional communication mode involves all full duplex nodes where each of the nodes transmit and receive at the same time and band. In bidirectional links, transmitter and receiver antennas are not spatially separated [71].

2.4.3. Challenges of Full-duplex communication

The main challenge in FD communication is how to efficiently communicate in the presence of potential transceiver's Self-Interference (S-I) which is local signal leakage from the transceivers output to input [71]. The received Signal-to-Interference plus Noise Ratio (SINR) is greatly degraded by significant S-I. Suppressing a node's S-I is been a daunting task but has recently received great attention and the successes recorded in antenna, digital baseband technology, and various S-I cancellation techniques [73] have paved way for more research in FD communication [71, 72]. S-I in underwater communication can significantly dominate the desired received signal, which may be larger than the S-I experienced in radio channels (in some cases can be up to 50 - 100 dB larger than the desired signal) depending on the distance between the transmitting and receiving nodes [71]. This makes the Signal to Noise Ratio (SNR) much lower than the desired received signal and as a result make a bit recovery very difficult. To this end, half duplex or out-of-band full duplex communication modes (transmit and receive either at different times, TDD or over different frequency bands, FDD) are more popular rather than in-band full duplex communication.

2.4.4. Rational for full-duplex in UAC

Full-duplex communication has the potential to boost data rate and spectral efficiency and create a basis for emergence of FD based wireless communication applications and services such as future generation cellular networks, FD cognitive networks, Device to Device (D2D) communications, heterogeneous networks and underwater acoustic networks [71]. It may also enhance Quality of Experience (QoE) of the user [71]. It increases the spectral efficiency, throughput, reduces latency and removes the problem of hidden and exposed terminals associated with CSMA based protocols [74]. Some of these advantages are briefly described below:

- Capacity Enhancement: FD exploits spectral resources in time and frequency which results in doubling channel capacity compared to HD.
- Potentially new channel access techniques: this brings about new opportunities for channel access protocols design that are able to exploit FD for enhanced transmission and collision detection
- Throughput and delay enhancement: in FD communication scenarios, data and control packages can be overlapped in time and frequency in order to reduce transmission delay and improve network throughput.
- Network Fairness: Concurrent transmission can improve fairness in networks such as centralised networks, where the central node can transmit at all times in parallel with other nodes transmitting.
- Enhanced relay transmissions: bidirectional transmission in FD cooperative communications where relay nodes can begin forwarding of data packets to another node while receiving data packets from another node. This brings about improved network performance and provides new cooperative communication opportunities and solves some of the problems such as hidden terminals associated with HD based cooperative communications.

To fully take advantage of FD communication technology, there is need for the successes achieved in the physical layer to be complemented by designing befitting media access techniques. In that vain, research into FD based MAC protocols that would support concurrent transmission and collision detection in real-time to guarantee nearly double throughput performance under high traffic loads are of great importance.

2.4.5. Self-Interference and Cancellation Techniques

This section provides a brief overview of some of the techniques that are employed to cancel S-I in full-duplex networks. As highlighted above, the major challenge limiting full-duplex communication is reducing the node's S-I. The two classifications of S-I cancellation techniques are passive and active. The former involves antenna placement, whereby, the latter can be further classified as active analogue cancellation and digital cancellation.

Antenna placement uses spatial separation of multiple antennas to cancel out the signals from the other transmitting antennas [75]. However, this is more effective with narrow band signals. Active analogue cancellation techniques [76] involve removing the S-I through adaptive duplication of the transmit antenna's propagation channel from that of receive antenna. While active digital cancellation techniques [77] use adaptive filter design techniques based on a training sequence to minimise the residual interference.

Because of the potential benefits of FD communication, which include capacity enhancement, improvement in network throughput and delay performance, as well as improving relay transmissions, among other things, there is an open research gap to investigate the design of new FD-based medium access control protocols that can exploit FD to provide better network performances. The next section examines multiple access approaches in order to provide an overview of the techniques, as well as key principles and issues associated with multiple access strategies in UANs.

2.5. Multiple Access Techniques

These are the techniques that allow more than two computer terminals or network nodes to share the capacity of a single communication channel or medium (radio, acoustic, etc.) for the transmission of data packets. In other words, multiple access is a strategy for partitioning available capacity in such a way that it can be accessed concurrently by a number of users. The most often used techniques are to divide user transmissions according to frequency, time, or codes, all of which are detailed in the following subsections. More so, the Medium Access Control (MAC) protocol is used to coordinate and control user access to the network's shared capacity.

MAC is a software-based protocol that is implemented at the data link layer (layer 2 of the International Standards Organization-Open System Interconnection (ISO-OSI)) [78]. It is used to communicate among computers over a network. While the primary goal of MAC protocols is to avoid collisions, they also address network throughput, latency, energy efficiency, scalability, and adaptability in order to ensure good Quality of Service (QoS). [60]. This section primarily focuses on MAC protocols for UANs.

The design of the MAC protocol is dependent on the application area and the communication channel, as some of the channel factors have an impact on the design. Table 2.2 outlines the comparison of underwater acoustic and radio frequency channel factors that may have an impact on the design of MAC protocols.

2.5.1. Classification of Multiple Access Techniques

Multiple access techniques can be classified as contention free and contention-based. Contention-free schemes are coupled directly to the physical layer and avoid collisions by allocating distinct frequency bands, time slots, or codes to distinct users or nodes. In this instance, nodes do not compete directly for access to the medium. While contention-based MAC protocols do not pre-allocate resources to specific users. Rather than that, users compete for on-demand medium access. The rest of this section provides an overview of currently available MAC protocols, beginning with contention-free approaches.

Table 2.2: Comparison between underwater acoustic and radio channel

Properties	**Underwater channel**	**Radio Channel**
Propagation speed	Low (1500m/s)	High (3 X 10ˆ8 m/s)
Propagation delay	Long (in seconds)	Short (in μ seconds)
Propagation nature	Complex, Anisotropic	Simple, Isotropic
Bandwidth	Low (in KHz)	High (in MHz)
Data rate	Low	High
Noise	Gaussian white noise	Uniform White noise
Channel Dynamics	Highly changing	More steady
Reliability	Low	High
Energy consumption	High	Low
Generalised topology	Not structured, sparse	Structured, dense
Deployment Cost	Expensive	Cheaper
Standards	Not well standardised	Standardised

(I) **Contention-free techniques:** Frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA) are the three fundamental forms of contention-free schemes. Although the theoretical overall flow of data is same in these scenarios, the physical-layer implications, practicality, and real-world performance may be rather different. Due to the low likelihood of collision, these have a high potential for underwater channel access; nonetheless, they are challenging for underwater sensor technology. Additionally, they suffer from a high control overhead, long propagation delay, lack of temporal synchronization, and limited scalability.

- FDMA (Frequency Division Multiple Access): This is a technique that makes use of frequency scheduling. Due to the limited bandwidth of underwater acoustic channels and their sensitivity to fading, FDMA schemes may not provide good network performance in underwater communication [16].

- TDMA (Time Division Multiple Access): Utilizes time slots to provide access to common channels. It needs high guards and synchronization, which may be challenging due to the long propagation delay and significant delay variance associated with underwater acoustic channels, as described in [16].

- CDMA (Code Division Multiple Access): This technique employs pseudo-noise codes spread across the available frequency range. It is affected by frequency selective fading, but requires synchronization, which is challenging in underwater channels due to delay spread [16].

(II) **Contention-based techniques:** In this case, carrier sensing protocols (e.g. Carrier Sense Multiple Access (CSMA)) (based on handshakes) [79–83] and random access protocols (e.g. ALOHA) [84–87] are used. CSMA schemes continually monitor the state of the channel during data transmission. It is based on control packet exchange and is susceptible to high latency due to the limitations of acoustic modems, such as a long preamble delay. This results in an increase in packet collisions and energy consumption when exposed and hidden terminals are present [88]. Thus, if the detection delay is too long, additional time is spent sensing an already-occupied channel, and if the propagation delay is too long, a higher probability of packet collision would become obvious. It avoids collisions at the sender node but not at the receiver node [16]. This has a detrimental effect on low-latency UASN applications.

ALOHA relies on collision detection and packet retransmission to ensure the delivery of reliable data; it does not, however, prevent packet collision. Packet retransmission can degrade network performance, particularly on channels with limited capacity, such as underwater channels [13]. In practice, retransmission can also reduce the lifetime of a network. The following section provides an overview of MAC protocols.

2.5.2. Overview of Medium Access Control protocols

Intensive research has been done with respect to terrestrial WSN MAC layer protocols. The peculiar underwater channel characteristics, as mentioned earlier, prevent direct adoption of these MAC protocols for underwater acoustic communication. CSMA and CDMA based MAC protocols have been largely researched towards underwater acoustic communication [60]. FDMA based MAC protocols are not suitable for underwater communication because of limited bandwidth, vulnerability to fading, multi-paths and frequency dependent noises [60]. A detailed review of MAC protocols for UANs is presented as follows:

2.5.3. MAC protocols for UANs

The major UAN-based MAC protocols are classified in Figure 2.10. As can be seen, MAC protocols based on handshaking have received more research attention than protocols based on random access. Similarly, time division MAC (TDMA) protocols have received more research attention than code and frequency division MAC protocols, with space division MAC protocols (that makes optimal use of the frequency spectrum by separating users spatially) being rarely investigated for underwater acoustic channels due to its complexity.

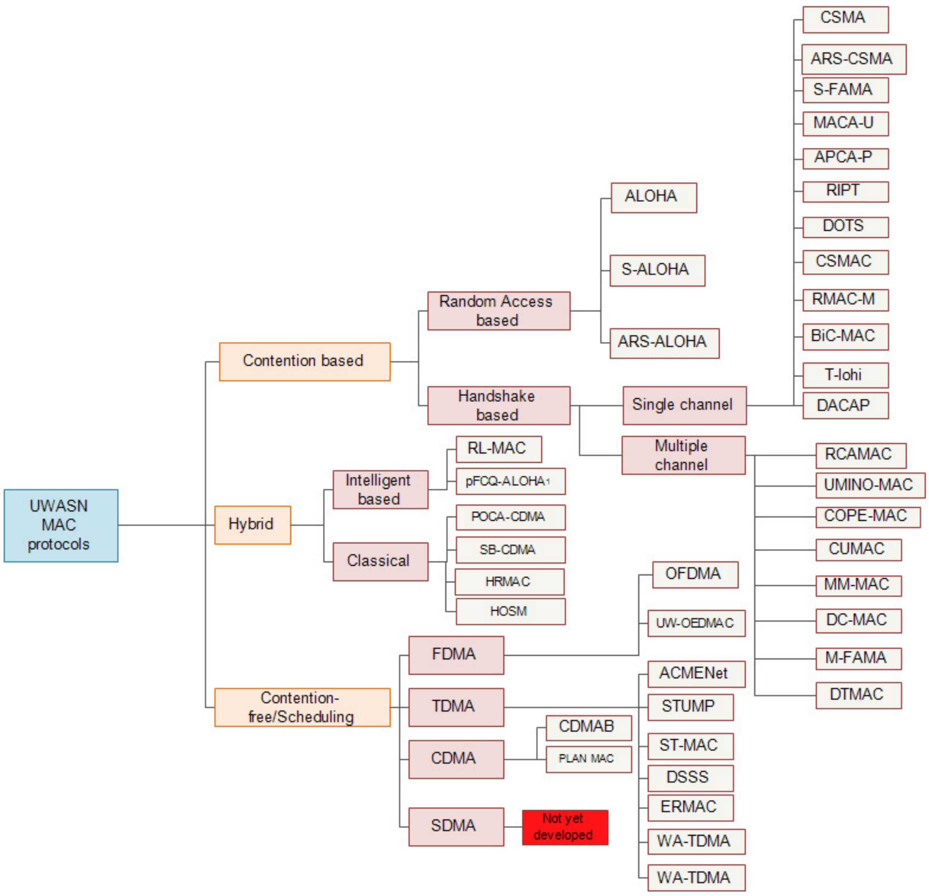


Figure 2.10: MAC protocol taxonomy.

As a result, the following are the key characteristics of random access, carrier sense or handshaking, and contention-free/scheduling MAC schemes that may influence their selection for underwater acoustic sensor network systems: Random access techniques eliminate the need for control packet exchange, rely on packet retransmission, and have a low channel utilization, a simple architecture, and a low overhead. While carrier sense/handshake schemes rely on the exchange of control packets, they have a high collision rate, a long packet delay, a lengthy preamble, a low QoS, a high energy consumption, and a hidden terminal problem. Additionally, contention-free/scheduling techniques have a low collision rate, multiple simultaneous access, a complex architecture, a high system overhead, synchronization difficulties, scalability issues, poor QoS, particularly with FDMA, and a near-far problem.

2.5.4. State-of-the-art Half-duplex MAC protocols for UAN

This subsection provides a review of the state-of-the-art half-duplex MAC protocols for UASN systems. ALOHA, [89], is the most fundamental MAC protocol; it is a random access protocol for media access in which network stations transmit immediately whenever data becomes available. The station then waits for an acknowledgement for a specified period of time (ACK). If an ACK is received within that time period, the data transmission is considered successful; if no ACK is received, the station assumes a data collision and transits to a random back-off within a specified time period, after which a retransmission is established. Collision is avoided, resulting in poor overall throughput performance, particularly at higher offered traffic levels. The theoretical maximum efficiency achievable with the pure ALOHA protocol is approximately 18.4 percent at half the offered traffic. Similarly, Slotted ALOHA was proposed to improve the efficiency of the pure ALOHA protocol [90]. Discrete timeslots were implemented, which means that a station may transmit only at the start of a timeslot. This reduces the likelihood of collisions and increases the maximum throughput to approximately 36.8% for a given network configuration, traffic characteristics, and certain assumptions.

Numerous MAC protocols have been recently developed with a primary focus on increasing throughput performance, energy efficiency, and latency reduction. However, the following paragraphs provide a summary of the reviewed MAC schemes, which include PCAP, DACAP, S-MAC, WISMAC among others. The selection of these protocols is motivated by their broad scope in terms of representation of various fundamental schemes ranging from contention-free to contention-based schemes, and demonstrates their limitations, which may pave the way for a new MAC protocol design for pipeline monitoring systems based on UANs.

Propagation delay tolerant Avoidance Protocol (PCAP) [91] is a CSMA-based scheme that enables the transmission of successive data packets while performing a handshake for the next queued data packet, thereby maximizing the use of long propagation delay. It guarantees higher throughput than conventional protocols, but is limited by the issue of clock synchronization (which may be complicated for UASN) and to homogeneous application scenarios, as points out in [60]. Distance Aware Collision Avoidance Protocol (DACAP) [92], a variant of PCAP, utilizes an internode distance-based waiting time to notify an intending receiver node of an impending collision. However, it suffers from excessive overhead and a lengthy preamble.

The Sensor-MAC (S-MAC) protocol proposed in [93] was based on adaptive listening via local synchronization and periodic sleep-listen schedules. It has a simple architecture and eliminates the overhead associated with time synchronization. However, it is prone to collisions due to overhearing, and poorly optimized adaptive listening can result in idle listening, wasting valuable power. Predefining sleep and listen periods can reduce the S-MAC algorithm's adaptability to different traffic models.

Similarly, WiseMAC [94] is based on non-persistent CSMA (np-CSMA), which employs a single channel with preamble sampling. The primary objective is to reduce idle listening by dynamically adjusting the length of the preamble. Because it does not require external time synchronization, it performs better than S-MAC when exposed to a variety of traffic models. It may, however, suffer from redundant communication, resulting in increased latency and power consumption, as it makes use of a decentralized sleep-listen mechanism [95]. Additionally, it does not address the hidden terminal issue associated with CSMA-based protocols.

Additionally, a TDMA-based scheme called Traffic-Adaptive (TRAMA) [96] schedules packet transmissions via a distributed election algorithm. The objectives are to maximize channel utilization while maintaining a reasonable energy level, to reduce collision probability, and to eliminate the hidden terminal problem. However, implementing a distributed election algorithm adds complexity to the MAC protocol, and overhearing reduces energy efficiency and increases latency.

A slot assignment scheme based on contention was presented in [97]. It allocates slots using a non-uniform probability distribution function. It achieves a lower latency than TRAMA under a variety of traffic models, but it is prone to idle listening and overhearing (low latency at the expense of energy efficiency), and requires time synchronization, which complicates implementation. While, DMAC [98] utilized data gathering trees to schedule slots for packet transmissions with extremely low latency for converge-cast communication. It achieves relatively low latency and energy consumption but suffers from low throughput due to the increased collision problem.

Additionally, a contention-based MAC protocol dubbed T-Lohi is presented in [99]; it broadcasts tone signals to neighbouring nodes in order to compete for the channel for impending data transmissions. Thus, each node has a unique arrival time instance that corresponds to its unique propagation delay. Nodes can only send data in this sense if they have not received tone signals. When a node detects a tone signal, it automatically enters a calculated back-off interval. This technique enables increased throughput. It improves performance by avoiding collisions, but it is complicated because the hardware would require specialized circuitry to receive wake-up tones.

Another Handshaking-based Ordered Scheduling MAC (HOSM) for underwater acoustic Local Area Networks [100] transmits data using ordered list channel reservation phases. It minimizes collisions by utilizing propagation delay information to adjust the timing of control packet transmissions. Although the protocol has a higher throughput rate, a low delay, and spatial fairness, it is inefficient in terms of energy consumption due to the high control overhead (set-up or initialization phase, synchronization and handshake control messages). In the same vain, Hybrid Reservation-based MAC (HRMAC) protocol [101] reserves channels via declaration. This protocol enables concurrent channel reservation and ordered data transmission between intending nodes, thereby increasing channel efficiency. Multi-hop underwater acoustic networks, on the other hand, are not supported.

Similarly, a contention-based MAC protocol for UASNs dubbed Adaptive Retransmission Scheme (ARS) was presented in [13] to address the issue of UASNs' poor performance. It makes use of the Adaptive Retransmission Scheme (ARS) to reserve optimal retransmission values, thereby increasing the likelihood of packet delivery. While applying ARS to ALOHA and CSMA improves network PDR and E2E delay, it is insufficient to meet UASN performance requirements. [102] presents a state-based MAC for UASN that avoids the RTS/CTS handshaking associated with protocols such as Slotted-FAMA [80], R-MAC [103], and POCA-CDMA [104]. It is based on hierarchical and distributed code assignment, as well as a divisive probability function that avoids conflict between spread codes.

Path-Oriented Code Assignment (POCA-CDMA) MAC is a CDMA-based scheme that enables simultaneous receipt of multiple packets. While multiple packet reception improves throughput, it does not address the issue of hidden terminals with inefficient energy consumption due to high overhead. This would be more noticeable in scenarios with low bandwidth and a long propagation delay. Similarly, because Slotted-FAMA utilizes the RTS/CTS handshaking technique, it is susceptible to low channel utilization, throughput, and latency. Additionally, R-MAC suffers from significant overhead as a result of scheduled control and data packet transmissions for collision avoidance.

To overcome the bandwidth constraint inherent in S-FAMA, the Multiple Sessions FAMA (M-FAMA) MAC protocol for UASN [105] utilizes neighbouring nodes' propagation delay information and expected transmission schedules to initiate concurrent multi-session transmissions. It resolves the issue of fairness through the use of a bandwidth balancing algorithm. Temporal and spatial reuse may be possible and may avoid collisions more effectively than S-FAMA. However, it requires a large number of control packets and the initiation of multiple sessions, which results in lower energy efficiency when compared to other channel reservation protocols. Additionally, bursty traffic and mobile topology scenarios degrade throughput performance. Likewise, the latency issue inherent in the majority of handshaking schemes was not addressed, even in the presence of multiple sessions. On the other hand, the CDMA-based scheme described in [102] attempts to eliminate the need for RTS/CTS handshaking by generating probability functions to support concurrent data transmission and thus reduce collisions. It optimizes channel utilization and reduces latency, energy consumption, and throughput. However, due to the difficulty of assigning pseudo-random codes on a large scale, it is not feasible.

DTMAC [106], another UASN-based MAC protocol, preallocates nodes' transmission times through distributed coupon collection; thus, nodes require only information about neighbouring nodes. This can help networks perform better during bursty traffic. By removing the need for handshaking and channel reservation, it significantly improves network performance. However, it only supports short data packets in the case of a single-hop network.

Another promising MAC protocol, ALOHA-Q [88], was developed for WSNs but has the potential to perform well when properly adapted for underwater communication channels. It transitions between random access based schemes (ALOHA) and scheduling by utilizing intelligent slot selection based on reinforcement learning. Simple complexity and control overheads improves network performance significantly; however, network performance may be effected by inaccurate frame size estimation. Likewise, an underwater MAC protocol, UW-ALOHA-QM was proposed in [107] as an enhancement to ALOHA-Q, and it employs reinforcement learning to enable nodes to adapt to a changing environment via trial-and-error interaction, hence increasing network resilience and flexibility. This was proposed, however, for underwater networks with mobile nodes whose trajectory is uncertain.

Although a number of intelligent-based MAC protocols have been investigated recently for WSNs [88, 108, 109], intelligent protocols for UASNs remain an under explored area. In a similar vein, the fading effects of radio communication have recently been addressed through cooperative multi-agent communication. Cooperative communication based on multi-agent reinforcement learning has been investigated in [109–111] in order to provide an acceptable quality of service for WSNs, spatial fairness, and increased energy efficiency. Cooperative communication can also be investigated in the context of underwater acoustic communication in order to improve network performance in the presence of extremely long delay, limited bandwidth, and a low data rate.

Lastly, LTDA-MAC protocol [9] uses 'greedy' optimization algorithm to generate efficient packet schedule to improve network performance and efficiency in linear UASN-based pipeline monitoring systems that do not require sensor node clock synchronization. It provides shorter frame duration and end-to-end delay without packet collisions. It has significant improvement in network performance for short pipelines and was developed for half-duplex network scenarios.

2.5.5. Comparison of half duplex based UAN MAC protocols

Performance analysis of MAC protocols for underwater acoustic communication and a radio based intelligent MAC protocol with respect to energy efficiency, throughput, delay/latency and channel utilization is presented in Table 2.3. It is shown that pure handshaking-based MAC protocols such as slotted FAMA MAC have poor energy efficiency, poor throughput, poor channel utilization and high packet transmission latency. Tuning of the handshaking process could considerably make the performance better, as can be seen with the POCA-CDMA scheme which has throughput, delay and channel utilization performances fairly improved, although energy efficiency performance is still poor. Likewise state-based CDMA MAC, a more tuned handshake process fairly improves the performance as can be seen from Table 2.3. Multiple access schemes such as M-FAMA as seen in Table 2.3 have fair throughput and channel utilization performances, but suffers from high packet delay and low energy efficiency. Random access based schemes such as S-ALOHA, have promising throughput but have poor performances in terms of delay, channel utilization and energy efficiency. Intelligently tweaking the slot selection process could improve the performances as can be seen for radio based ALOHA-Q in Table 2.3 having promising performances in terms of energy efficiency, throughput and channel utilization.

2.5.5.1 Challenges in Designing MAC Protocols in UAC

As discussed thus far in this chapter, underwater acoustic channels present some challenges for designing MAC protocols in UANs due to their unique characteristics. Some of these challenges are summarized below:

- Acoustic modems are more energy-intensive than conventional motes used in terrestrial WSNs. Nodes, on the other hand, are powered by batteries that will be extremely difficult to recharge or replace, and solar energy cannot be used

Table 2.3: Comparison of some MAC protocols

MAC	**Technique**	**Energy Efficiency**	**Throughput**	**Delay**	**Channel utilization**
S-ALOHA	Random access, Retransmission	low	high	moderate	low
S- FAMA MAC	Handshaking	low	low	high	low
R-MAC	Scheduling	low	high	moderate	moderate
POCA-CDMA MAC	Handshaking	low	moderate	low	moderate
M-FAMA	Multiple Access	low	moderate	high	moderate
state-based CDMA MAC	Virtual handshaking	moderate	moderate	low	moderate
D-TMAC	Handshaking	low	moderate	high	moderate
ALOHA-Q	Random Access/scheduling	high	high	moderate	high
LTDA-MAC	scheduling	high	high	low	high

in an underwater environment. As a result, energy efficiency is critical when designing MAC protocols for UANs.

- Another challenge is that, due to the vastness of water bodies such as the sea and ocean, deployments are typically sparsely based, which can result in passive movement of nodes due to water currents or other underwater disturbances, resulting in a dynamic network topology.
- Additionally, node failure is more susceptible to UANs as a result of energy depletion or hardware failure due to corrosion or fouling.
- Accurate time synchronization of the nodes is extremely difficult to achieve due to the variable and long propagation delay, which limits approaches that rely entirely on duty cycling.
- Moreover, with contention-based collision avoidance MAC protocols, situations involving hidden and exposed nodes in underwater channels become more prevalent.
- Due to the slow propagation speed of underwater channels, handshaking experiences a significant delay, which can impair the performance of MAC protocols that rely on the RTS/CTS handshake process.

- Given the power challenges associated with UASNs, MAC protocols for UASNs should be capable of avoiding power loss during collisions.
- Likewise, it is critical to understand that centralized networking is unsuitable with UASNs due to the creation of a single point of failure. That is why, in order to fully improve the reliability of UASN systems, a self-organizing and self-adaptive scheme is required.
- Subsequently, research on MAC protocols has revealed that the majority of MAC protocols designed for (radio-based) WSNs are not optimized for extremely long propagation delays, low data rates, or energy efficiency in underwater acoustic channels. Additionally, some Intelligent MAC schemes suffer from issues of fairness, difficulty estimating frame sizes, and degraded delay performance.

Due to the aforementioned challenges, UANs will always have a dynamic network topology. Along with additional difficulties, such as a long and variable propagation latency, low bandwidth, and a high bit error rate, designing a MAC protocol for UANs presents significant problems. FD-based MAC schemes, on the other hand, can have a substantial positive effect on hash channels with low link quality, such as underwater acoustic channels. To assess the potential of FD-based MAC schemes for applications such as underwater pipeline monitoring, a few FD-based MAC protocols for terrestrial and underwater channels are reviewed in the following subsection.

2.5.6. Full-duplex MAC protocols for UANs

FD based MAC protocols can exploit physical layer to achieve concurrency in channel sense (spectrum detection) and data transmission [71]. With FD communication, real-time collision detection could be achieved, which can greatly reduce the time of failed transmission, enhance channel utilization (as compared to underutilization of channel in half duplex communication) and improve throughput performance.

2.5.6.1 Review of the state-of-the-art Full-duplex MAC protocols

Full-duplex based MAC protocols can take advantage of full-duplex physical layer to achieve improved network performance due to concurrent transmission within the same frequency and time [71]. This can enhance real-time collision detection, improve channel utilization and provide better throughput. In this view, RTS/FCTS FD MAC [112] designed for a radio channel is based on a handshaking mechanism. The model considered a sparse topology using a saturated network traffic model. It supports both unidirectional and bidirectional full duplex data flows where HD/FD node coexistence could be possible. It is a classical MAC protocol implemented by an analytical model. It was analytically validated, and numerical evaluation was performed to compare its performance to a p-persistent CSMA protocol, taking only throughput into account. The key features are support for both data flow, thus, backward compatible with half-duplex systems, potentially addresses hidden terminal problems in FD networks, and good throughput at very small traffic level. However, the results were based only on numerical evaluation since the protocol was not simulated nor experimented in real live scenario. Transmission delay was also not considered, and only low loads were considered in the analysis. Throughput performance decreases sharply with increasing number of nodes, thus, may not be suitable for large network deployment.

Similarly, Relay Full-Duplex MAC [113] is a classical radio channel based protocol that uses primary and secondary transmissions to achieve full duplex communication. The model considered a multi-hop random network topology with asynchronous data traffic. Simulation model was designed and evaluated for end-to-end throughput. It shows a better throughput performance as compared to CSMA/CA, FD-MAC and MFD-MAC.

Furthermore, a distance aware CSMA based protocol called FD-MAC [114] is designed for underwater channel. It is a bidirectional Frequency Division Duplex (FDD) and contention based protocol that uses the approach of virtual channel separation into data transmit and control packet transmit channels. The model is tested on sparse network and random topology using low traffic with Poisson distribution model. It was simulated on OMNET++ 4.0 and sea trials conducted. It was evaluated for throughput, end-to-end delay and power consumption against the traditional CSMA. It shows improved performance against CSMA, addresses the problems of hidden and exposed terminals, and reduces interference from bidirectional communication. However, only a small network and non-dynamic topology were considered. Also, it is a TDD (Time Division Duplex) implementation that divides channel into two in the frequency domain which may amount to waste of resources as channel reuse cannot be explored and consequently degrade throughput performance.

In the same vain, an handshaking based protocol, FDCA (Full-Duplex Collision Avoidance) MAC [115] supports bidirectional synchronous full-duplex transmission in underwater channel. It uses multiple handshaking processes to transmit multiple packets. The model is based on single-hop, sparse network and dense mobile multi-hop network topologies using Poisson traffic process. It is evaluated on Aqua-sim for throughput and energy consumption and has better throughput and energy performance as compared with classical ALOHA, M-FAMA, DOTs and FD-MAC protocols. However, the handshaking process causes long delay and performance degrades with increasing transmission range and may not be suitable for large sparse topology application scenarios. Also, passive overhearing can lead to energy wastage and multiple handshakes can increase the overhead and complexity of the protocol.

Energy-Efficient F-D MAC presented in [116] is also a radio channel based unidirectional and bidirectional full-duplex MAC protocol for distributed networks. The protocol was validated by analytical analysis and numerical evaluation. It supports backward compatibility with half duplex nodes. However, only energy performance was considered in the evaluation and simulation. There is need for further testing of the protocol to involve simulation and perhaps, real-life experimentation. Additionally, the protocol can further be evaluated for other metrics such as throughput, latency, etc.

A random access based protocol called Janus protocol was presented in [117]. It is a synchronous protocol designed for radio channel and uses a heuristic approach to optimally schedule transmission by controlling the rate and timing of packet transmission either for half-duplex or full-duplex mode. It can transmit at a lower rate and guarantees fairness for all nodes by allocating slots to acknowledge received packets during each cycle. It was implemented using WARP (Wireless Open Access Research Platform) v2 platform test-bed and evaluated for throughput and fairness performance. However, it has not been validated for larger and diverse network topologies which provide some scope for more evaluation of throughput, fairness and latency under different traffic patterns and network topologies. Full-duplex based MAC protocols can take advantage of full-duplex physical layer to achieve improved network performances due to concurrent transmission within the same frequency and time [71]. Table 2.4 presents the summary of some of the state-of-the-art full-duplex based MAC protocols.

Table 2.4: Summary of state of the art Full-Duplex based MAC protocols

Scheme	Channel	Access type	Topology	Data flow	Validation	performance metric(s)	Feature(s)	Limitaion(s)
RTS/FCTS FD MAC [112]	Radio	Handshaking	Sparse	Uni & bidirectional	Analytical models and numerical evaluation	Throughput	Support both data flow, addresses hidden terminal problems, good throughput at very small traffic	Not simulated, delay not considered, low loads considered, poor throughput at larger nodes
Relay FD MAC [113]	Radio	Handshaking	Multi-hop random network	Asynchronous FD	Simulation model	End-to-End throughput	Better throughput as compared to CSMA/CA, FD-MAC and MFD-MAC	High delay
FD-MAC [114]	Underwater	Handshaking	Single hope, sparse network	Bidirectional FDD	Simulation model and sea trials	Throughput, end-to-end delay and power consumption	Improved performance against CSMA, addresses hidden and exposed terminals issues, reduced interference	Small network was considered, no channel reuse, low throughput
FDCA (FD Collision Avoidance) MAC [115]	Underwater	Handshaking	Single-hop, sparse network and dense mobile network	Synchronous FD	Simulation model	Throughput and energy consumption	Better throughput and energy performance as compared with pure ALOHA, M-FAMA, DOTs and FD-MAC	Long delay, poor performance at longer range, energy waste due to passive overhearing, higher overhead due to multiple handshakes
Energy-Efficient FD MAC [116]	Radio	Contention-based	Distributed network	Uni- and bidirectional FD	Analytical model and numerical evaluation	Energy consumption	Backward compatibility with HD nodes	Only energy efficiency was considered
FD radio MAC [117]	Radio	Random access	Single-hop sparse network	Synchronous FD	Emulation on WARP (Wireless Open Access Research Platform) v2	Throughput and fairness	Good performance at lower data rate, fairness	Not validated for large and diverse networks
FD MAC for UAV [118]	Radio	Contention based	Single-hop	FD	Simulation model	Throughput and delay	Improved throughput & delay at lower loads	Poor performance on higher loads, not tested on multi hop networks

From Table 2.4, it is evident that, although, some of the full-duplex based MAC protocols presented are promising, they still have some limitations such as poor QoS, scalability, coverage, and some could be further evaluated for other important performance metrics. Also, an handful of these protocols are originally designed for radio channel and do not take into account MAC challenges in underwater environment.

2.6. Summary

Developing a MAC protocol for UANs is difficult due to underwater channel characteristics such as extremely long propagation delay, limited available bandwidth, and low data rate. This means that the MAC protocol for UANs require high throughput, have minimal latency or transmission delay, and be energy efficient. Numerous half-duplex MAC approaches have been developed to improve network performance in UANs, however they have low throughput, high latency, low energy efficiency, and in some cases limited scalability and flexibility, particularly for long underwater pipeline monitoring applications. Furthermore, approaches used in terrestrial radio networks are either incompatible with UANs or result in poor network performance. The network performance concerns become even more obvious in multi-hop UANs due to the difficulty in channel prediction because of the long propagation delay. In-band full-duplex communication, on the other hand, shows significant promise for improving the spectrum efficiency and throughput of acoustic communication systems. Interestingly, this can address a number of MAC layer difficulties by potentially improving network performance in terms of improved throughput and reduced latency, as well as allowing a node to sense the channel while receiving a packet. Although, a few number of FD based MAC protocol have been developed, however, issues of poor network performance still persist. This paves the way to further research into FD-based MAC protocols for monitoring multi-hop linear underwater pipelines that can significantly improve monitoring rate as a function throughput and packet end-to-end delay. The chapters that follow discuss the development of a full-duplex MAC protocol for multi-hop chain underwater pipeline monitoring systems, as well as their comparison to state-of-the-art underwater MAC protocols, with an emphasis on throughput and end-to-end delay performance.

Chapter 3. Experimental Methodology

3.1. Introduction

This chapter describes the experimental approach that was used in the course of carrying out the work described in this thesis. There are detailed descriptions of the materials/tools, methods/approaches, data sources and acquisition, as well as performance metrics, that were used in the development and evaluation of full-duplex-based Media Access Control (MAC) protocols for linear underwater acoustic full-duplex chain networks. It describes the methodologies utilized in developing realistic channel, network, and simulation models that were employed in the algorithm development process, as well as in the simulation and evaluation of the MAC protocols described in this thesis. These insights provide more detailed explanations for some of the topics discussed in various sections of Chapters 4 and 5. The scenarios and design of the network are provided first, followed by a discussion of acoustic propagation and the associated channel models. Figure 3.1 depicts a flowchart that outlines the steps involved in implementing the study approach. For underwater acoustic communication, this entails the investigation of design objectives and requirements for algorithms, propagation, channel, network, and simulation models in order to develop and implement full-duplex based MAC protocols for underwater acoustic communication.

The next section presents a brief overview of the state-of-the-art test-beds and simulation tools for Underwater Acoustic Communication (UAC).

3.2. Test-bed and Simulation tool

Conducting real-world sea/ocean-centric experiments for underwater acoustic communication is time-consuming and costly [119]. Due to these limitations, testing, evaluating, and validating underwater network protocols via sea trials is difficult. Additionally, there is the issue of underwater experiment repeatability and the lack of a controlled environment, which may result in erroneous results. The alternative is to use software-based simulation tools and/or hardware-based laboratory test-beds (emu-

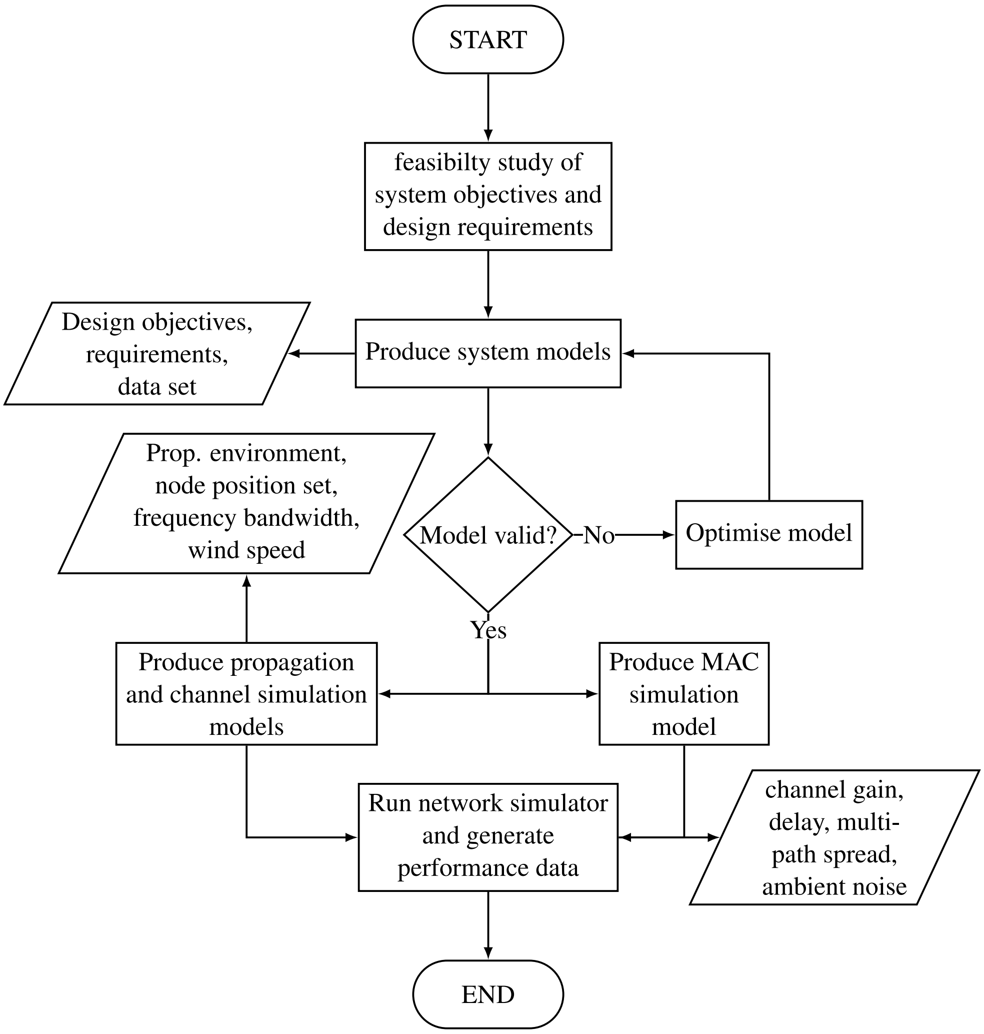


Figure 3.1: Flow chart of experimental procedure.

lation), which enables simple and cost-effective reconfiguration of systems to support a variety of application scenarios, traffic patterns, topologies, and propagation models. Although other limitations, such as inaccurate representation of channel models, may impair the validity of the results, because simulation channel models typically omit some environmental variables and consider only simplified channels with low environmental dynamics [119], error bounds and assumptions should be properly accounted for.

Although test-beds and and simulation tools such as Aqua-lab [120], Versatile laboratory [121], Aqua-Net Mate [122, 123], Aqua-TUNE [124], SeaNet [125], Aqua-Sim [126], Aqua-Sim Next Generation [127], UnetStack [128], DESERT [129], and SUNSET [130] are available for consideration, Matrix Laboratory (Matlab) [131] is employed in this thesis. Matlab has evolved through time, and a number of add-ons, collectively referred to as toolboxes, have demonstrated its adaptability and extension to numerous research fields such as mathematics, sciences, engineering, economics, and medicine, among others. It is very user-friendly, well-maintained, and well-documented.

Due to the fact that hardware description language (HDL) Coder™ enables hardware implementation via Matlab, Matlab may be used to seamlessly interface generated algorithms with supporting hardware. This allows for an easier interface and more realistic representation of the channel models proposed in this thesis. Thus, the thesis implements, tests, and evaluates the MAC algorithms proposed in the thesis using a MATLAB-based network simulator. This simplifies the integration of the BELLHOP ray tracing channel model, which provides a more accurate representation of the underwater environment.

3.2.1. System Architecture

The underwater pipeline monitoring system is divided into two modules: the underwater pipeline monitoring module and the network protocol module. In the context of this thesis, the pipeline monitoring module is viewed from the perspective of the propagation, channel and network topology models. While the network protocol development which is the main focus of this thesis presents the development of full-duplex based

MAC protocol. The block diagram of a typical pipeline monitoring system is shown in Figure 3.2. The system is separated into two sections: the underwater pipeline part, which represents the area of interest for the development of the MAC protocol, and the surface sink, satellite, and control room sections. It is critical to keep in mind that the latter region falls outside the scope of this thesis. The sensor nodes on the pipeline span the range N_0 to N_m, with N_0 acting as the source node, transmitting and receiving Request (REQ) and data packets to and from the master node, N_m, using an acoustic horizontal communication architecture. The acoustic modems have a single stack, in contrast to the surface sink and offshore sink, which have multiple stacks and can communicate by RF and satellite.

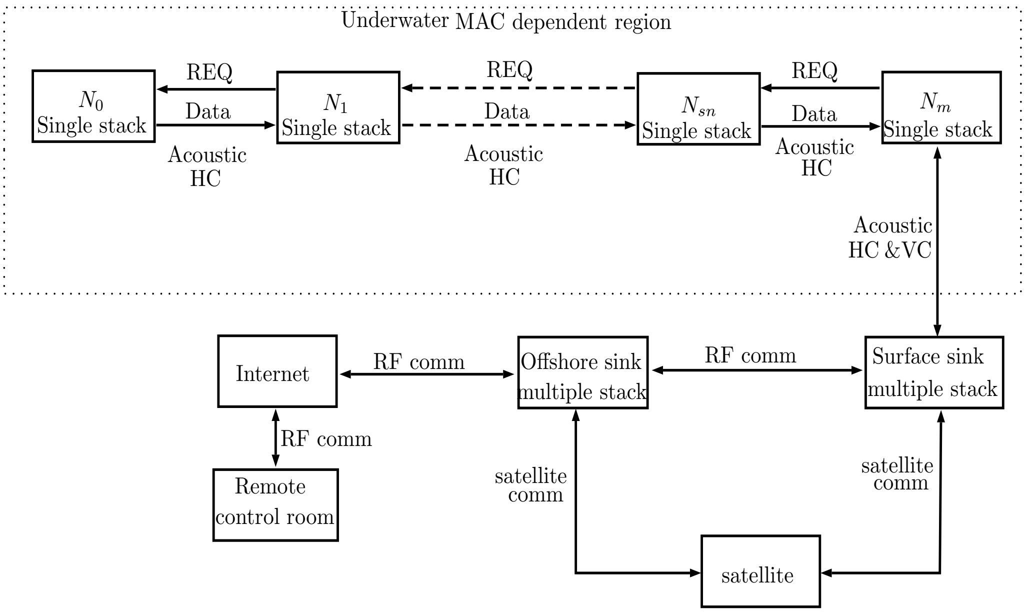


Figure 3.2: A block diagram of the underwater acoustic sensor network pipeline monitoring system (RF = radio Frequency, HC = horizontal Communication, VC = vertical Communication).

3.2.2. Network Architecture

In this section, the description of the scenarios considered in this thesis is presented. The scenarios are categorised into small scale, medium scale and large scale scenarios. The scenarios are configured for both half-duplex and full-duplex communication. In each case, there is one sink (gateway) node which queries the other nodes for data packets by broadcasting request (REQ) packets. The other nodes serve as data source and relay nodes. The general case is depicted in Figure 3.3.

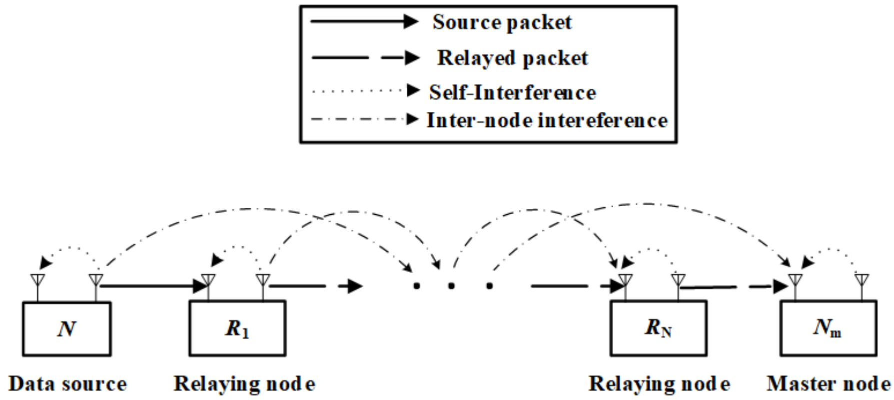


Figure 3.3: Multi-hop chain underwater network.

The sensor nodes are deployed linearly throughout the pipeline at a depth of 480 m and then connected to the platform via a riser. The nodes are connected hop by hop, with each node connecting one hop closer to the sink node and one hop farther down the chain. The sink node broadcasts REQ packets down the chain in order to query for data packets (s). Except for the last transmitting node in the chain, each node forwards the REQ packet to the nearest nearby node until it reaches the final transmitting node in the chain. Each transmitting node, upon receipt of a REQ packet, either sends its own data packet or relays the data packet from a node farther down the chain to a node higher up the chain. The sink node receives data packets from nodes farther down the chain and forwards them to the sea surface communication platform. The last transmitting node in the chain does not relay packets; instead, it transmits only its own data packets to the next transmitting node in the chain. Except for the last transmitting node, which serves solely as a data source, each transmitting node serves as a data source or data forwarder.

3.2.3. Assumptions

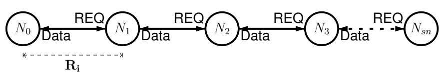
The following assumptions are used in the network models presented in this thesis:

- All nodes have the same performance capabilities.
- The network topology presented in Figure 3.3 is an ideal case, as in reality and the channel model employed and the topology may vary according to time-varying channel.

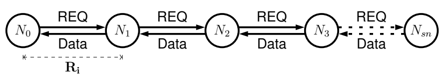
- All packets from the source node flow through the chain hop by hop to the destination (master) node.
- The transmission range required for connectivity with respect to the addressing of packets of each node is 1-hop away from the neighbouring node and the interference range, R_i is 2-hop neighbour away.
- Packet collisions are a result of overlap in packet duration of two or more packets and are responsible for packet losses.
- The collided packets are discarded.
- Packet size for all nodes are assumed to be constant.
- Every node is a data source except the sink node.
- An amplify and forward relay node is assumed.
- Frame length is equal to the data reception time plus the data packet duration
- An ideal self-interference cancellation (zero self-interference) is assumed for the full-duplex scenarios (only for simulation).

3.2.4. Network Topologies

A subsea asset (pipeline) monitoring scenario is represented by a generic network topology as depicted in Figure 3.4 showing half-duplex (HD) and full-duplex (FD) Linear Underwater Acoustic Sensor Network (LUASN) topology. The nodes in the chain network topology are able to operate either in half-duplex or full-duplex fashion. For the case of full-duplex communication shown in Figure 3.4b, the relay nodes are able to transmit and receive simultaneously in time and frequency.



(a) HD network scenario



(b) FD network scenario

Figure 3.4: Linear UASN Network topology.

The network scenarios are classified as small, medium, or large in accordance with the pipeline length. The scenarios range from very small networks with a few nodes to long pipelines with numerous nodes. Sensor nodes are distributed evenly throughout the length of the pipeline in all scenarios, at equidistant points of 1 km / 2 km based on the acoustic modem range. A range of 1 km is considered to be a reliable range, while 2 km is considered to be approaching the range limit. The choice of 1 km / 2 km range is based on the experimental design and the physical characteristics of the modem used. While different acoustic modems may be used, a nano-modem [10] is considered in this case. This enables scalable implementation at a far lower cost. Additionally, the range/modem selection is motivated by the requirement for regular monitoring points along the pipelines; otherwise, larger ranges and fewer hops would be preferable. The transmission range is critical for underwater acoustic network deployments. It has an effect on the efficiency of energy use and network connectivity. The acoustic nano-modem characteristics are listed in Table 3.1.

Table 3.1: Acoustic modem specification ([10])

Supply voltage	3 – 6.5V dc (5V or 6V supply recommended)
Supply current (5V supply)	Listening: 2.5 mA Receiving: 5 mA Transmitting: max 300 mA
Acoustic frequency	24 - 32 kHz
Acoustic source level	∼168 dB re 1uPa @ 1m
Acoustic directivity	Near omnidirectional (reduction around cable entry of potted unit)
Physical layer	Aperiodic orthogonal code keying with BPSK modulation and error correction code
Acoustic data rate (raw)	640 bits/s, unicast and broadcast data messages up to 64 bytes in length
Acoustic throughput (max)	463 bits/s
Addressing	Up to 256 units (addresses 0-255)
Ranging increment	4.7 cm (wind speed at 1500 m/s)
Ranging variance	∼10 cm
Maximum Range	$>$ 2 km
RS232 interface	9600 Baud, 8-bit, no parity, 1 stop bit, no flow control

- **Small scale scenarios:**

Small scale scenarios represent applications that involve short pipeline deployments between 2 km to 20 km based on 1 km and 2 km equidistant range between nodes. They are generally denoted as Small_L_H, where L and H are the pipeline length and the number of hops in the network, respectively. In the small scale scenarios, L is set to 2, 10 and 20 km while, H varies with 2, 4, 10 and 20 hops.

- **Medium scale scenarios:**

Similarly, a generic medium scale scenario denoted by Medium_L_H, is used to represent applications involving moderately long pipelines. in this case, L is set to 50 and 100 km and in each case considering 25, 50 and 100 hops for H.

- **Large scale scenarios:**

The large scale scenarios are represented by Large_L_H have values of L and H between 200 and 1000 km, and 100 to 1000 hops respectively.

The different configurations of small scale, medium scale and large scale scenarios are shown in Table 3.2.

Table 3.2: Network scenarios and description

Scenario Category	**Pipeline length (km)**	**Scenario name**	**Description**
Small scale	2	Small_2_2	2 km pipeline with 2 hop (3 nodes)
		Small_2_4	2 km pipeline with 4 hop (5 nodes)
		Small_2_10	2 km pipeline with 10 hop (11 nodes)
		Small_2_20	2 km pipeline with 20 hop (21 nodes)
	10	Small_10_2	10 km pipeline with 2 hop (3 nodes)
		Small_10_4	10 km pipeline with 4 hop (5 nodes)
		Small_10_10	10 km pipeline with 10 hop (11 nodes)
		Small_10_20	10 km pipeline with 20 hop (21 nodes)
	20	Small_20_2	20 km pipeline with 2 hop (3 nodes)
		Small_20_4	20 km pipeline with 4 hop (5 nodes)
		Small_20_10	20 km pipeline with 10 hop (11 nodes)
		Small_20_20	20 km pipeline with 20 hop (21 nodes)
Medium scale	50	Medium_50_25	50 km pipeline with 25 hop (26 nodes)
		Medium_50_50	50 km pipeline with 50 hop (51 nodes)
	100	Small_100_50	100 km pipeline with 50 hop (51 nodes)
		Small_100_100	100 km pipeline with 100 hop (101 nodes)
Large scale	200	Large_200_100	200 km pipeline with 100 hop (101 nodes)
		Large_200_200	200 km pipeline with 200 hop (201 nodes)
	500	Large_500_250	500 km pipeline with 250 hop (251 nodes)
		Large_500_500	500 km pipeline with 500 hop (501 nodes)
	1000	Large_1000_500	1000 km pipeline with 500 hop (501 nodes)
		Large_1000_1000	1000 km pipeline with 1000 hop (1001 nodes)

3.2.5. Acoustic propagation

In this section, the acoustic propagation model assumed in this work is described, this model is used in the simulation of the work presented in Chapters 4 and 5. Although, there are several available propagation models such as Ray tracing, Normal mode, Parabolic equation, Wavenumber Integration, Energy flux, Finite Difference and Finite Element models [132], the acoustic propagation model employed is based on the BELLHOP [133] beam tracing method described in [134]. The choice is influenced by computational cost and model efficiency with respect to topology and application scenarios. Spatially varying local environment can influence underwater acoustic propagation. In order to accurately provide a representation of acoustic propagation, the following environmental variables that serve as the model input data are considered: bathymetry, sea surface, Ambient Noise Power, sound speed profile, source and receiver locations.

3.2.5.1 Bathymetry

The bathymetry (characteristics of the sea bed) influences the propagation pattern of the sound wave, in order to provide an accurate multipath propagation pattern, this thesis employed a generic bathymetry model presented in [134] where small-scale variations are described by the sinusoidal shape bathymetry [134–136] represented by the following model:

$$z(x) = R(x) \times \frac{z_{max}}{2} \left(\sin \left(-\frac{\pi}{2} + \frac{2\pi x}{L_{hill}} \right) + 1 \right), \tag{3.1}$$

where $z(x)$ is the random elevation of the hills along horizontal range, x, z_{max} represents the maximum hill elevation, and the length of single hill is L_{hill}, while, $R(x)$ is a uniform random number between 0 and 1. For the acoustic propagation model assumed in this work, z_{max} is set to 10 and a generic sea bottom layer represents sand-silt with 1 g cm^{-3} density [132, 133]; the generated bathymetry is shown in Figure 3.5.

3.2.5.2 Sea surface

The sea surface causes reflection of acoustic waves which leads to phase shift of 180^0 to the acoustic signal. This results in a destructive multipath interference and signifi-

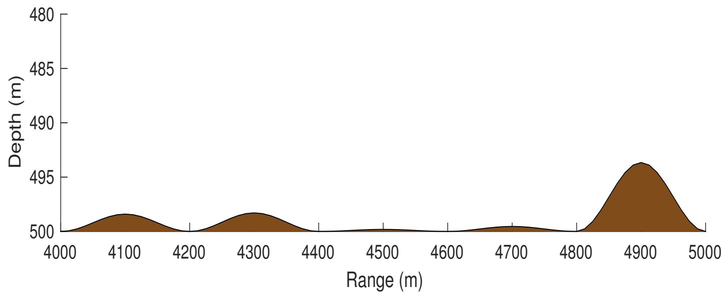


Figure 3.5: Sinusoidal bathymetry with 200 m long hills and random hill height.

cantly influence the multi-path structure of underwater acoustic channel [137].

In order to accurately represent a sea surface to realize scattering patterns of signal paths, the omnidirectional Pierson-Moskowitz's spectral model [136, 138] given in Equation (3.2) is utilised.

$$\mathscr{S}_{PM}(k) = \frac{\alpha}{2k^3} \exp\left[-\beta(\frac{g}{k})^2 \frac{1}{U^4}\right] \quad [\mathrm{m}^2/(\mathrm{rad/m})], \tag{3.2}$$

where $\alpha = 0.0081$, $\beta = 0.74$, the acceleration of gravity, $g = 9.82\,\mathrm{m\,s^{-2}}$, U in m s^{-1} is the speed of wind at 19.5 m above the surface, and $k = \frac{2\pi}{\lambda}$ is the angular spatial frequency in rad m^{-1} where, λ is the wavelength in m.

The method described in [134] is used to obtain a realization of the random surface wave. The impulse response of all the multipath arrivals of a BELLHOP ray tracing based on the model of Equation (3.2) is depicted in Figure 3.6. It shows the change in the multipath arrivals caused by the simulated sea surface of the assumed model. The Gaussian beams ensure that more multipath components are traced to the receiver which provide a more accurate amplitude estimation.

3.2.5.3 Beam model

Typically, Gaussian [139] (where Gaussian intensity profile is used to broadly spread the energy of the beam) and geometric [133] (where only the rays with hat-shaped boundary enclosing the receiver location are considered by separating the beams at the departure point) are used for underwater acoustic propagation model. A Gaussian beam spreading model is considered here, because, it produces a more accurate estimates of the total acoustic intensity at the receiver [139]. An example set of arrivals

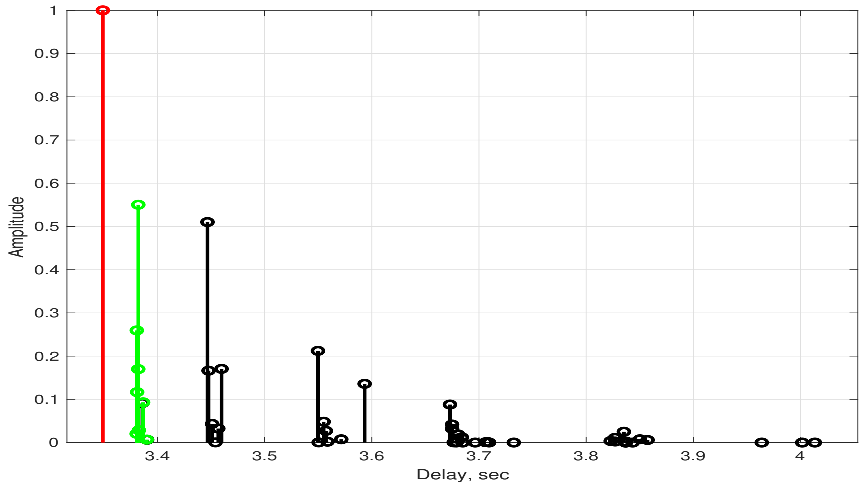


Figure 3.6: BELLHOP Impulse response of Gaussian beams based multipath arrivals in the UAC propagation model.

produced by Gaussian based beam tracing simulation is shown in Figure 3.7, the signal at the receiver are reflected off the sea surface at different random angles.

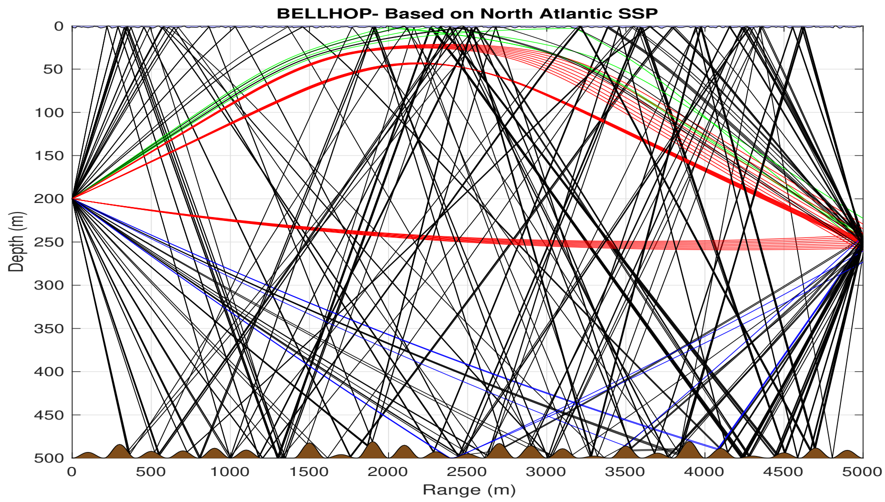


Figure 3.7: BELLHOP ray tracing of signal from the receiver to the source based on Pierson-Moskowitz sea surface model, bathymetry model sea bed and Gaussian beams.

3.2.5.4 Received Signal Power

The channel impulse response data comprising of the attenuation, phase and delay of multipath components is used to compute the total wideband received signal power. The wideband signal power considered ensures the negligible frequency bandwidth are considered. The BELLHOP based ray tracing is used to compute the distance-dependent channel characteristics of each path. While, the absorption loss, which depends on both the distance and frequency is calculated for any specified frequency. The overall channel gain, G (the ratio of received signal power, P_{rx} at the receiver to transmitted signal power, P_{tx} at source) is calculated based on the method described in [134] using the following model:

$$G = \int_{f_{\text{min}}}^{f_{\text{max}}} \left| \sum_{n=1}^{N} A_{\text{spr}}[n] A_{\text{abs}}(n, f) e^{j(-2\pi(\tau[n]-\tau_0)+\theta[n])} \right|^2 df, \tag{3.3}$$

where f_{min} and f_{max} are the channel's minimum and maximum frequencies respectively, N is the total number of the multipath components, $A_{\text{spr}}[n]$ is the spreading loss of the n^{th} path, $A_{\text{abs}}(n, f)$ is the absorption loss of the n^{th} path at frequency f, $\theta[n]$ is the phase shift of the n^{th} path, $\tau[n]$ is the propagation delay of the n^{th} path, and τ_0 represent the propagation delay of the first received signal path.

Figure 3.8 shows the calculated received signal strength (P_{rx}) of a wideband signal considering 170 dB re µ Pa at 1 m source level and 480 m source depth.

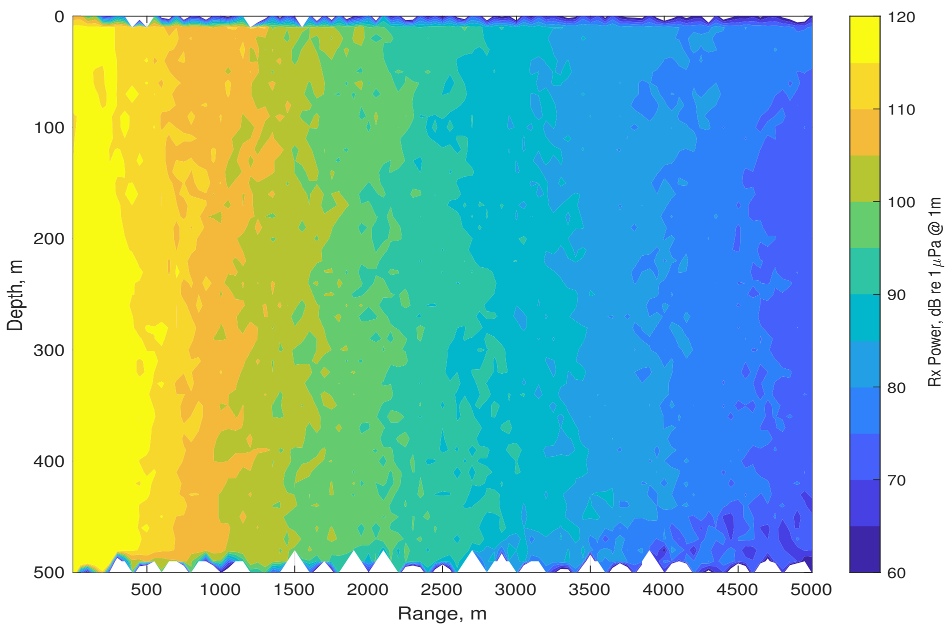


Figure 3.8: Wide band signal strength at receiver for 170 dB re µ Pa at 1 m, source at 480 m depth.

In order to create a manageable and computationally efficient data of the propagation model for network simulation which in some cases involve large networks with several links, the multipath arrival data is compressed. As can be seen in Figure 3.6, there are several components of multipath arrivals, most of these components have near-zero amplitude of impulse response and have negligible effect on the channel properties. Thus, the multipath arrival data is compressed to account for strongest signal paths such as paths constituting 99% or 95% of the total received signal power. This is done without losing the majority of the channel information. Figure 3.9 shows the impulse response of both 99% or 95% of total received signal power, where, the multipath components have been reduced to 13 and 8 respectively.

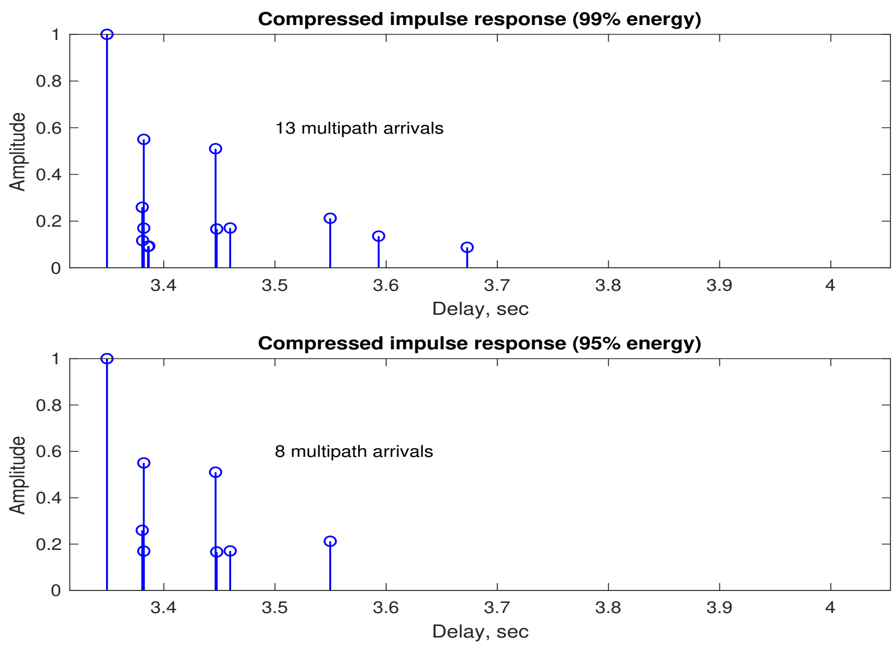


Figure 3.9: BELLHOP Impulse response of 99% and 95% total received signal power.

3.2.5.5 Ambient Noise Power

A well established ambient noise model [59] is used to calculate acoustic noise at the receiver with the power spectral density

$$N_{ambient}(f) = logN_t(f) + N_s(f) + N_w(f) + N_{th}(f). \tag{3.4}$$

The components in Equation (3.4) are described as

$$N_t(f) = 17 - 30logf, \tag{3.5}$$

$$N_s(f) = 40 + 20(s - 0.5) + 26logf - 60log(f + 0.03), \tag{3.6}$$

$$N_w(f) = 50 + 7.5w^{\frac{1}{2}} + 20logf - 40log(f + 0.4), \tag{3.7}$$

$$N_{th}(f) = -15 + 20logf, \tag{3.8}$$

where N_t, N_s, N_w and N_{th} are the turbulence, shipping, wind and thermal noise components, respectively. The shipping activity factor, s is set between 0 and 1, representing low and high activity, respectively, and the wind speed w is given in m s^{-1}.

3.2.5.6 Signal-to-Noise Ratio (SNR)

SNR is a measure of the desired signal level compared to the noise level. In other words, it is the ratio of the received signal power to the noise power, given as:

$$\text{SNR} = \frac{P_{\text{signal}}}{P_{\text{noise}}} = \frac{P_{\text{rx}}}{P_{\text{noise}}}, \tag{3.9}$$

where P_{rx} is the received signal power and P_{noise} is the noise power. Given a channel with the gain:

$$G = \frac{P_{\text{rx}}}{P_{\text{tx}}}, \tag{3.10}$$

where, P_{tx} is the transmitted signal power, and expressing the P_{noise} as the integral of the noise PSD between minimum and maximum frequencies, the SNR is computed as

$$\text{SNR} = \frac{GP_{\text{tx}}}{\int_{f_{\text{min}}}^{f_{\text{max}}} N_{\text{ambient}(f)df}}, \tag{3.11}$$

where GP_{tx} is the received signal power, G is the channel gain, P_{tx} is the transmitted signal power and $N_{\text{ambient}}(f)$ is the noise PSD between the lower and upper limit of the communication frequency band of the communication system. Figure 3.10 shows the SNR as a function of range and depth for the source at 480 m depth and source level of 170 dB re µ Pa at 1 m, 24 kHz center frequency and 7.2 kHz bandwidth. Assuming a source placed at 480 m, and a minimum SNR of 0 dB is required to decode a signal (transmitted at 170 dB re 1 μPa at 1 m) at the receiver, then, the source-receiver range can be approximated as 3.5 km as can be seen in Figure 3.10. In this case, we neglect residual self-interference in the case of full-duplex nodes.

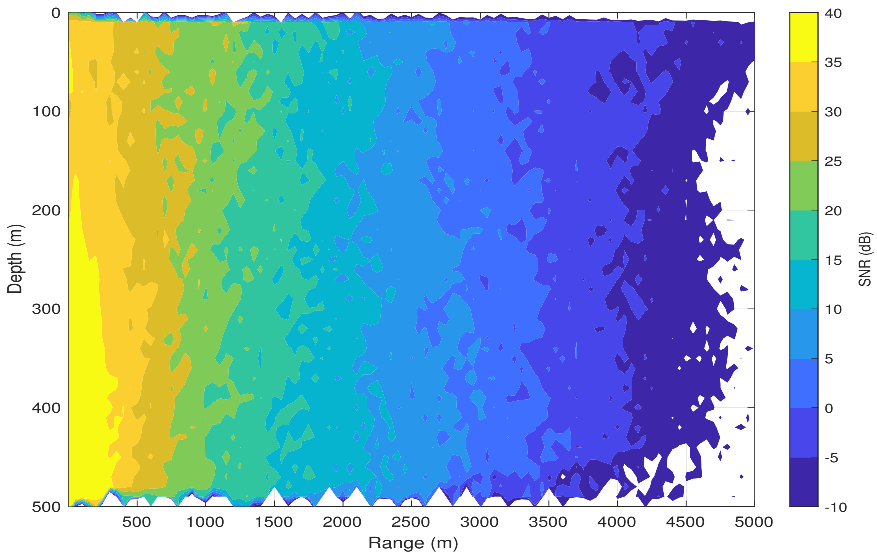


Figure 3.10: SNR as a function of range and depth for the source at 480 m depth, source level: 170 dB re 1 μPa at 1m, 24 kHz centre frequency and 7.2 kHz bandwidth.

3.2.6. Channel model

This section builds on the underwater acoustic propagation model described in Section 3.2.5 and describes how the propagation model comprising hundreds or thousands of links is realised for network simulation. The links are modelled setting the maximum number of links to $\frac{1}{2}N(N-1)$, where N is the number of transmitting nodes in a given scenario.

The channel model is firstly simulated and the results of the simulated channel data generated using BELLHOP is formatted into a 'lookup table' and fed into a MATLAB based network simulator alongside ambient noise power model described in the acoustic propagation model. This approach ensures that the channel simulation is separated from the network simulation, this provides better computational efficiency.

The 'lookup table' contains the channel metrics (channel gain in dB between the source and the receiver, channel propagation delay in s of the first received path and multipath channel delay spread in s). Channel delay spread can be represented as $(A_{\text{last}} - A_{\text{first}})$, where A_{last} and A_{first} are the last and first multipath arrivals, respectively. As earlier described in the propagation model, the strongest multipath components amounting to about 95% of the total received signal power are considered. The channel model uses the ambient noise power model described in the propagation model for SNR calculation.

The acoustic channel is modelled by simulating the link between given pair of source and receiver nodes several times. This generates a statistical characterisation of the underwater acoustic channel. This statistical channel model based on BELLHOP simulations ensures that the small scale random spatial variations of the underwater environment (sea surface), the receiver and the source are accounted for. In this model, source-receiver spatial variation is set to 50 allowing the generation of 50 times random spatial variations of both the source and the receiver nodes within a given radius sphere, which in this model is set to 10 m. The channel is then simulated for every combination of 2500 (50 X 50) source-receiver nodes locations. This means that 2500 channel variations are generated for every simulation run. The simulation is repeated several times with a different seed value to create randomness, thereafter, average channel realization is calculated and stored in the lookup table. Thus, the channel simulator takes the propagation model (described in Section 3.2.5), set of node positions, frequency bandwidth (7.2 kHz, between 20.4 and 27.6 kHz), wind speed, and shipping factor based on the North Atlantic sound Speed Profile (SSP) and generate the required 'lookup table' data. The channel gain, propagation delay and delay spread of a typical scenario comprising of a 10 km pipeline and 11 sensor nodes arranged in multi-hop linear fashion deployed at a depth of 480 m are depicted in Figures 3.11 to 3.13.

3.2.7. Simulation model

The network simulator implemented in MATLAB incorporates the results of the channel model described in Section 3.2.6 to implement network protocol algorithm(s) based on a certain network topology to generate as output the frame duration, end-to-end (E2E) packet delays and number of collisions incurred.

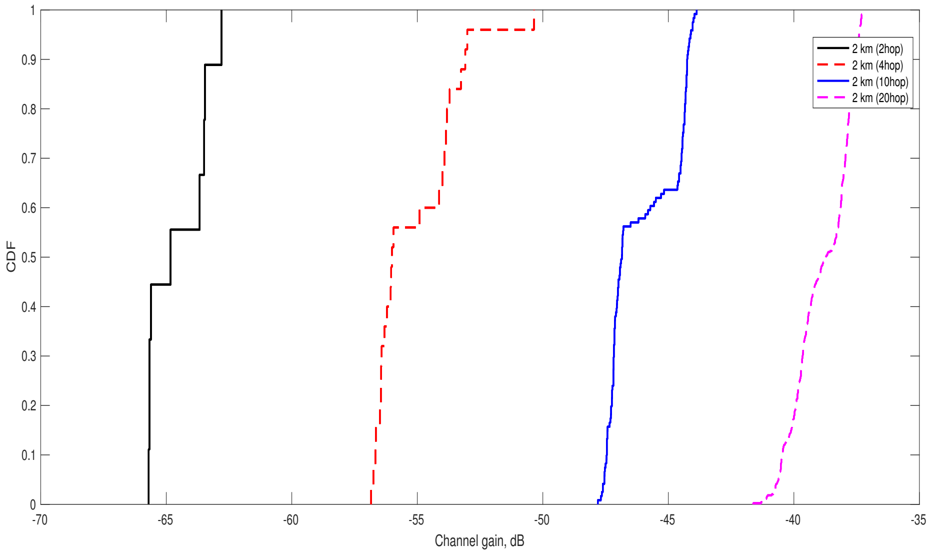


Figure 3.11: cdf of channel gain for a 2 km pipeline network topology.

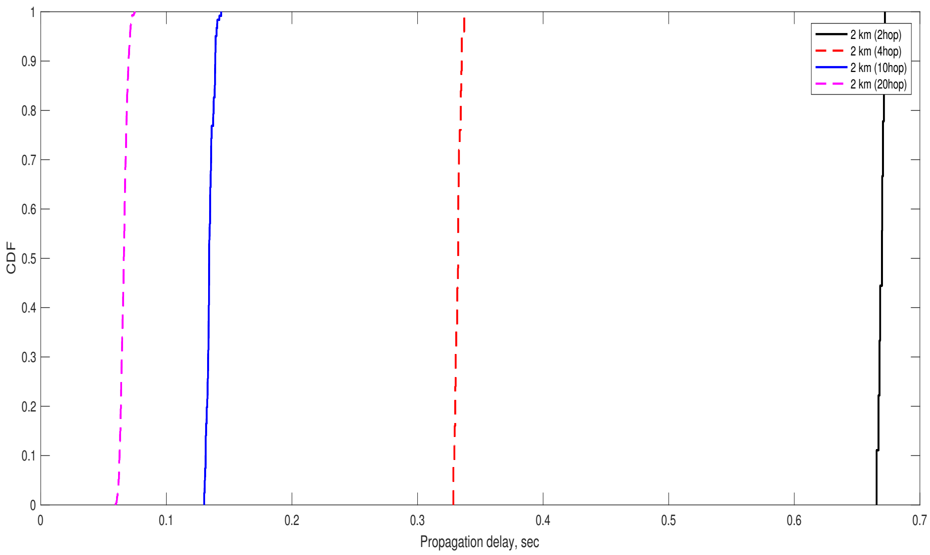


Figure 3.12: cdf of propagation delay for a 2 km pipeline network topology.

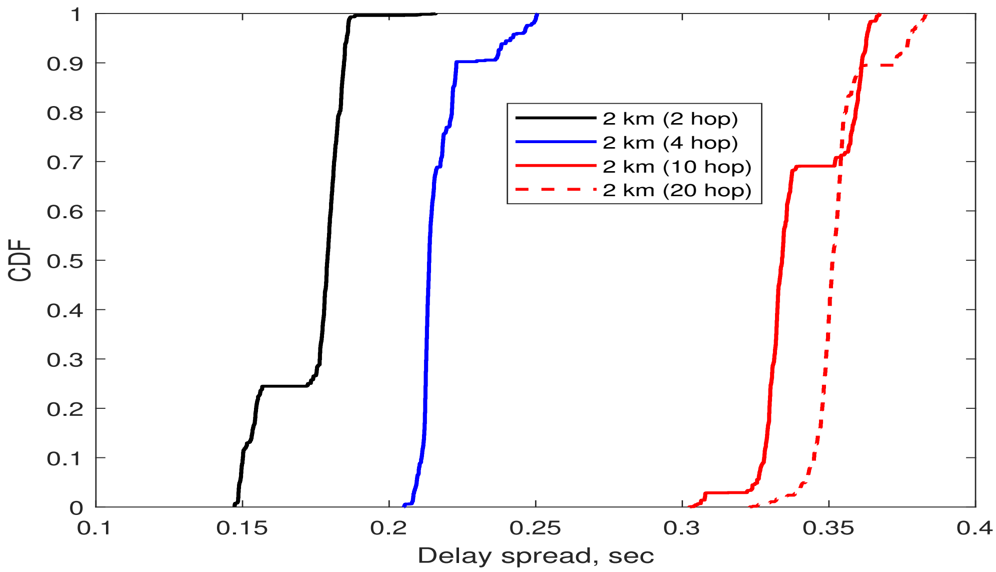


Figure 3.13: cdf of delay spread for a 2 km pipeline network topology.

3.2.7.1 Simulation Scenario Description

This section describes the network simulation scenarios that the network simulator implements. This section presents a general case as an illustration of a subsea pipeline monitoring scenario. The generic architecture is a multi-hop linear network with many transmitting sensor nodes, N_{tx}, and a single sink node, N_m. Except for the last node, all transmitting nodes act as relay nodes. The nodes are linearly placed near the seabed and are spaced equidistantly apart by either 1 km or 2 km. The equidistant range is consistent with the physical limit of the nano-modem used in [10], however in other instances, the equidistant range is less or more than the modem's physical limit to explore the best and worst cases.

2500 channel realizations are generated for each hop distance using the statistical channel model. Thus, for networks with a n-hop topology, this gives rise to $(n-1)$ distinct channel 'lookup tables,' where n is the network's hop count. To construct a complete network model, the channel gain, propagation delay, and delay spread of each link are randomly allocated from a corresponding 'lookup table'. Additionally, the $(N \times N)$ interference binary matrix, $\boldsymbol{I}$, is used to define the complete network topology. This specifies which nodes in the network are permitted to interfere with one another's transmissions. The $\boldsymbol{I}$ value for a link pair (source and receiver) is denoted as $I[i, j]$, where i and j are nearby nodes on either side of the link. If $i = j$, it indicates that the link is free of interfering nodes based on the 0 dB SNR threshold for signal reception. However, if $i \neq j$, which indicates that a signal from node i is received at node j with a signal-to-noise ratio (SNR) of ≥ 0 dB, the nodes are deemed to be interfering. A sample simulated node deployment scenario including a 10-kilometer-long pipeline and 11 sensor nodes is depicted in Figure 3.14, the source is deployed at a 480 meters depth together with nine relay nodes and a sink node. The nodes' positions indicate an average of random node displacements within a 10 m radius sphere.

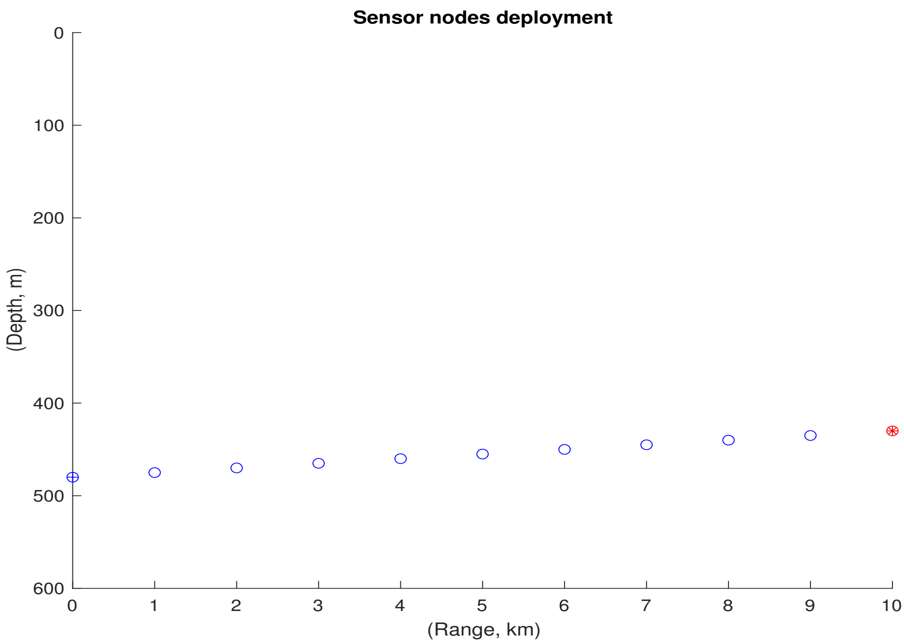


Figure 3.14: Node deployment for a 10 km, 10 hop scenario.

The key parameters used for the channel models and simulation in this thesis is shown in Table 3.3.

3.3. Empirical Evaluation

In order to evaluate the developed MAC protocol, the following network performance metrics are defined:

- Frame duration: this refers to the time taken to complete transmitting a frame from the beginning to the end of the frame
- End-to-end (E2E) packet delays: The E2E packet delays is a measure of the time taken for a packet to be transmitted across the underwater chain network from a

Table 3.3: Channel and simulation Parameters [10].

Parameter	Value
Transmit power (Small scale scenarios)	140 dBrePa^{2}m^2
Transmit power (Medium and large scale)	170 dBrePa^{2}m^2
Noise power	85 dBrePa^{2}m^2
$\tau_d p$ (Small/Medium and Large scale)	200 ms / 500 ms
$\tau_r p$ (Small/Medium and Large scale)	50 ms / 100 ms
τ_g (Small/Medium and Large scale)	25 ms / 100 ms
Acoustic modem range	1 km / 2 km
Centre frequency/Bandwidth	24 kHz / 7.2 kHz
Acoustic data rate	640 bits/s
Shipping activity factor	0.5
Wind speed	10 m/s
wave resolution	10
Sound speed profile	North Atlantic Ocean SSP
Pipeline length (L)	2 km to 1000 km
Number of hops (H)	2 to 1000 hops
Impulse response cut off point	0.95
Source depth	480 m
Receiver depth	10 m
Water depth	500 m
Hill length	200 m
Maximum hill length	20 m
Number of rays (Gaussian beams)	1001
Minimum angle (Gaussian beams)	-90
Maximum angle (Gaussian beams)	90
Number of sensor nodes	3 to 1000
Random movement within sphere	10 m

transmitting node to the sink node.

- Monitoring rate: this is inversely proportional to the frame duration. It defines the rate at which sensor data can be accessed, which indirectly provides an information about the network throughput and the channel utilisation of the network. Monitoring rate on the other hand, is a function of frame duration. Similarly, throughput is a function of frame duration and in this case inversely proportional to frame duration. The less the frame duration, the more the throughput, hence, the better the monitoring rate. Thus, the cdf plots of frame duration indirectly shows the results of the throughput, hence provides the information on QoS of the network.

3.3.1. Result Validation

In order to ensure that the developed models are valid and that key results presented are statistically correct, the following approaches are employed where applicable.

- The cumulative density function (cdf) plots of network performance in terms of frame duration contains data points that are obtained through about 100 simulation runs using different random seeds.
- A model of a state-of-the-art system is firstly reproduced and the generated results validated against the results of the state-of-the-art presented in Chapter 4. This ensures that the models are correctly represented.

3.4. Summary

The study and experimental methodology utilized to evaluate the proposed full-duplex MAC protocols in this thesis are described. The system level simulation model is based on a linear underwater acoustic chain network in a pipeline monitoring scenario. Additionally, an underwater acoustic environment is characterised using a BELLHOP ray tracing-based channel model. Frame duration, E2E packet delays, and monitoring rate are the primary network performance measures utilized in the performance evaluation. The parameters stated here are used throughout the remainder of this thesis's simulation experiments.

Chapter 4. LTDA-MAC protocol in Full-duplex Underwater Chain Networks

4.1. Introduction

The purpose of this chapter is to investigate the potential performance gains that could be achieved in full-duplex network scenarios using the LTDA-MAC protocol. This follows on from [8] and [9] which apply the LTDA-MAC to a half-duplex chain underwater network. Consequently, this can allow simultaneous transmission and reception and thereby enhance spatial spectrum reuse and efficient packet scheduling to achieve high monitoring rates over long range underwater pipelines using low cost, mid range, low rate and low power acoustic modems such as those presented in [10]. This study also shows the benefits that can be achieved from the LTDA-MAC protocol simply by switching on full-duplex capabilities without having to change the protocol. Additionally, this chapter investigates the merits of a multi-hop relay network to improve network coverage especially for long range applications such as underwater oil and gas pipeline monitoring.

Establishing communication between nodes in underwater linear networks for applications such as offshore petroleum exploration and underwater pipeline monitoring is a difficult task due to the intricate properties of underwater channels ([13–15, 83]. As a result, developing a MAC protocol for UANs is challenging in the presence of the aforementioned underwater channel characteristics, and techniques employed in terrestrial radio networks are either unsuitable or result in low throughput, high latency, and low energy efficiency [11, 140]. Numerous half-duplex MAC techniques have been developed to increase network performance in UANs. These protocols are either contention-free, such as Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), Code Division Multiple Access (CDMA), or Space Division Multiple Access (SDMA), or they are contention-based, such as carrier sensing, handshaking, or random access techniques [16].

However, issues with QoS and energy efficiency persist, owing to the underwater channel's long propagation delays and limited available bandwidth [141]. These performance issues become more pronounced in multi-hop UANs. In a similar vein, long propagation delays introduce uncertainty into the prediction of channel idle/busy status, reducing the effectiveness of carrier sense protocols in UANs, an impact that is magnified in multi-hop UANs. Additionally, handshaking techniques such as Request-To-Send/Clear-To-Send (RTS/CTS) based protocols [80, 103, 105, 142] are significantly impacted by long propagation delay, as well as other issues such as low scalability and robustness, putting their suitability for multi-hop UANs into question. The LTDA-MAC protocol was developed to improve network performance and efficiency by optimizing packet scheduling in linear UASN-based pipeline monitoring systems that do not require sensor node clock synchronization [8, 9]. The rationale for adopting LTDA-MAC for this application was discussed in Chapter 2. Alternatively, in-band full-duplex communication holds great promise for enhancing the spectrum efficiency and throughput of acoustic communication systems [71, 77, 143]. Interestingly, this can address several MAC layer issues by potentially enhancing network performance in terms of increased throughput and low latency, as well as by allowing a node to sense the channel while receiving a packet [144–148].

The purpose of this chapter is to examine the potential performance advantages that could be realized using the LTDA-MAC protocol in full-duplex network scenarios. This builds on [8] and [9], in which the LTDA-MAC is applied to a full-duplex chain underwater network. As a result, this enables simultaneous transmission and reception, enhancing spatial spectrum reuse and packet scheduling efficiency, allowing for high monitoring rates over long distance underwater pipelines using low-cost, mid-range, low-rate, and low-power acoustic modems such as those described in [10]. Additionally, this study demonstrates the benefits of the LTDA-MAC protocol merely by enabling full-duplex capabilities without modifying the protocol. Additionally, this chapter discusses the advantages of a multi-hop relay network in terms of increasing network coverage, particularly for long-range applications such as underwater oil and gas pipeline monitoring.

4.2. LTDMA-MAC Protocol

LTDA-MAC is a protocol that utilises packet schedule optimization to generate efficient packet schedules devoid of collisions with significantly shorter frame duration for UASN without the need to synchronize sensor node clocks. It uses on line optimization to derive a short frame duration and short packet delays to avoid collisions at the nodes. LTDA-MAC schedules packet transmission times based on delays accrued at nodes as the time difference between a request (REQ) packet and transmission of data packets.

Two communication steps are defined for the LTDA-MAC operation. The first step involves the transmission of a data packet from a node (acting as a source node) up the chain after receiving a REQ packet, while, at the second step, a node (acting as a relay) forwards a data packet up the chain after receiving a data packet from a node further down the chain. The transmit delays introduced due to the first and the second steps define the LTDA-MAC schedules.

The earlier version of LTDA-MAC [8] uses a Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) to jointly find good sub-optimal packet schedules for transmissions. Furthermore, an improved version of LTDA-MAC is presented in [9] which uses a greedy optimization algorithm. The later version shows a significantly improved packet schedules with shorter frame durations and lower computational cost.

4.2.1. Network model

LTDA-MAC has been evaluated for a Half-Duplex (HD) based Linear Underwater Acoustic Sensor Network (LUASN) topology in [8] and [9]. The network is considered to have a one-hop interference range and can be simplified as shown in Figure 4.1.

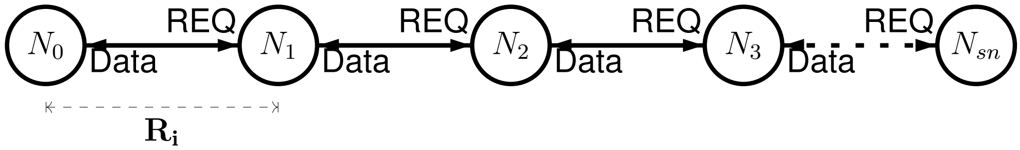


Figure 4.1: Linear chain UASN.

The network comprises N_{sn} half-duplex sensor nodes (relay sensor nodes plus a master node N_0) deployed linearly as (N_0, N_1, N_2, N_3, ... N_{sn}) having an interfering range of R_i as depicted in Figure 4.1. The principle operation of LTDA-MAC scheduling is summarised in Figure 4.2.

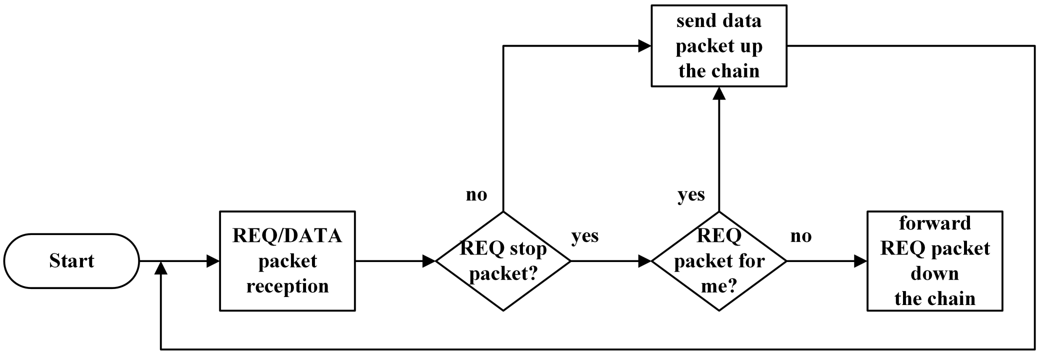


Figure 4.2: LTDA-MAC network node operation.

4.2.2. LTDA-MAC optimization model

Given that the LTDA-MAC version presented in [9] has shown a significant improvement in performance compared to its predecessor presented in [8], it is pertinent to consider and describe the improved version here. The greedy optimization algorithm proposed in [9] produces a good sub-optimal solution for packet schedules by iterating over each transmit delay in transmit delay space (a triangular matrix of transmit delays, $\boldsymbol{T_{tx}}$). The two communication steps described in Section II are defined as constraints imposed on the transmit delays.

Consider a node, N_i, acting as a source node sending its own data packet up the chain after receiving a REQ packet with a transmit delay $T_{tx}[i, i]$. The node acting as a relay node receiving a data packet from a node, N_j down the chain and forwarding it up the chain has a transmit delay $T_{tx}[i, j]$ (i.e $i < j$). The optimization algorithm uses interference and propagation delays conditions to find a good sub-optimal solution for $N_{sn}(N_{sn} + 1)/2$ in $\boldsymbol{T_{tx}}$ as the minimum frame duration. As detailed in [9], the minimum frame duration is given as min $\tau_{\text{frame}}(\mathcal{N}, \boldsymbol{T_{tx}})$ (the turn around time of sending the initial REQ packet and receiving the final data packet by the sink node) in the presence of zero packet collisions, $\eta_{col}(\mathcal{N}, \boldsymbol{T_{tx}}, \tau_g)$, where, $\mathcal{N}$ and τ_g denote a given network topology and guard time, respectively. The minimum transmit delay, $T_m[n, n]$ for the first and second communication steps are given in [9] as:

$$\forall n \in \{1..N_{sn}\}\,,\ T_m[n,n] = \begin{cases} \tau_{rp} + 2\tau_g, & n < N_{sn} \\ \tau_g, & n = N_{sn} \end{cases}, \tag{4.1}$$

and

$$\begin{gathered} \forall n,k \in \{1..N_{sn}\}\,, k > n, \\ T_m[n,k] = 2(\tau_p[n+1] + \tau_g) + \tau_{rp} + \tau_{dp} + T_{tx}[n+1,k], \end{gathered} \tag{4.2}$$

where τ_{rp} represents the REQ packet duration, τ_{dp} denotes the data packet duration, τ_g is the guard time, $\tau_p[i]$ is the propagation delay on the link between the i^{th} and $i+1^{th}$ nodes and $T_{tx}[n+1,k]$ is the transmit delay between $(n+1)^{th}$ receiving a REQ packet and transmitting the data generated by node k.

The packet collision term, $\eta_{col}(\mathcal{N}, \boldsymbol{T_{tx}}, \tau_g)$, is calculated using the transmit and receive times of each packet in a frame. Hence, for the HD case, any overlap in a pair of transmit/receive packets at the same node signals a packet collision and increases the value of $\eta_{col}(\mathcal{N}, \boldsymbol{T_{tx}}, \tau_g)$ by 1. However, the above collision rule is relaxed for the case of FD and so transmit/receive packets overlapping in time at the same node are not counted as collisions and in this case $\eta_{col}(\mathcal{N}, \boldsymbol{T_{tx}}, \tau_g)$ is not incremented. More information on the derivation of (4.1) and (4.2) can be found in [9].

The greedy optimization algorithm iterates through each value in $\boldsymbol{T_{tx}}$ in the order that maximises the probability of scheduling concurrent spatially separated transmissions. It begins by evaluating the LTDA-MAC schedule for each transmit delay $T_{tx}[i,j]$ using $T_{tx}[i,j] = T_m[i,j]$, i.e., the smallest possible value according to (4.1) and (4.2). If the schedule contains collisions, $T_{tx}[i,j]$ is incremented by a step and the schedule is assessed again. This incremental search will continue until the schedule is clear of collisions.

4.3. Application of LTDA-MAC protocol in full-duplex Scenarios

The description of the full-duplex network topologies used to investigate the performance of the LTDA-MAC protocol in full-duplex scenarios is presented in this section. The linear chain network topology is retained but the nodes are able to operate in full-duplex fashion rather than half-duplex. Figure 4.3 depicts full-duplex communication in a linear underwater chain network, and it also follows the same network operation as summarised in Figure 4.2, only that the relay nodes are able to transmit and receive simultaneously in time and frequency. This allows the nodes to send and receive REQ or data packets in-band thereby potentially improving LTDA-MAC schedules unlike the HD topology in Figure 4.1 where sending and reception of REQ or data packets cannot happen at the same time within the same band.

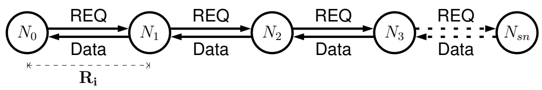
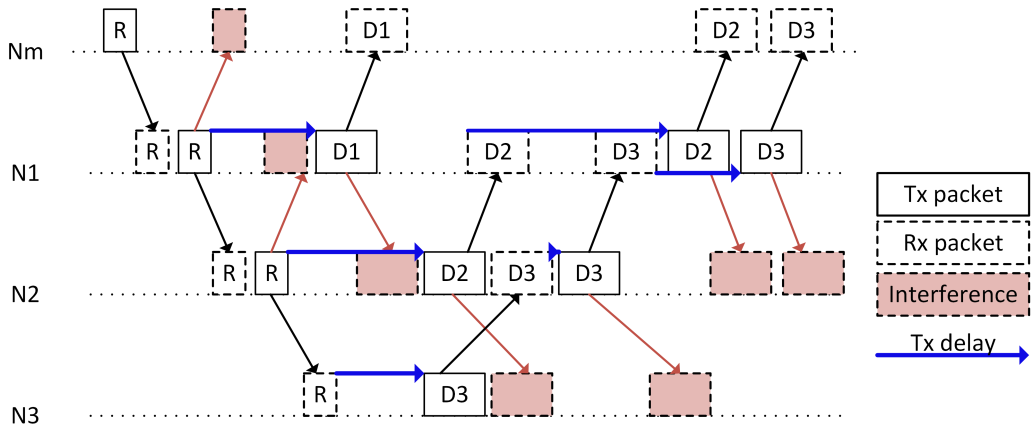


Figure 4.3: FD-based LUASN network scenario.

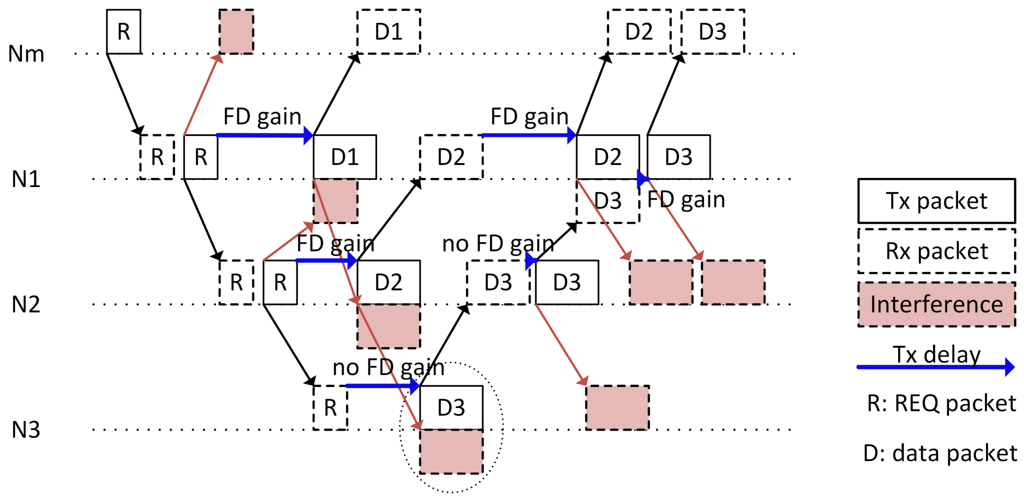
Considering a one-hop interference range example, the corresponding LTDA-MAC schedule is depicted in Figure 4.4.

Comparing the frame length in full-duplex scenario depicted in Figure 4.4 (b) to that in half-duplex scenario shown in Figure 4.4 (a), it can be observed that a significant reduction in frame length is possible with full-duplex scenario. This is because, in the full-duplex case, overlap between packet transmission and reception in a node is possible and thus, reduce the frame duration that is accounted for as the FD gain (a measure of the reduction in frame duration of FD compared to HD) in Figure 4.4 (b).

Transmit delay is a major parameter of packet scheduling in LTDA-MAC as shown in [8] and [9]. The solution produces a minimum transmit delay thereby producing the shortest possible frame duration. For any node N_i to transmit its own data packet up the chain and to forward a REQ packet down the chain, the minimum transmit delay, $T_m[n, n]$ to be ensured as modified from (4.1) to account for full-duplex operation is:



(a) HD network scenario [9]



(b) FD network scenario

Figure 4.4: Typical LTDA-MAC schedules in three-hop network.

$$\forall n \in \{1..N_{sn}\}\,,\; T_m[n,n] = \begin{cases} \tau_{rp} + \tau_g, & n < N_{sn} \\ \tau_g, & n = N_{sn} \end{cases}. \tag{4.3}$$

Comparing (4.3) with (4.1), we can see that a transmit delay reduction that is proportional to a half of the guard time can be saved in this operation compared to the HD case and this further explains the transmit delay gain obtainable for the topology shown in Figure 4(b).

Algorithm 1 is used to ensure that full-duplex communication is possible at the sensor nodes without causing any collisions. Initialization of integer flags for different types of events is accomplished by assigning 1 to Tx, 2 to Rx, and 3 to INTF (interference) in the order listed above. It then calculates the transmit/receive times for all of the packets sent and received by the nodes in the network. This is followed by a looping through each node in order to compute the number of packet collisions by comparing the start of the second event with the start of the first event. With the exception of the following event types: Tx/Rx, Rx/Tx, Tx/INTF, INTF/Tx, and INTF/INTF, if the start of the second event is sooner than the end of the first event plus a guard interval, τ_g, an overlap in event durations is detected and the packet(s) is or are deemed collided. Because of the full-duplex communication, the event types TX/RX, RX/Tx, Tx/INTF, and INTF/Tx are not detected as collisions, but rather as successful packet transmission and reception at the intended nodes.

4.4. Performance of LTDA-MAC in FD scenarios

The simulation procedure used to evaluate the performance of LTDA-MAC for full-duplex pipeline monitoring scenarios is based on BELLHOP beam tracing method described in Chapter 3 to generate a statistical underwater channel characterisation for the scenarios considered in this section. The scenarios are categorised as small, medium and large scale in accordance with the pipeline lengths and modem ranges of 1 km and 2km respectively, taking into account the capabilities of the considered acoustic modem with 1 km being a reliable range and 2 km approaching the range limit.

Algorithm 1 Collision-free full-duplex transmission at the nodes

```
Define integer flags for types of events (Tx=1, Rx=2, INTF=3)
Calculate all packet Tx/Rx times
Initialize number of collision (col = 0)
for n ∈ {1..N_sn} do
    Create Tx/Rx event types (type 1 and type 2)
    Create Tx/Rx event times (time 1 and time 2)
    Create event duration (τ_tx, τ_rx and τ_I)
    Calculate number of events (event_no) as sum of event times
    for type 1 = (1..event_no − 1) do
        for type 2 = type 1 + (1..event_no) do
            if (type 1 = Tx and type 2 = Tx) or (type 1 = Rx and type 2 = Rx) or
            (type 1 = INTF and type 2 = INTF) or (type 1 = INTF and type 2 = Rx) then
                if (time 1 + type 1 event duration +τ_g + 10^−3) > time 2 then
                    increment col
                else
                    break (stop checking for overlap with subsequent events)
                end if
            end if
        end for
    end for
end for
```

This evaluation focuses on this particular modem and its range capability due to its low cost which makes it feasible to consider deploying large number of monitoring devices. A further benefit of considering relatively short range acoustic communication is the provision of regular monitoring points for the detection of problems such as leaks and movement of pipelines. The key modem, channel and simulation parameters can be found in Table 3.3 of Chapter 3.

4.4.1. LTDA-MAC schedules

Figures 4.5 and 4.6 show simulated LTDA-MAC schedules for both HD and full-duplex network scenarios for a 10-hop 2 km pipeline. As can be seen from Figure 4.5, packets are correctly received at the desired destination nodes despite the overlap in time between the transmit and interference packets. The correct reception of packets in the presence of overlap in time is made possible as result of the simultaneous transmit and receive capability of full-duplex communication, this is in contrast with Figure 4.6 which does not allow in-band transmission. As a result, frame durations and end-to-end mean packet delays are shorter in the full-duplex scenario compared to the HD scenario. The implication of this significant improvement is discussed as follows.

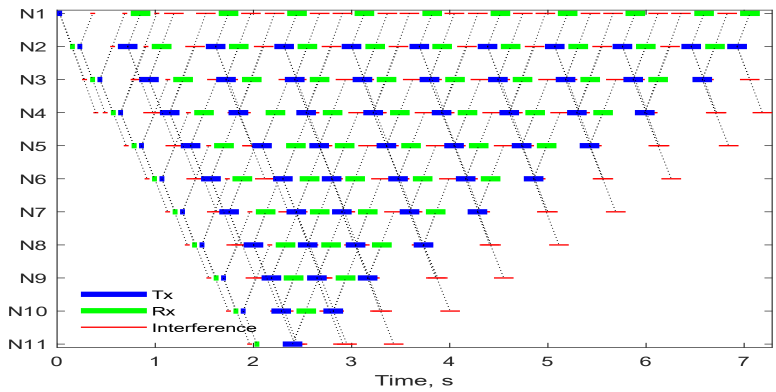


Figure 4.5: LTDA-MAC schedules for full-duplex 2 km 10-hop scenario.

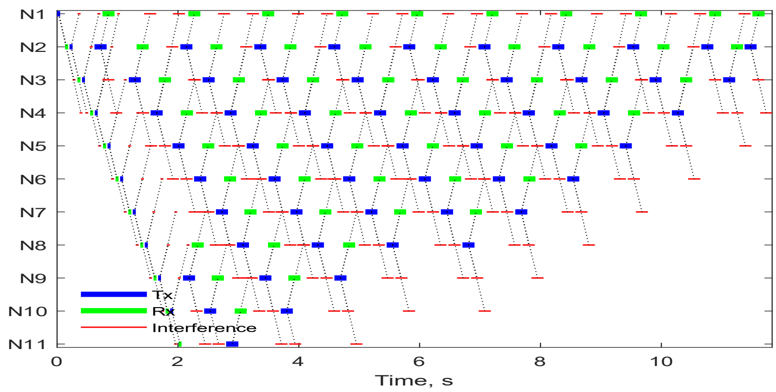


Figure 4.6: Illustration of LTDA-MAC schedules for half-duplex 2 km 10-hop scenario [8].

4.4.2. Monitoring rate and Delay

Results presented in this section consider short pipelines of a few kilometres to longer pipelines of several thousands kilometres. Short pipelines are considered in order to understand the benefits of full-duplex communication in simple situations where there is a limited opportunity and requirement for spatial re-use. The longer pipelines correspond to underwater oil and gas pipeline monitoring systems that in many cases span thousands of kilometres such as the Langeled pipeline in the North Sea measuring about 1,200 km [63], and the 7,200 km long pipelines under the gulf of Mexico [149].

In order to validate the correctness of the results obtained, we first depict in Figure 4.7 the graph comparing the cumulative distribution function (cdf) of frame durations of

LTDA-MAC with FD nodes against established results of Spatial TDMA (STDMA) and LTDA-MAC as presented in [9] for a simulated 2 km pipeline.

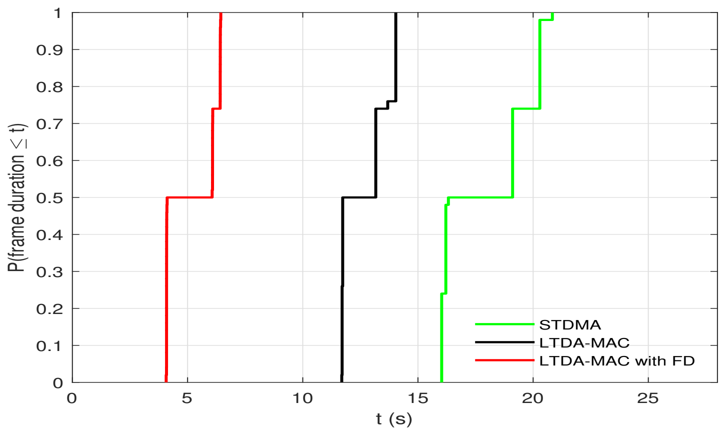


Figure 4.7: Packet schedules in STDMA, LTDA-MAC and LTDA-MAC with FD nodes for a 2 km pipeline.

Comparing the LTDA-MAC protocol with FD nodes to the LTDA-MAC protocol traditionally deployed with HD nodes and the typical Spatial TDMA protocol for the scenario, the LTDA-MAC with FD nodes provides much better packet scheduling with shorter frame duration, resulting in significantly improved throughput.

Afterwards, as illustrated in Figures 4.8, 4.9, 4.10 and 4.11, we present the cdfs of frame durations for each of the scenarios considered in this chapter. Particularly , frame duration is crucial because it determines the frequency with which each node can transmit a new sensor reading; in other words, it is inversely proportional to the network throughput. Therefore, the shorter the frame duration, the better the packet scheduling and the higher the throughput of the network. It can be observed in Figures 4.8, 4.9 and 4.10 that the frame durations derived for full-duplex cases are much shorter than those derived for half-duplex cases. As a result of this capability, improved packet scheduling are obtained, which results in a significant increase in network throughput.

Applications such as leak detection necessitate timely sensor readings at predetermined intervals, as well as a high level of resolution in the data collected. The findings of HD cases, particularly for longer pipelines (50 km and 100 km), as shown in Figure 4.11, demonstrate that high monitoring rates are not possible, with intervals of approximately 3000 and 4500 seconds per sensor node, respectively. This may be too

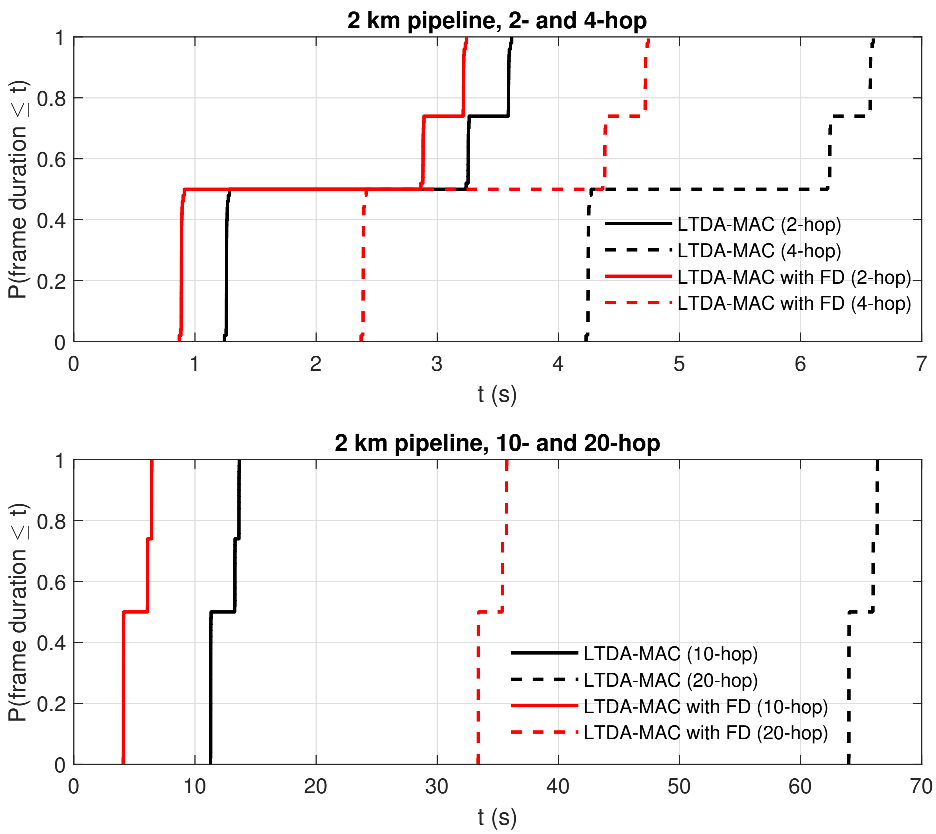


Figure 4.8: LTDA-MAC packet schedules in HD versus FD for 2 km pipeline small scale scenarios.

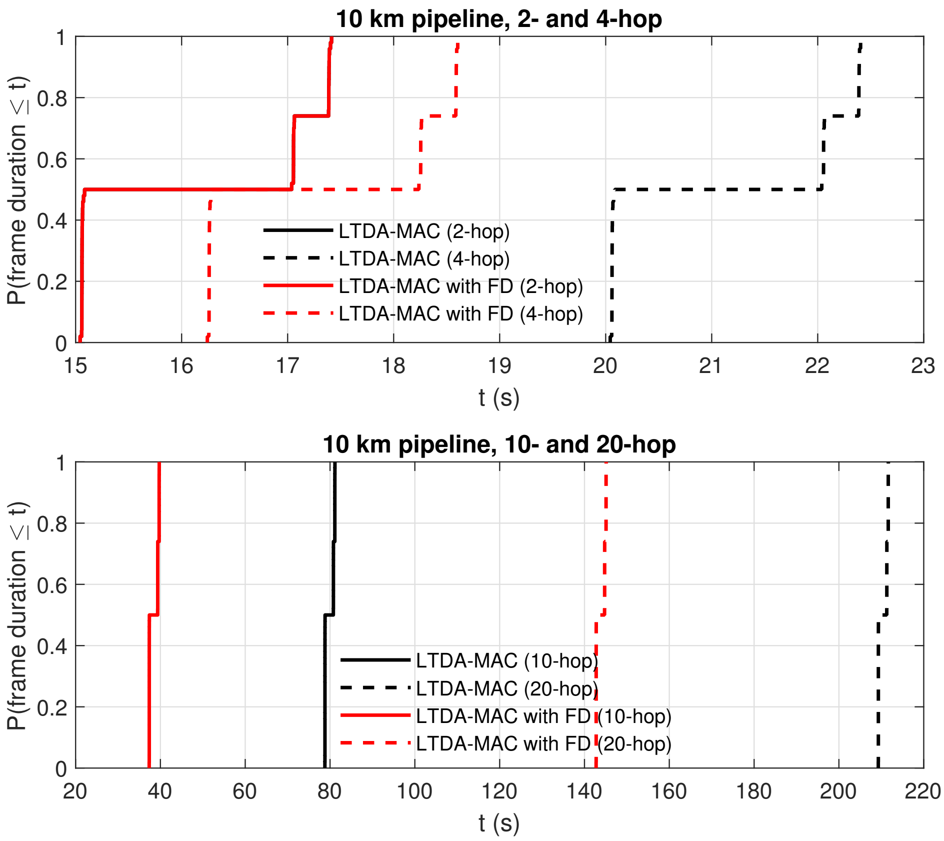


Figure 4.9: LTDA-MAC packet schedules in HD versus FD for 10 km pipeline small scale scenarios.

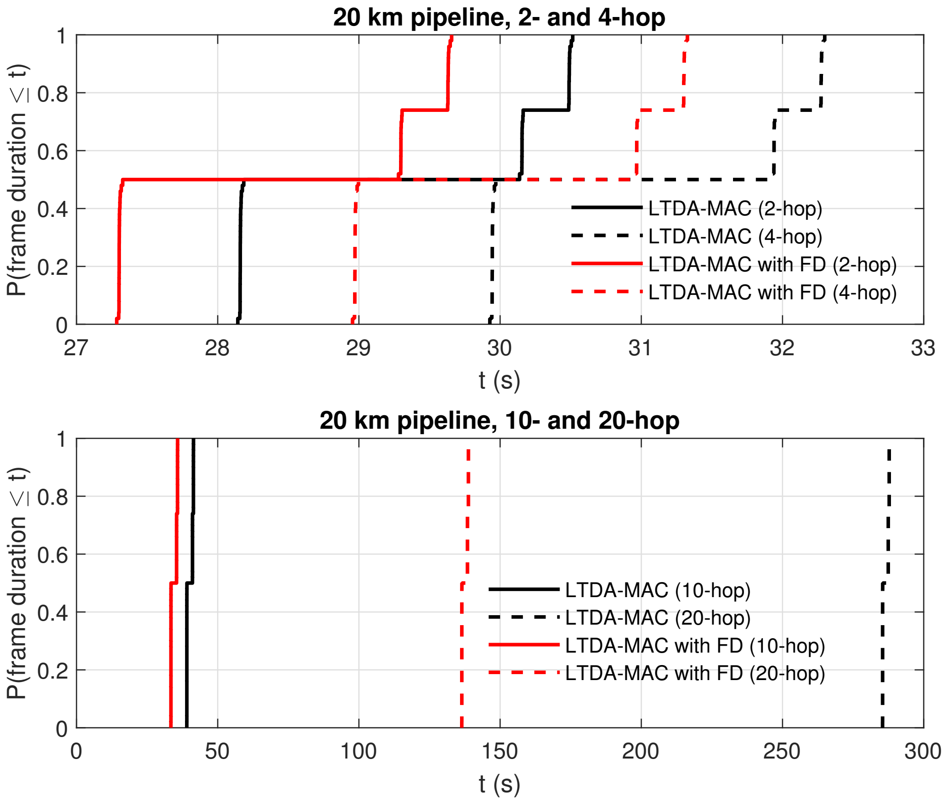


Figure 4.10: LTDA-MAC packet schedules in HD versus FD for 20 km pipeline small scale scenarios.

long for some applications that require sensor readings on a more frequent basis; however, the corresponding results of the FD cases show that the monitoring interval per sensor node is decreased to approximately 800 seconds at the most in these cases. The monitoring rate could be significantly improved with full duplex nodes, reaching more than five times that of the corresponding half duplex scenario based on the use of an acoustic modem with a sensing range of 1 km.

Additionally, for sensing applications that require regular sensing along a pipeline but require a greater monitoring rate, more frequent monitoring can be accomplished by using acoustic modems with a sensing range of 2 km. As illustrated in Figure 4.11, the monitoring interval per sensor node is reduced further to approximately 200 and 150 seconds for 50 km and 100 km pipelines, respectively.

The significant performance improvement achieved with the medium scale scenarios compared with small scale scenarios suggests that the LTDA-MAC algorithm exploits full-duplex communication capabilities better in a more dense scenarios.

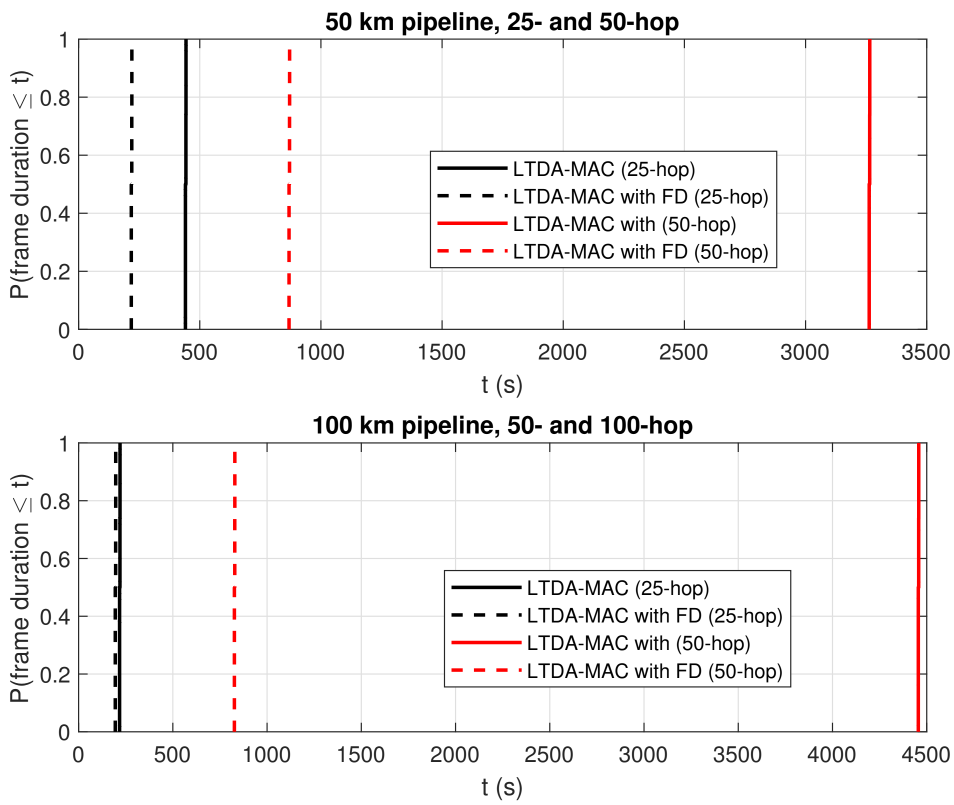


Figure 4.11: LTDA-MAC packet schedules for medium scale pipeline scenarios.

For the large scale network scenarios which consist of pipelines with lengths 200 km,

Table 4.1: Mean values of frame duration and E2E packet delay

Pipeline (km)	hop	Frame duration(s)		E2E packet delay(s)		% reduction in E2E packet delay
		LTDA-MAC	LTDA-MAC with FD	LTDA-MAC	LTDA-MAC with FD	
200	100	607	298	400	194	52
	200	4457	1256	2326	876	62
500	250	828	406	545	263	52
	500	6085	1620	4526	1129	75
1000	500	1131	553	744	365	51
	1000	8307	2796	6180	1790	71

500 km and 1000 km, a hierarchical approach can be employed using LTDA-MAC in 10 - 100 km segments. The monitoring intervals here may be very long as can be seen in Table 4.1 for the HD 1000 km pipeline case requiring up to 8000 seconds which may be impractical for many pipeline monitoring applications. Providing more regular monitoring for these longer pipeline scenarios may require high power and longer range costly acoustic modems, however, FD based scenarios configured with 2 km sensing range acoustic modems could relatively reduce the monitoring rate to acceptable values such as 553 seconds for a 500-hop 1000 km pipeline scenario. It is thus important to state that although longer range acoustic modems could be employed to achieve higher monitoring rates across a lower numbers of hops (the number of sensor nodes required), the cost effectiveness of nano modems provides a relatively cheaper alternative and along with FD communication can achieve an acceptable monitoring rate whilst maintaining more regular sensing points along a pipeline. The mean frame duration and End-to-End (E2E) packet delays derived for the large scale scenarios are given in Table 4.1. Exploitation of FD transmission has given rise to substantial decrease in E2E packet delay. A reduction in E2E packet delay of 51.6 % is achieved comparing LTDA-MAC with FD versus LTDA-MAC in a 200 km pipeline, 100-hop scenario. The considerable reduction in E2E packet delay for LTDA-MAC with FD against LTDA-MAC cases is sustained for other scenarios evaluated as well, as is shown in Table 4.1, with up to 75.1 % reduction in packet delay for the 500 km pipeline, 100-hop scenario. The 1 km range modem separation between nodes produces a superior performance in E2E packet delay compared to a 2 km range modem as is observed in Table 4.1.

4.5. Summary

In this chapter the performance evaluation of the LTDA-MAC protocol in full-duplex underwater acoustic chain network scenarios was presented. It investigated the network performance benefits from the application of the 'Greedy' optimization based LTDA-MAC protocol on full-duplex underwater pipeline network monitoring scenarios. Advantage of spectrum re-usability of LTDA-MAC is leveraged by the full-duplex communication mechanisms to exploit long propagation delay and interference patterns to provide a more efficient packet schedules, which in turn provides greater network throughput performance in the studied scenarios. Results that are based on simulation of small scale (2 km, 10 km and 20 km), medium scale (50 km and 100 km) and large scale (200 km, 500 km and 1000 km) scenarios demonstrated that a significant performance enhancement is achieved by the application of LTDA-MAC protocols to full-duplex pipeline monitoring scenarios with respect to their half duplex counterparts.

Chapter 5. FD-LTDA-MAC protocol for Full-duplex Underwater Chain Networks

5.1. Introduction

As previously stated in the preceding chapters, particularly in Chapter 2, the vital significance of underwater oil and gas pipeline monitoring cannot be overstated. Additionally, subsea acoustic communication, sensor, and acoustic modem technologies have paved the way for a variety of subsea and ocean operations [11–13, 23, 54]. Monitoring subsea oil and gas infrastructure is a key application area for underwater acoustic sensor technology, as there are several underwater pipeline networks that span long distances. Given that the majority of these pipelines transport petroleum products, early detection of leaks and corrosion is vital to avoiding financial loss and, more significantly, preventing water body pollution caused by oil spillage.

This chapter describes the development of a new MAC protocol that is applied to a multi-hop chain underwater acoustic network topology for the purpose of monitoring underwater pipelines efficiently and effectively. Packets are relayed from a source node to one or more sink nodes via neighbouring nodes. An example underwater pipeline sensor network monitoring system based on a multi-hop chain is depicted in Figure 5.1.

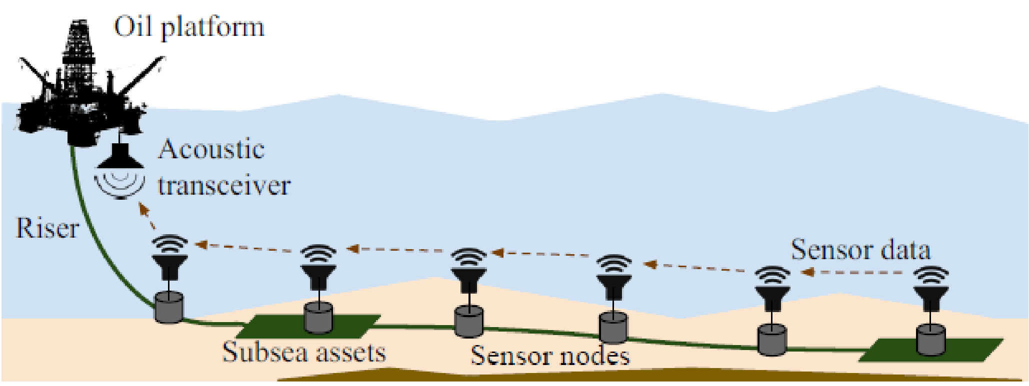


Figure 5.1: A typical linear UASN subsea asset monitoring scenario (copied with permission from [9]).

Likewise, as indicated in Chapter 4, the benefits of FD communication [71, 77], particularly when using LTDA-MAC, cannot be emphasized, as significant performance improvements have been realized when comparing LTDA-MAC with FD to LTDA-MAC implemented with conventional networks (HD nodes). However, there is scope for further investigations in developing a new FD-based MAC protocol that can better exploit FD to improve network performance by potentially providing higher throughput, lower latency, and the ability for a node to sense the channel while receiving a packet [144–146]. In that vein, the chapter proposes the Full-Duplex Linear Transmit Delay Allocation MAC (FD-LTDA-MAC) protocol which is designed to achieve further performance improvement by re-developing the traditional LTDA-MAC protocol to fully exploit full-duplex capabilities and enhance spatial reuse for full-duplex underwater multi-hop chain networks. Consequently, this protocol provides much more efficient packet scheduling to achieve higher monitoring rates over long range underwater pipelines using low cost, mid range, low rate, and low power acoustic modems, such as those presented in [10]. This study is based on numerical simulation and a BELLHOP [133] based underwater channel model. It builds on prior work, in particular, related to the LTDA-MAC protocol. Hence, this chapter presents a new protocol designed for full-duplex communication in chain networks. Although FD-LTDA-MAC was designed for FD nodes, its backward compatibility allows it to be used in scenarios involving HD nodes or hybrid networks that include both HD and FD nodes.

The FD-LTDA-MAC protocol leverage full-duplex communications to generate efficient collision-free packet schedules with significantly shorter frame duration. This can significantly enhance spectrum reuse, especially in the long range pipeline scenarios. The benefit of full-duplex as explored in [150], shows the potential performance gains that can be achieved in full-duplex network scenarios by switching on full-duplex capabilities without having to change the LTDA-MAC protocol. Although simultaneous packet scheduling in the full-duplex nodes achieved collision-free packet schedules with up to 39 % and 34 % throughput improvement for simple (short pipeline) and challenging (long pipeline) cases, respectively, compared to the half-duplex case, it was observed that spectrum re-use could be improved especially for longer pipelines by designing a new protocol capable of fully exploiting the full-duplex capabilities of nodes. Also, the new protocol should have backward compatibility, in order to achieve seamless coexistence with legacy networks (HD networks). Hence, this chapter presents the design and evaluation of FD-LTDA-MAC protocol which is designed to achieve further performance improvement by re-developing the traditional LTDA-MAC protocol to fully exploit full-duplex capabilities, enhances spatial reuse for full-duplex underwater multi-hop chain networks and provides backward compatibility to HD based UANs. The main contributions of this chapter are:

- Design and implementation of FD-LTDA-MAC for chain UANs in order to achieve higher monitoring rates over long range underwater pipelines. The goal is to provide much more efficient packet scheduling to achieve higher monitoring rates over long range underwater pipelines.
- Performance evaluation of the FD-LTDA-MAC protocol in FD based underwater acoustic chain network.

5.2. FD-LTDA-MAC Protocol

The FD-LTDA-MAC protocol is developed for full-duplex underwater multi-hop chain networks. It is an unsynchronized protocol that locally derives transmission times at the nodes by measuring the delays between nodes receiving a request (REQ) packet and transmitting their data packets. This section presents the design of the FD-LTDA-MAC protocol considering a linear underwater chain FD network.

In summary, the following are the features of the FD-LTDA MAC protocol. It uses linear constraints to calculate transmit delays for forwarding packets to reflect full-duplex capabilities. It allows the greedy scheduling algorithm to utilise the full-duplex based initial starting point that excludes data transmission time and the corresponding propagation delay components from the transmit delay time, as allowed by full-duplex communication. Moreover, it includes full-duplex support in the algorithm to evaluate schedules that are derived for full-duplex transmissions. Additionally, it provides backward compatibility with legacy networks by defaulting to half-duplex transmission schedule.

5.2.1. Linear UWA Chain Full-duplex Network

Consider a conceptual diagram of multi-hop chain Full-Duplex Relay (FDR) network shown in Figure 5.2.

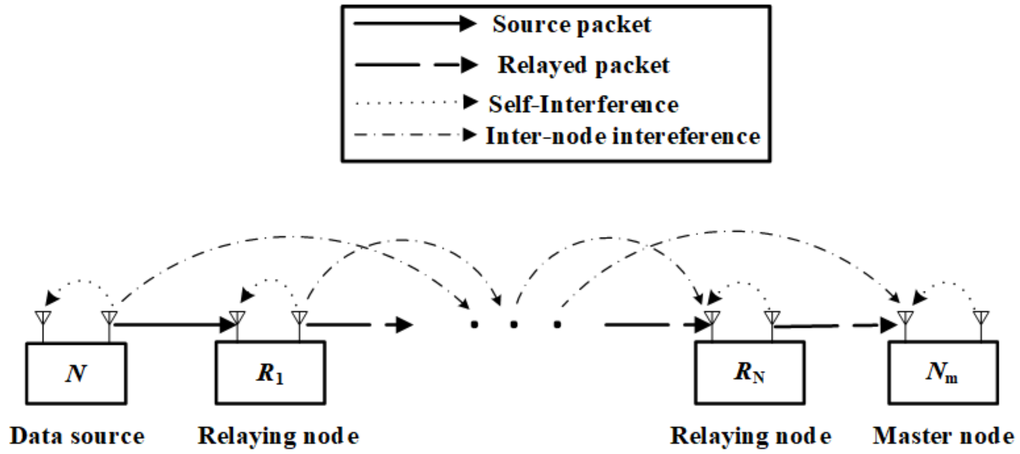


Figure 5.2: Multi-hop chain FDR network.

Each sensor node utilises two-way connections, it connects to the node one hop closer to the sink node up the chain and to a node further down the chain. Upon receiving an REQ packet, transmitting nodes forward REQ packets down the chain to the last node. Every transmitting node responds to the REQ packet query by either acting as a source node and transmitting its own data packet up the chain or by acting as a relay node forwarding data packets up the chain that it received from the node further down the chain. It is critical to highlight that while the simulation assumes an ideal network model, in practice, the topology may alter based on the underwater dynamic factors. In this situation, a neighbouring node may not necessarily be a single hop distant. The sink node is responsible for sending the REQ packets to request data packets from the transmitting nodes and to handle eventual reception of data packets from the transmitting nodes. The last transmitting node down the chain does not relay packets, it only transmits its own data packets. Every transmitting node serves as data source or data forwarder except the last transmitting node which serves only as a data source. It is assumed that the self-interference is totally cancelled.

The new linear constraint is based on full-duplex communication structure to calculate transmit delays for an enhanced packet forwarding among full-duplex nodes. A greedy scheduling algorithm also employs a full-duplex based initial starting point of search, which decreases both the time lost in waiting for an interference gap before commencing a new transmission as well as the related propagation delay components associated with that waiting period.

The timing diagram for the FD-LTDA MAC schedule is presented in Figure 5.3 for a typical one-hop interference range full-duplex underwater chain network. It is composed of a master node, N_m, that acts as the sink node, and three transmitting sensor nodes, N_1, N_2, and N_3. The master node sends REQ packets down the chain to node N_3 via nodes N_1 and N_2. After an allowable guard interval, τ_g, the nodes N_1 and N_2 relay the REQ packets. When a node receives a REQ packet, it generates and schedules data packets for transmission or schedules the transmission of a relayed packet up the chain towards N_m after waiting a certain amount of time called the transmit delay. The wait time is calculated using only the REQ packet interval, τ_{rp}, but this does not include the time required for interference reception. This is because the FD-LTDA MAC protocol is capable of scheduling packet transmission and reception concurrently. The full-duplex gain (FD gain) is the measure of transmit delay required for the FD-LTDA MAC protocol to schedule packet transmissions successfully and without packet collisions. FD gain is seen in Figure 5.3, where N_1 can transmit data packets (D2 and D3) much earlier than the LTDA-MAC protocol can. Additionally, D2 can be transmitted quicker by N_2 when using the FD-LTDA-MAC protocol rather than the LTDA-MAC protocol.

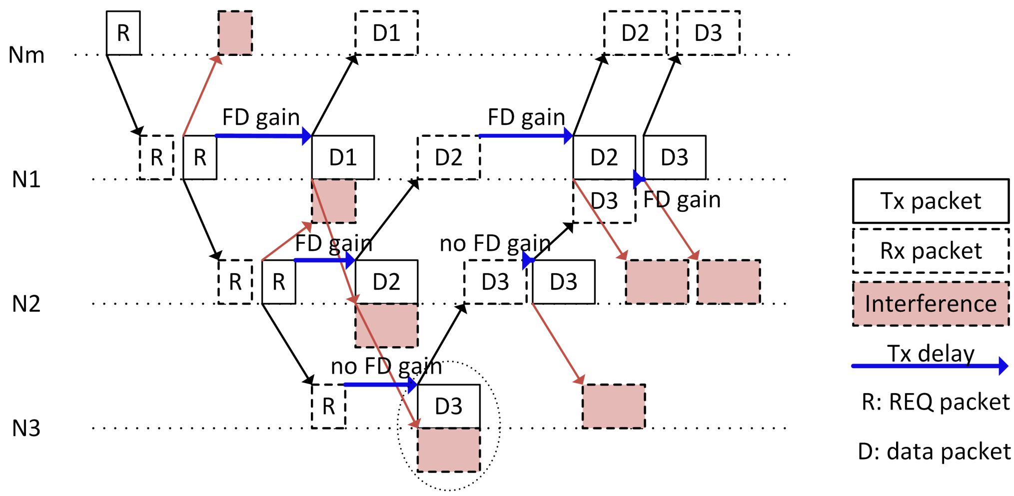


Figure 5.3: FD-LTDA-MAC schedules in a three-hop network.

5.2.2. FD-LTDA-MAC Scheduling Greedy Optimization

The transmission scheduling is based on the timings and these timings are based on the scheduling algorithm which is described below. In order to find the transmission times, as labelled in Figure 5.3, the 4-node network of Figure 5.3 is extended to a case with N_{sn} transmitting sensor nodes and calculated using the algorithm discussed below. The FD-LTDA-MAC schedule transmit delays incurred by a node transmitting its own data packet to a node up the chain are represented by a triangular matrix,

$$\boldsymbol{T_{tx}^{FD}} = \begin{pmatrix} T_{own}^{FD}[1,1] & T_{forw}^{FD}[1,2] & \cdots & T_{forw}^{FD}[1,N_{sn}] \\ \varnothing & T_{own}^{FD}[2,2] & \cdots & T_{forw}^{FD}[2,N_{sn}] \\ \vdots & \vdots & \ddots & \vdots \\ \varnothing & \varnothing & \cdots & T_{own}^{FD}[N_{sn},N_{sn}] \end{pmatrix}, \tag{5.1}$$

where,

$$T_{own}^{FD}[i,i] = T_{tx}[i,i] - \tau_{rp}, \tag{5.2}$$

$$T_{forw}^{FD}[i,j] = T_{tx}[i,j] - \tau_{dp}, \tag{5.3}$$

$T_{own}^{FD}[i,i]$ represents the transmit delays incurred by node i for sending its own data packet(s) and $T_{forw}^{FD}[i,j]$ represents transmit delays for node i to forward node j's data packet(s) given that $(i < j)$. Furthermore, $T_{tx}[i,i]$ and $T_{tx}[i,j]$ represent the respective transmit delays for a node sending its own data and relaying data from a node down the chain based on the traditional LTDA-MAC scheme.

Transmission schedules are derived by optimally solving for $N_{sn}(N_{sn}+1)/2$ values in $\boldsymbol{T_{tx}^{FD}}$ and the solution yields a minimum frame duration ($\tau_{\text{frame}}(\mathcal{N}, \boldsymbol{T_{tx}})$) with zero packet collisions ($\eta_{col}(\mathcal{N}, \boldsymbol{T_{tx}}, \tau_g)$), where τ_g is the allowable guard interval between scheduled packets and $\mathcal{N}$ is a tuple that represents a typical underwater full-duplex chain network topology. The full network topology is defined by an $(N \times N)$ interference binary matrix, $\boldsymbol{I}$, propagation delay matrix, $\boldsymbol{T_p}$, REQ and data packet durations,

τ_{rp} and τ_{dp}. The interference matrix can be expressed as:

$$\boldsymbol{I} = \begin{pmatrix} I[1,1] & I[1,2] & \cdots & I[1,N] \\ I[2,1] & I[2,2] & \cdots & I[2,N] \\ \vdots & \vdots & \ddots & \vdots \\ I[N,1] & I[N,2] & \cdots & I[N,N] \end{pmatrix}, \tag{5.4}$$

where $I[i,j] = 1$ if node i is in interference range of node j, and $I[i,j] = 0$ otherwise. The Interference matrix depicts how sensor nodes interfere with one another. The adjacent neighbouring node is assumed to be an interfering node with its nearest neighbour up and down the chain in our scenarios. The interference matrix is populated with 0s and 1s based on the previously specified interfering rule. Also, the propagation delay from node i to node j is given as $T_p[i,j]$.

The FD-LTDA-MAC protocol uses a greedy algorithm to derive collision-free transmission schedules by iterating over transmit delays in $\boldsymbol{T_{tx}^{FD}}$ to check for overlaps in time in any pair of transmit/receive packets at a node, or where a separation between scheduled packets is less than τ_g. It compares the data transmission, interference and reception times to detect a full-duplex transmission, and then forces the algorithm to choose a starting point (the initial transmit delays or transmit delay of first transmission) for the transmit delay search, selecting a local optimal value for it. Moreover, in the case of full-duplex transmission, the initial schedule accounts for the allowable guard time, τ_g, between the REQ packet interference and transmit data packet at a node without additional cost in time delay. This is because, in full-duplex transmission mode, a receive/transmit overlap in time at a node does not count as a collision but a successful transmission, thus, accounting for τ_g becomes unnecessary. Also, in evaluating the schedule, the additional delay incurred at a node given full-duplex transmission is τ_g. The minimum transmit delay constraint to be imposed on any transmitting node to send its own data packet is given as:

$$\forall n \in \{1..N_{sn}\},\ T_m^{FD}[n,n] = \begin{cases} \tau_{rp} + \tau_g, & n < N_{sn} \\ \tau_g, & n = N_{sn} \end{cases}, \tag{5.5}$$

where $T_m^{FD}[n,n]$ is the minimum transmit delay for a node to send its own data. Similarly, the minimum transmit delay constraint imposed on a node for relaying a data packet up the chain from a node further down the chain is represented as:

$$\begin{gathered} \forall n, k \in \{1..N_{sn}\}, k > n, \\ T_m^{FD}[n,k] = 2\tau_p[n+1] + \tau_g + \tau_{rp} + T_{tx}[n+1,k], \end{gathered} \tag{5.6}$$

where $T_m^{FD}[i,j]$ is the minimum transmit delay assigned to node i for transmitting a packet generated by node j and $\tau_p[i]$ is the propagation delay on the ith link between adjacent nodes of the network. This constraint provides for the allowable time for a node to receive a packet while transmitting another data packet. Nonetheless, for a node transmitting its own data packet up the chain and forwarding a data packet received from a node further down the chain in a half-duplex mode will resort to the respective minimum transmit delay [9],

$$\forall n \in \{1..N_{sn}\}, \ T_m[n,n] = \begin{cases} \tau_{rp} + 2\tau_g, & n < N_{sn} \\ \tau_g, & n = N_{sn} \end{cases}, \tag{5.7}$$

and

$$\begin{gathered} \forall n, k \in \{1..N_{sn}\}, k > n, \\ T_m[n,k] = 2(\tau_p[n+1] + \tau_g) + \tau_{rp} + \tau_{dp} + T_{tx}[n+1,k]. \end{gathered} \tag{5.8}$$

The FD-LTDA-MAC protocol is described in Algorithm 2. The network instance is firstly created with appropriate τ_g and time step, τ_{step}. The τ_{step} is an incremental value which is set to the half of the value of τ_g. Then, the initial collision-free schedule is calculated using a large value of transmit delay, T_{large}, set to 10^6, so as to provide collision-free transmit delay matrix. The algorithm then checks for full-duplex transmissions by looking for overlap in time of transmit times, τ_{tx}, and interference time, τ_I, among the nodes transmitting their own data packets. Every value in $\boldsymbol{T_{tx}^{FD}}$

is iterated over thereby maximizing the chances of collision-free simultaneous transmissions schedules. Upon detecting a full-duplex transmission, the algorithm uses $T_{tx}[i,i] = T_m^{FD}[n,n]$ to evaluate FD-LTDA-MAC schedule for full-duplex transmission for nodes transmitting own packet(s) using Equation (5.5). The above process is repeated for relay transmissions, but Equation (5.6) is used to evaluate the FD-LTDA-MAC schedule for forwarding the data packets by relay nodes ($T_{tx}[i,j] = T_m^{FD}[n,k]$). If the evaluated schedule is not collision-free, the transmit delay value is incremented by τ_{step} and the FD-LTDA-MAC is evaluated again until a collision-free schedule is achieved. For backward compatibility and coexistence with half-duplex nodes, the algorithm defaults to half-duplex transmission mode upon detecting half-duplex transmission using Equations (5.7) and (5.8) for transmitting own and forwarded packet(s) respectively.

Algorithm 2 FD-LTDA-MAC scheduling based on greedy optimization algorithm

```
Create 𝒩 using initial network discovery
Set the desired guard interval and time step τ_g and time step τ_step
Initialize collision-free schedule using: ∀n,k ∈ {1..N_sn}, k≥n, T_tx[n,k] = (N_sn n + k)T_large
for i ∈ {1..N_sn} do
    for n ∈ 1..(N_sn − i + 1) do
        Calculate the packet index k = n + i − 1
        Calculate τ_tx and τ_I
        if τ_tx≤τ_I then
            Calculate T_m^FD[n,k] using Equation (5.5) if n = k, or (6.6) if n≠k
            Initialise Tx delay: T_tx^FD[n,k] = T_m^FD[n,k]
        else
            Calculate T_m[n,k] using Equation (5.7) if n = k, or (6.8) if n≠k
            Initialise Tx dealy: T_tx[n,k] = T_m[n,k]
        end if
        while η_col(𝒩, T_tx, τ_g) > 0 do
            Increment Tx delay: T_tx[n,k]←T_tx[n,k] + τ_step
        end while
    end for
end for
```

5.3. Simulation Scenarios

5.3.1. Scenario description

The full-duplex based underwater acoustic network scenarios studied here are representative of the subsea asset (pipeline) monitoring scenario depicted in Figure 5.1. A pipeline is deployed at a depth of 480 m and then connected through a riser to the platform. The network is made up of multiple transmitting sensor nodes and a sink node arranged in a chain multi-hop fashion such that each node connects to a node one hop closer to the sink node and to a node one hop further down the chain. The sink node sends REQ packets to the transmitting nodes. The transmitting nodes propagate the REQ packets down the chain to the last node. The transmitting sensor nodes either send their own packet up the chain or forward packet(s) up the chain after receiving them from a node further down the chain upon receiving an REQ packet.

The nodes in the chain network topology are able to operate in full-duplex fashion. Figure 5.4 depicts full-duplex communication in a underwater chain network, where the relay nodes are able to transmit and receive simultaneously in time and frequency. This allows the nodes to send and receive REQ or data packets in-band thereby potentially improving spectrum reuse. Further detail on description of the scenarios employed here can be found in Section 3.2.7.1.

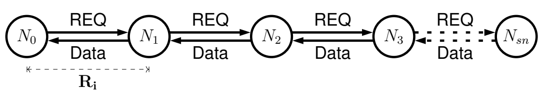


Figure 5.4: FD-based linear UASN network scenario.

The different scenarios are described in Table I. The nano-modem [10] assumed in this work has the advantage of low cost, which makes it feasible to consider deploying a large number of monitoring devices. Another benefit for considering short range acoustic communication is the provision of regular monitoring points for the timely detection of problems such as leaks and movement of pipelines.

- **Small scale scenarios:** The small scale scenarios are denoted as Small_L_H, where L and H are the pipeline length and the number of hops in the network, respectively. In the small scale scenarios, L varies between 2 and 20 km while, H varies from 2 to 20 hops. 2, 10 and 20 km pipelines configured with 2, 4, 10 and 20 hops are considered for the small scale scenario.

- **Medium scale scenarios:** Similarly, medium scale scenarios are denoted by Medium_L_H, where L ranges from 50 to 100 km and H ranges from 25 to 100 hops.
- **Large scale scenarios:** The large scale scenarios represented as Large_L_H have values of L and H between 200 and 1000 km, and 100 to 1000 hops respectively.

The transmission range is important for the deployment of underwater acoustic networks. It influences energy efficiency, network connectivity and network reliability. The transmission range is determined by the acoustic modem assumed [151]. For practical applications such as underwater pipeline monitoring, regular sensing is required.

Typically, there may be a need to communicate over longer ranges, nano-modems [10] could be used to provide this capability. Although, other acoustic modems with higher ranges (300 m - 10 km), data rates (up to 62,500 bps) and transmit power (up to 80 W) such as Evologics, DiveNET, LinkQuest [43, 152, 153], etc. are alternatives, however, there is need to consider a trade-off between performance and cost effectiveness in terms of scalability for large scale deployment. In other words, low powered modems exhibit lower power consumption which improves energy efficiency with the appropriate protocols to extend network lifetime.

5.3.2. Simulation set-up

Statistical channel models of the scenarios described above are created using the BELLHOP beam tracing method [133] as described in [134]. To achieve this, an array of the node positions for 1-N_{sn} hop distance (N_{sn} ranges from 2 to 1000 depending on the scenario) is created with the first node as the sink node plus n other transmitting nodes. The N_{sn} transmitting nodes and the sink node are arranged as described in Section 5.3.1.

The statistical channel model uses random node positions set to be within 10 m sphere around of $N_{sn} + 1$ random displacements in both source and receiver positions to generate underwater acoustic channel realizations for every possible hop distance. Then channel gain, delay and delay spread for every link in the network scenario is used to generate a full network model based on a corresponding lookup table.

Thereafter, a binary interference matrix ($N \times N$), $\boldsymbol{I}$ is generated such that $I[i,j] = 0$ if $i = j$ (i.e not interfering nodes) or $I[i,j] = 1$ if $i \neq j$ with SNR $\geq$ 0 dB (i.e the interfering nodes). The FD-LTDA-MAC schedule is derived by loading the pre-simulated BELLHOP channel data of the node set (1-50) on to the algorithm that runs the FD-LTDA-MAC. More detail on the simulation set-up, simulation parameters and the channel model can be found in Equation (2.3) and Table 5.1.

Table 5.1: Simulation Parameters [10].

Parameter	**Value**
Transmit power (Small scale scenarios)	140 dB re µ Pa^{2}m^2
Transmit power (Medium and large scale)	170 dB re µ Pa^{2}m^2
Noise power	85 dB re µ Pa^{2}m^2
τ_{dp} (Small/Medium and Large scale)	200 ms / 500 ms
τ_{rp} (Small/Medium and Large scale)	50 ms / 100 ms
τ_g (Small/Medium and Large scale)	25 ms / 100 ms
Acoustic modem range	1 km / 2 km
Centre frequency/Bandwidth	24 kHz / 7.2 kHz
Acoustic data rate	640 bits/s
Shipping activity factor	0.5
Wind speed	10 m/s
Interfering link detection threshold	0 dB SNR
Sound speed profile	North Atlantic Ocean SSP
Pipeline length (L)	2 km to 1000 km
Number of hops (H)	2 to 1000 hops
Scenario	***Description***
Small_L_H	Small scale scenario
Medium_L_H	Medium scale scenario
Large_L_H	Large scale scenario

5.4. Performance evaluation and discussion

Here we consider simulation results of FD-LTDA-MAC, LTDA-MAC and LTDA-MAC with FD enabled nodes. The comparison is done using the frame duration, where the frame duration is the time taken to complete transmitting a frame from the beginning of the frame to end of the frame. It is important, because it defines the rate at which each node can send a new sensor reading. It is also important to state here that the frame duration is equal to the inverse of the monitoring rate, in other words, the shorter the frame duration, the higher the monitoring rate and network throughput. The other parameter used in the evaluation is end-to-end (E2E) packet delays. The term ”end-to-end (E2E) packet delay” refers to the amount of time required for a packet to be transmitted from one network node to another. The E2E delay is measured in seconds. It is composed of transmission delay, propagation delay, processing delay, and queuing delay components in most UANs. For an underwater pipeline monitoring application, the packet E2E delay must be kept to a minimum to ensure the system’s QoS. The frame duration and packet E2E delays for various scenarios are provided in this section via various statistical plots. We display the distribution of frame duration with respect to time using cdf plots, as well as the mean values of E2E packet delay.

5.4.1. Transmit Schedule

Simulated MAC schedules for FD-LTDA-MAC and LTDA-MAC for a 10-hop 2 km pipeline are presented in Figures 5.5 and 5.6, respectively. They show packet schedules for data transmission and reception in the presence of interference. FD-LTDA-MAC achieves a 44% reduction in the frame duration and packets are still correctly received at the desired destination nodes despite the overlap in time between the transmit and interference packets compared to the LTDA-MAC with HD enabled nodes as can be observed in Figure 5.5. This also provides a 10% compression of frame duration against LTDA-MAC with FD enabled nodes presented in [150]. This compression in the frame duration given correct reception of packets in the presence of overlap in time is made possible by the ability of the FD-LTDA-MAC to fully exploit spectrum reuse.

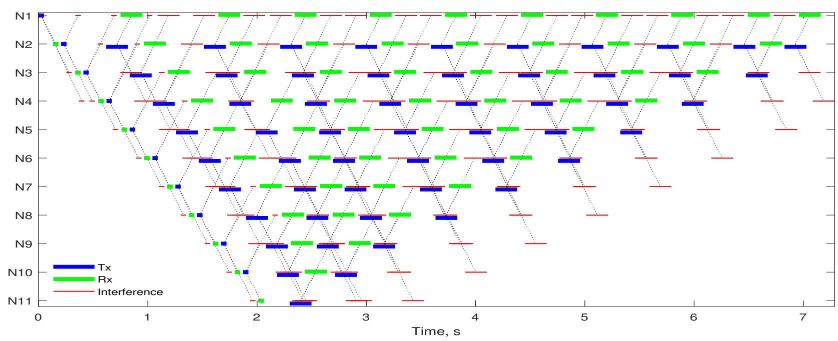


Figure 5.5: Simulated FD-LTDA-MAC schedules for the 2 km 10-hop scenario. Tx:Transmission, Rx: Reception.

In contrast, Figure 5.6 shows a longer frame duration because the half-duplex nodes do not allow simultaneous in-band transmission and LTDA-MAC lacks the capability to handle full-duplex transmissions. As a result, frame durations and end-to-end packet delays are shorter with the FD-LTDA-MAC protocol compared to the LTDA-MAC protocol with HD enabled nodes and LTDA-MAC protocol with FD enabled nodes scenarios.

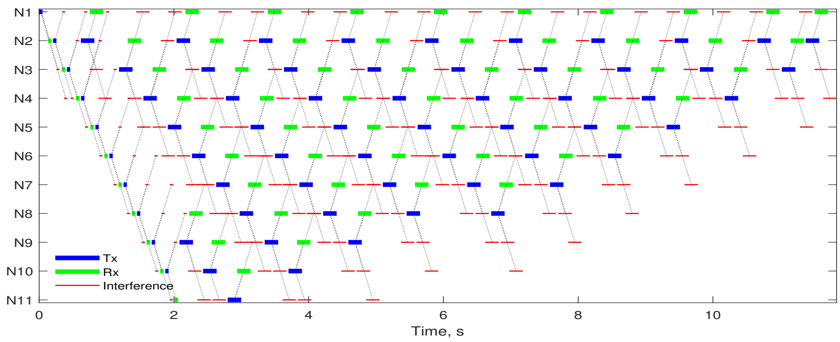
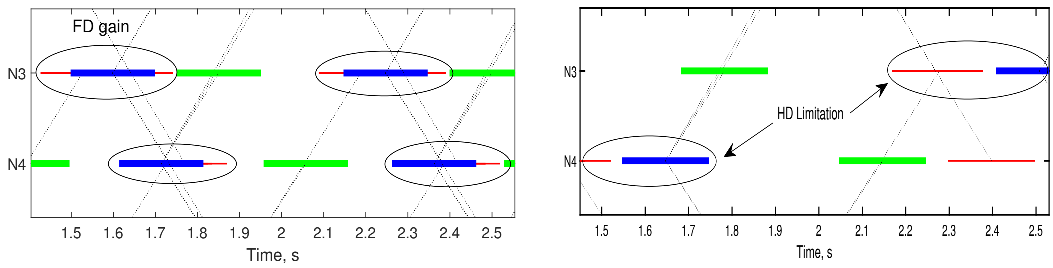


Figure 5.6: Simulated LTDA-MAC schedules for the 2 km 10-hop scenario [8]. Tx:Transmission, Rx: Reception

Figure 5.7 shows sections of MAC schedule presented in Figures 5.5 and 5.6, representing a time interval of 1.4 - 2.5 s involving N3 and N4 nodes. It can be seen that the FD-LTDA-MAC protocol exploits spatial re-use better by scheduling simultaneous in-band transmission and reception, which reduces transmit delays and compresses the overall frame duration, as can be seen as FD gain in Figure 5.7 (a). The LTDA-MAC protocol has the limitation of this capability as shown in Figure 5.7 (b), where data packet transmissions are scheduled after interference packet reception allowance. This causes waste of resources (time), thus, resulting in longer transmit delays.



(a) FD-LTDA-MAC

(b) LTDA-MAC

Figure 5.7: Zoomed in sections of Simulated MAC Schedule in Figures 5.5 and 5.6.

5.4.2. Monitoring Rate

The following sections discuss the impact of the frame duration enhancement on the monitoring rate.

- **Small scale Scenarios: 2, 10 and 20 km pipelines:** The simulation results for small scale scenarios considering short pipelines of few kilometres (2, 10 and 20 km) are presented here. It is important to firstly consider short pipelines with a varying number of hops in order to understand the performance of the FD-LTDA-MAC protocol in simple situations where there is a limited opportunity for spatial reuse.

  The cdf (cumulative distributive function) plot of frame durations for FD-LTDA-MAC, LTDA-MAC and LTDA-MAC with FD protocols in small scale scenarios are shown in Figures 5.8 to 5.13. The results for a 2 km pipeline configured with 2, 4, hops can be seen in Figure 5.8, while Figure 5.9 shows the cdf of frame durations of a 2 km pipeline with 10 and 20 hops. These shows that FD-LTDA-MAC can achieve shorter frame durations compared to the LTDA-MAC and LTDA-MAC with FD protocols.

  The frame duration is reduced on average by 29% and 9% against LTDA-MAC and LTDA-MAC in FD, respectively. Hence, this capability provides better packet schedules which translates into improvement in network throughput even with limited opportunity for spatial reuse.

  The frame durations obtained for 10 km and 20 km pipelines shown in Figures 5.10 to 5.13 demonstrate a more significant performance improvement compared with the 2 km pipeline scenarios. The FD-LTDA-MAC protocol shortens the frame duration by 64% against the LTDA-MAC protocol, whereas LTDA-MAC in FD improves by 53% against LTDA-MAC protocol. The significant improvement achieved by FD based protocols especially for longer pipelines, is because the search algorithm is able to better exploit larger search space which that offer better solution.

- **Medium scale scenarios: 50 and 100 km pipelines:** For underwater oil and gas pipeline monitoring, applications such as leak detection require timely sen-

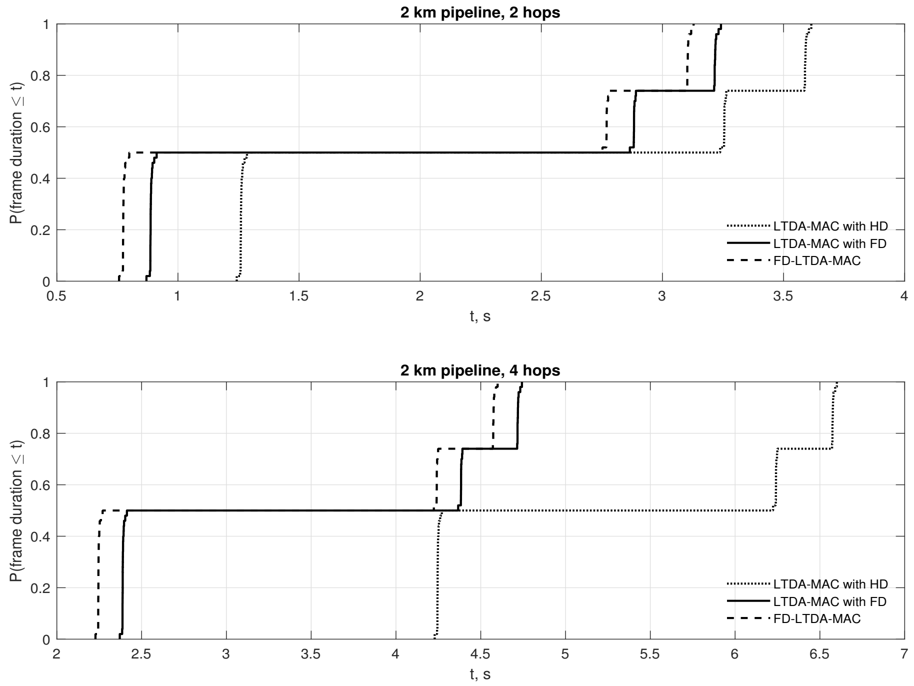


Figure 5.8: Frame duration cdfs of LTDA-MAC with HD nodes, LTDA-MAC with FD nodes and FD-LTDA-MAC for a 2km pipeline (2 and 4 hops).

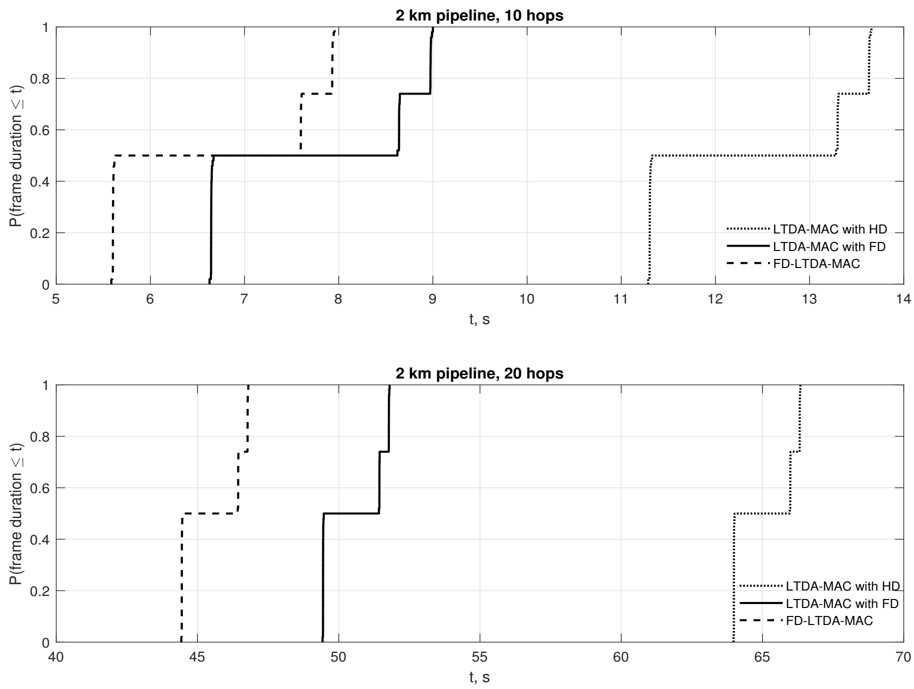


Figure 5.9: Frame duration cdfs of LTDA-MAC with HD nodes, LTDA-MAC with FD nodes and FD-LTDA-MAC for a 2km pipeline (10 and 20 hops).

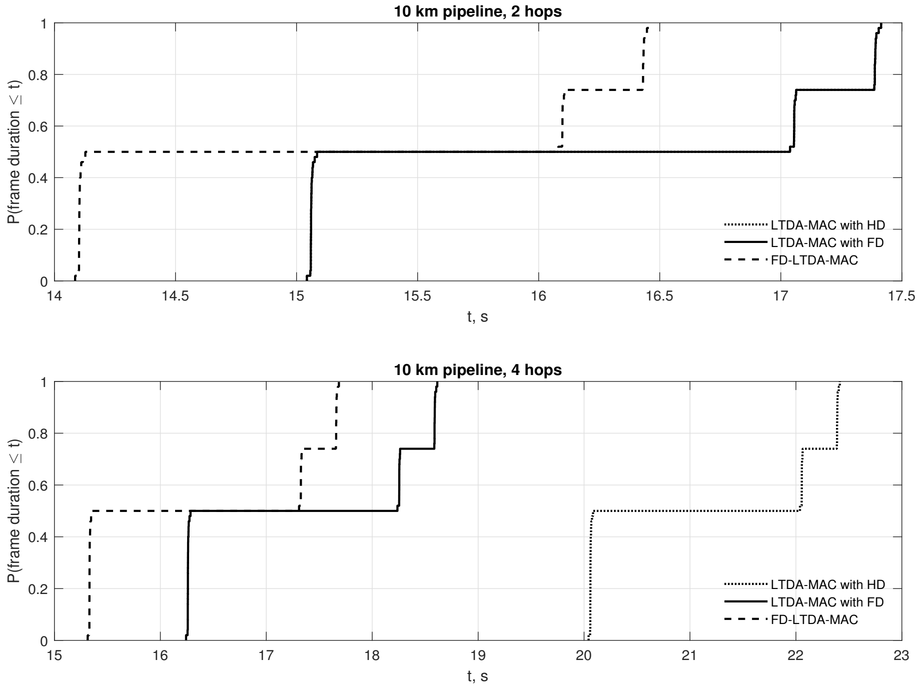


Figure 5.10: Frame duration cdfs of LTDA-MAC with HD nodes, LTDA-MAC with FD nodes and FD-LTDA-MAC for a 10km pipeline (2 and 4 hops).

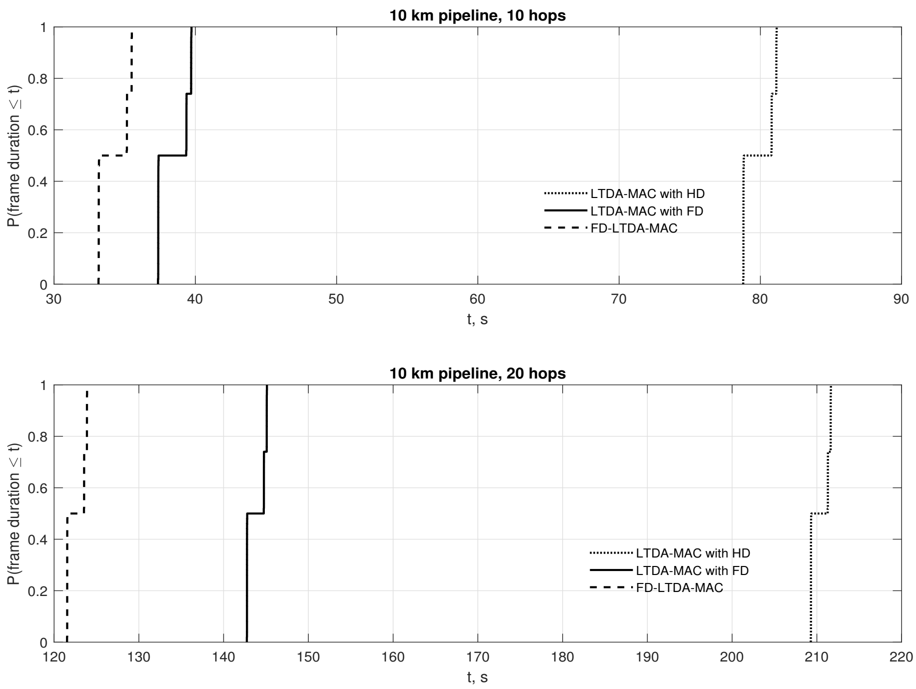


Figure 5.11: Frame duration cdfs of LTDA-MAC with HD nodes, LTDA-MAC with FD nodes and FD-LTDA-MAC for a 10km pipeline (10 and 20 hops).

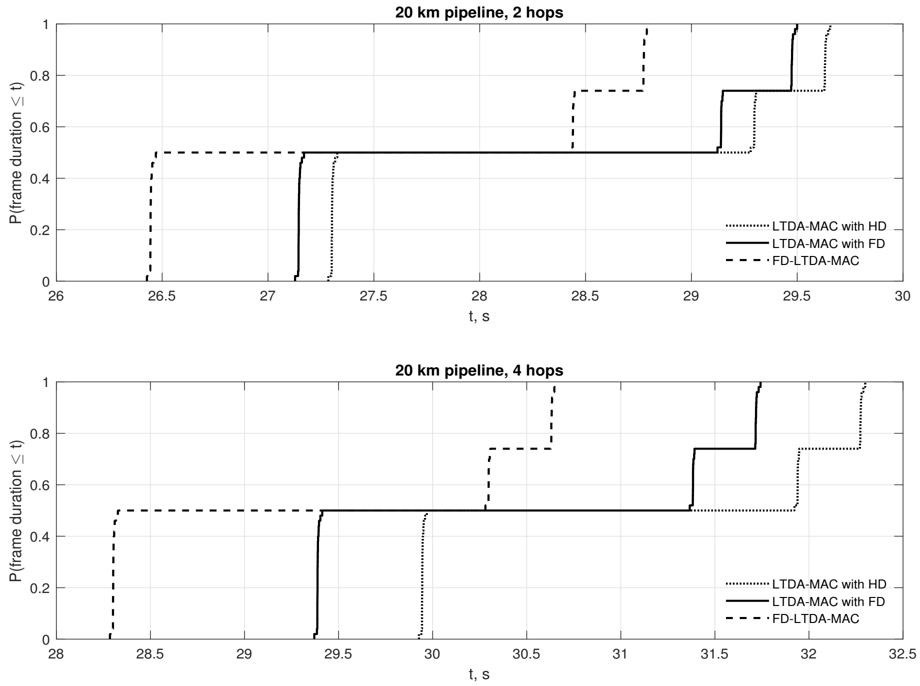


Figure 5.12: Frame duration cdfs of LTDA-MAC with HD nodes, LTDA-MAC with FD nodes and FD-LTDA-MAC for a 20km pipeline (2 and 4 hops).

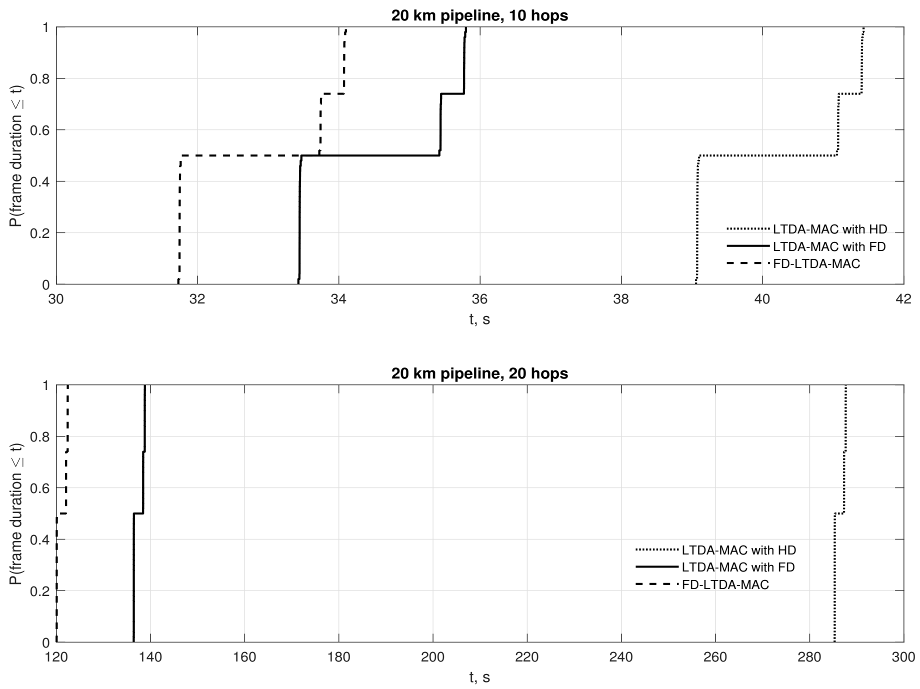


Figure 5.13: Frame duration cdfs of LTDA-MAC with HD nodes, LTDA-MAC with FD nodes and FD-LTDA-MAC for a 20km pipeline (10 and 20 hops).

sor readings at certain intervals and demand a high resolution of sensed data. This motivates studying the deployment of FD-LTDA-MAC protocol in medium scale scenarios, so as to understand intermediate performance improvement and to track the improvement by understanding where the optimum performance enhancement lies. The frame durations derived by FD-LTDA-MAC for 50 and 100 km pipelines with 25 and 50 hop configurations as seen in Figures 5.14 and 5.15 are of the range 104 s - 779 s, with the lower bound corresponding to the 25 hop case and the upper bound the 50 hop case. In comparison with the frame durations ranging from 218 s - 4457 s and 144 s - 1192 s derived by LTDA-MAC and LTDA-MAC over FD nodes respectively, there is significant reduction in the frame duration. The performance improvement as a ratio can be approximated as 1:1.4:2 for the lower bound and 1:2:6 for the upper bound. Thus, LTDA-MAC performs poorly in medium scale scenarios compared to FD-LTDA-MAC. This means FD-LTDA-MAC can achieve higher monitoring rates compared to LTDA-MAC and LTDA-MAC in FD.

Furthermore, the 25 and 50 hop scenarios for 50 and 100 km pipelines, respectively, show that more regular sensing along a pipeline can be achieved by FD-LTDA-MAC protocol with a 2 km sensing range. The results also indicate that the greedy optimisation algorithm in FD-LTDA-MAC can achieve a better solution in longer pipelines with full-duplex capability. This is the reason why performance improvement achieved in medium scale scenarios is superior compared with small scale scenarios.

- **Large scale scenarios: 200, 500 and 1000 km pipelines:** In practice, pipelines span several hundreds to thousands of kilometres such as the Langeled pipeline in the North Sea measuring about 1,200 km [63], and the 7,200 km long pipelines under the gulf of Mexico [149]. In this thesis, large scale network scenarios include pipelines that span from 200 km to 1000 km. The achieved frame durations are presented in Figures 5.16 to 5.18. The results show that monitoring intervals for LTDA-MAC and LTDA-MAC over FD are low as frame durations are very long (607 s - 4457 s and 404 s - 2326 s for LTDA-MAC and LTDA-MAC over FD respectively). From Figure 5.16, we can see that FD-LTDA-MAC com-

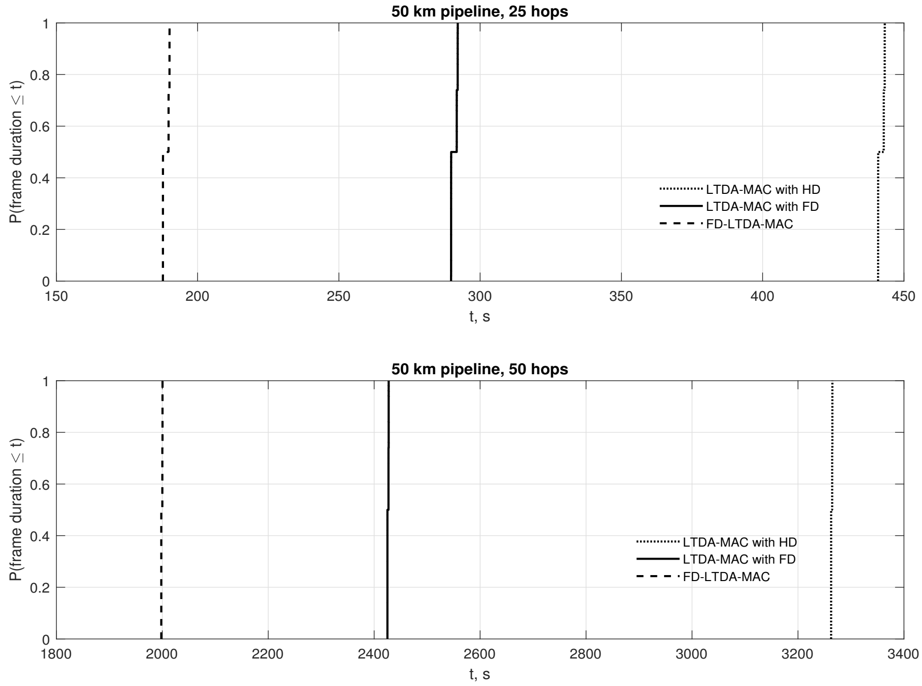


Figure 5.14: Frame duration cdfs of LTDA-MAC with HD nodes, LTDA-MAC with FD nodes and FD-LTDA-MAC for a 50km pipeline (25 and 50 hops).

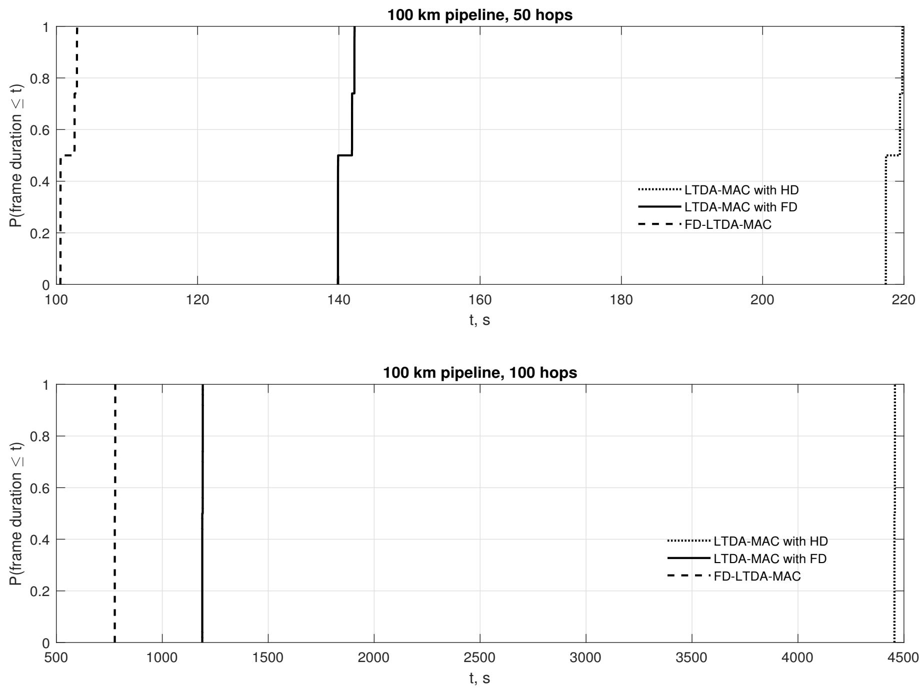


Figure 5.15: Frame duration cdfs of LTDA-MAC with HD nodes, LTDA-MAC with FD nodes and FD-LTDA-MAC for a 100km pipeline (50 and 100 hops).

presses the frame durations to about 276 s - 1399 s, thus providing much higher monitoring rates. Here, LTDA-MAC for the 1000 km pipeline may require up to 8000 seconds which may be impractical for some pipeline monitoring applications. Providing more regular monitoring for these longer pipelines may require high power and longer range costly acoustic modems, however, FD-LTDA-MAC on scenarios configured with 2 km sensing range acoustic modems significantly reduce the monitoring rate to more acceptable values such as 498 s for a 500-hop 1000 km pipeline scenario. It is thus important to state that there should be a need to monitor quite regularly along the pipeline, this is the main reason for more hops which is backed up by the low cost modem making a greater number of devices a reasonable prospect.

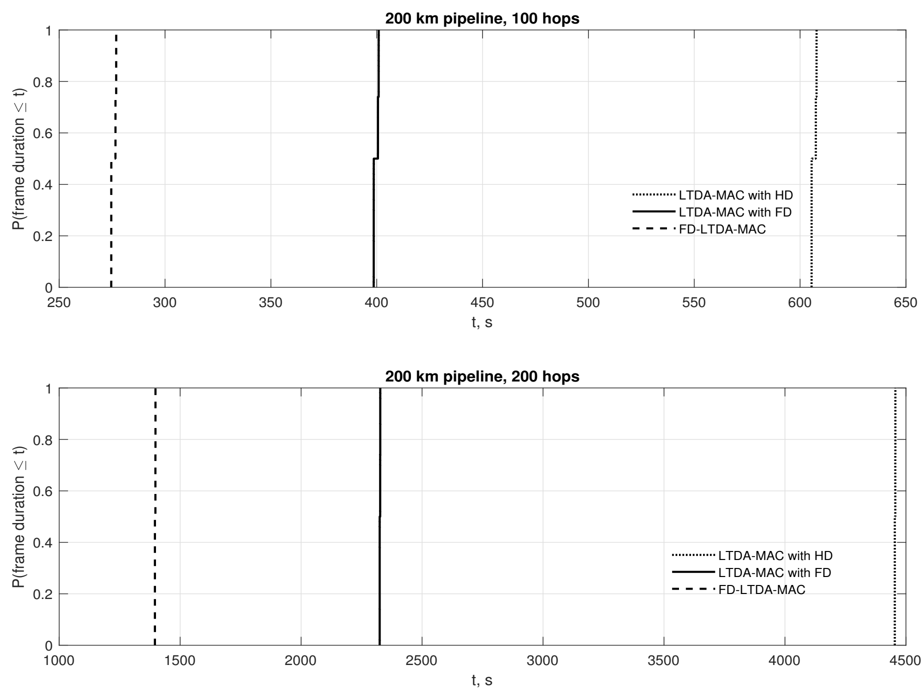


Figure 5.16: Frame duration cdfs of LTDA-MAC with HD nodes, LTDA-MAC with FD nodes and FD-LTDA-MAC for a 200km pipeline (100 and 200 hops).

5.4.3. Percentage reduction in frame duration

The percentage reduction in frame duration across the pipeline length for both LTDA-MAC with FD nodes and FD-LTDA-MAC compared to LTDA-MAC with half-duplex nodes is shown in Figure 5.19. While the monitoring rate im-

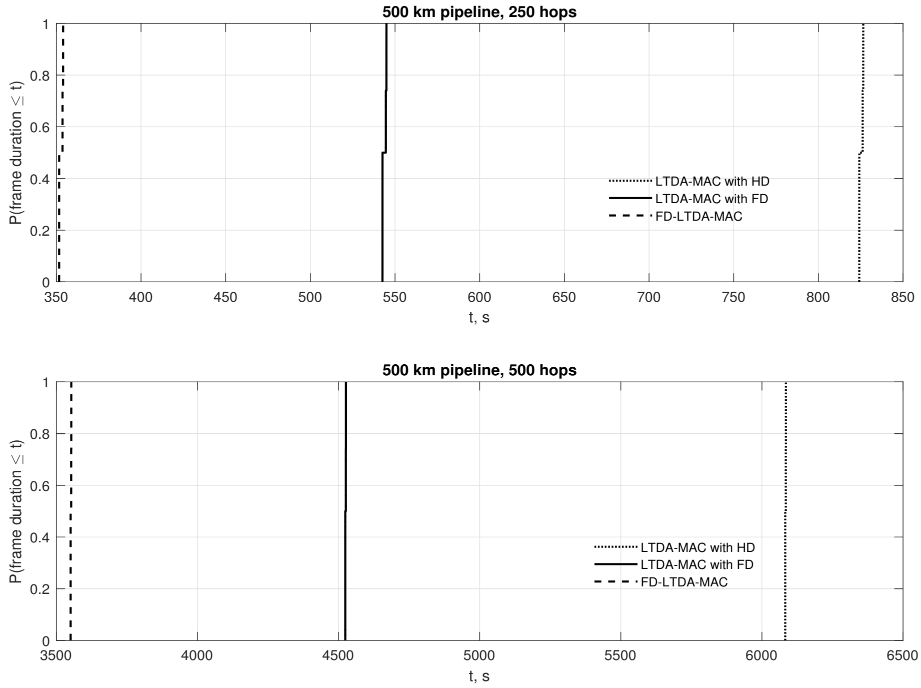


Figure 5.17: Frame duration cdfs of LTDA-MAC with HD nodes, LTDA-MAC with FD nodes and FD-LTDA-MAC for a 500km pipeline (250 and 500 hops).

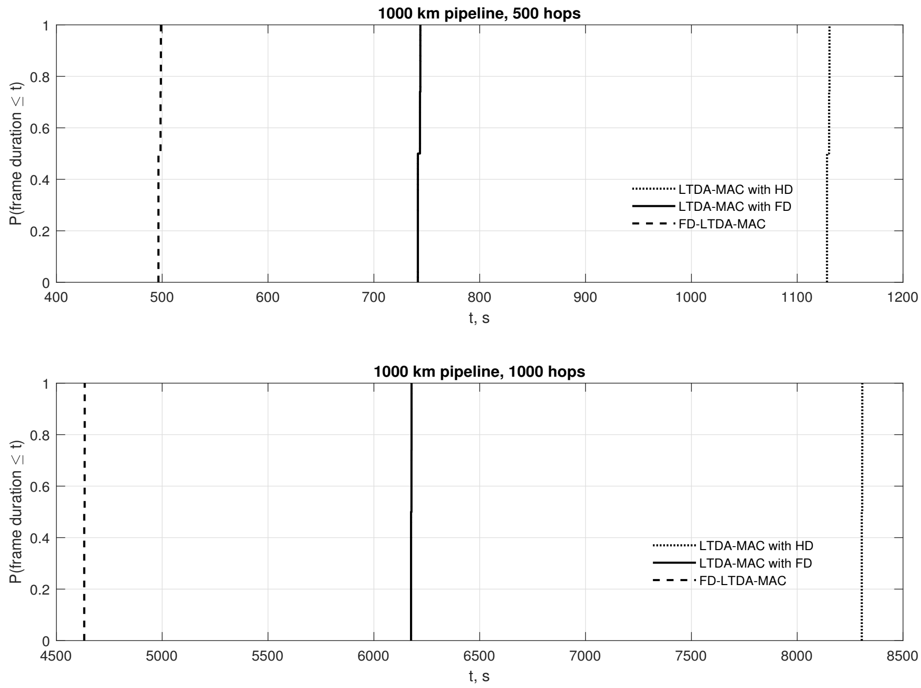


Figure 5.18: Frame duration cdfs of LTDA-MAC with HD nodes, LTDA-MAC with FD nodes and FD-LTDA-MAC for a 1000km pipeline (500 and 1000 hops).

proves across the pipeline length, the FD-LTDA-MAC shows higher percentage reduction in frame duration compared with LTDA-MAC and LTDA-MAC in FD. This is because the FD-LTDA-MAC is able to better exploit the spatial re-use. Consequently, FD-LTDA-MAC has better prospect with scalability than LTDA-MAC and LTDA-MAC in FD.

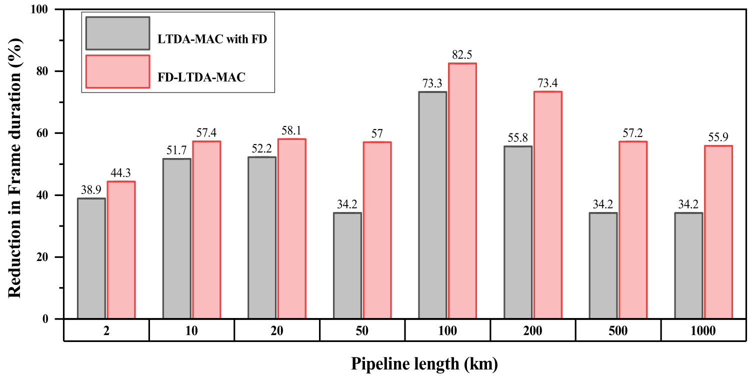


Figure 5.19: Percentage reduction in the Frame duration across pipeline scenarios.

5.4.4. Average values of E2E packet delays

The average End-to-End (E2E) packet delays is a measure of the time taken for a packet to be transmitted across the underwater chain network from a transmitting node to the sink node. The average E2E packet delays incurred by FD-LTDA-MAC, LTDA-MAC over full-duplex and LTDA-MAC protocols is shown in Table 5.2.

Table 5.2: Mean E2E packet delays

Pipeline length (km)	No. of hops	LTDA-MAC delay (s)		FD-LTDA-MAC delay (s)
		with HD nodes	with FD nodes	
2	2	1.0	0.9	0.6
	4	2.8	2.6	2.28
	10	6.6	4.2	3.8
	20	42.4	33.6	30.4
10	2	11.4	11.4	10.8
	4	13.0	10.5	9.7
	10	52.4	24.6	21.6
	20	137.8	95.4	81.3
20	2	21.4	21.4	20.8
	4	19.1	19.1	18.3
	10	22.8	19.7	18.4
	20	189.2	89.0	78.1
50	25	218.8	142.4	124.8
	50	869.6	643.6	511.4
100	50	196.5	127.8	67.6
	100	828.6	577.9	379.2
200	100	297.8	193.7	156.1
	200	1255.6	875.8	526.0
500	250	405.8	262.5	197.8
	500	1619.8	1128.8	1065.9
1000	500	552.7	364.7	204.3
	1000	2795.6	1790.0	1228.5

It can be seen that FD-LTDA-MAC provides significantly lower packet delays for both 1 km and 2 km modem ranges compared with LTDA-MAC and LTDA-MAC with full-duplex counterparts. This shows that FD-LTDA-MAC provides higher data packet throughput, thus provides improved QoS of the network.

5.5. Summary

This chapter proposes the FD-LTDA-MAC protocol, a new protocol which builds on LTDA-MAC but it provides efficient packet schedules for full-duplex based underwater acoustic chain network scenarios. This protocol signisficantly improves spatial re-use on a time shared channel but fully exploits full-duplex operation to compress frame durations especially for the longer pipelines spanning thousands of kilometres to improve the monitoring. The FD-LTDA-MAC protocol produces a better packet schedule for underwater acoustic chain network scenarios. Linear constraints in FD-LTDA-MAC allow for the calculation of transmit delays for forwarding packets to reflect full-duplex capabilities, extension to the greedy scheduling algorithm to utilise full-duplex optimised starting point for transmit delay search and modify the initial schedule and evaluation algorithms to accommodate full-duplex capability. The advantage of spectrum re-usability of FD-LTDA-MAC is leveraged by the full-duplex communication mechanisms to deal with long propagation delay and interference patterns to provide a more efficient packet schedules, which in turn provides greater network throughput performance for the longer pipeline scenarios. Results that are based on simulation of small scale (2 km, 10 km and 20 km), medium scale (50 km and 100 km) and large scale (200 km, 500 km and 1000 km) scenarios show that FD-LTDA-MAC achieves a performance improvement in terms of reducing frame duration by 44%, 83% and 56% in small, medium and large scale scenarios, respectively compared to LTDA-MAC protocol.

Chapter 6. Conclusions and Further Work

6.1. Conclusions

Full-duplex based Medium Access Control protocols for Underwater Acoustic Networks are technologies for efficient channel utilisation for underwater operations. The ability of nodes to simultaneously transmit and receive packets in-band will significantly improve network throughput and reduce packet delays. Challenges of underwater acoustic channels such as very long propagation delays and limited available bandwidth have limited the performance of the state-of-the-art MAC protocols for UANs as discussed in Chapter 2. The performance degradation is further worsened in applications involving monitoring long pipelines where nodes need to communicate in multi-hop fashion over long distances. Full-duplex can exploit temporal spectrum re-use of an underwater acoustic channel for efficient packet scheduling. The work presented in this thesis focused on the investigation of Medium Access Control protocols for full-duplex Underwater Acoustic networks (UANs) used in pipeline monitoring applications. To accomplish this, the fundamental principles of underwater acoustic communications, the state-of-the-art MAC protocols, MAC protocol design requirement and challenges for UANs were investigated as presented in Chapter 2.

In Chapter 3, the description of the experimental methodology used in the approaches to developing MAC protocols proposed in this thesis is presented. The scenario is based on a linear underwater acoustic chain network in a pipeline monitoring application which represents the basis for system level simulation model. The network, simulation and BELLHOP ray tracing based channel models were developed for the characterisation of the underwater acoustic environment and the evaluation of the MAC approaches in the thesis. The key network performance metrics used in the performance evaluation are frame duration, E2E packet delays and monitoring rate.

In Chapter 4 the performance evaluation of the LTDA-MAC protocol in full-duplex underwater acoustic chain network scenarios was presented. It investigated the network performance benefits from the application of the ’Greedy’ optimization based

LTDA-MAC protocol in full-duplex underwater pipeline network monitoring scenarios. The advantage of spectrum re-usability of LTDA-MAC is leveraged by the full-duplex communication mechanisms to take into account the long propagation delay and interference patterns to provide a more efficient packet schedules, which in turn provides greater network throughput performance in the studied scenarios. Results that are based on simulation of small scale (2 km, 10 km and 20 km), medium scale (50 km and 100 km) and large scale (200 km, 500 km and 1000 km) scenarios demonstrated that a significant performance enhancement is achieved by the application of LTDA-MAC protocols to full-duplex pipeline monitoring with respect to their half duplex counterparts.

Chapter 5 proposed the FD-LTDA-MAC protocol, a new protocol which builds on LTDA-MAC but it provides efficient packet schedules for full-duplex based underwater acoustic chain network scenarios. This protocol significantly improves spatial re-use on a time shared channel but fully exploits full-duplex operation to compress frame durations especially for the longer pipelines spanning thousands of kilometres to improve the monitoring. The FD-LTDA-MAC protocol produced a better packet schedule for underwater acoustic chain network scenarios. New linear constraints defined to accommodate full-duplex in FD-LTDA-MAC allow for the calculation of transmit delays for forwarding packets to reflect full-duplex capabilities. Extension to the greedy scheduling algorithm to utilise full-duplex optimised starting point for transmit delay search and the modification of the initial schedule and evaluation algorithms gave room for exploiting full-duplex capability to provide shorter schedules without packet collisions. The advantage of spectrum re-usability of FD-LTDA-MAC was leveraged by the full-duplex communication mechanisms to deal with long propagation delay and interference patterns to provide a more efficient packet schedules, which in turn provided greater network throughput performance for the longer pipeline scenarios. Also, FD-LTDA-MAC algorithm supports backward compatibility by having the ability to handle both half-duplex and full-duplex communications. Results that were based on simulation of small scale (2 km, 10 km and 20 km), medium scale (50 km and 100 km) and large scale (200 km, 500 km and 1000 km) scenarios showed that FD-LTDA-MAC achieves a performance improvement in terms of reduction in frame duration of 44%, 83% and 56% in small, medium and large scale scenarios, respectively compared to LTDA-MAC protocol with half-duplex and full-duplex nodes.

6.2. Original Contributions

The original contributions of the work presented in this thesis are summarised below according to the MAC approaches and models used for the evaluation of the MAC algorithms.

6.2.1. MAC scheme related

- An original approach to the adaptation of LTDA-MAC access scheme in full-duplex based linear underwater acoustic chain networks as presented in Chapter 4. This approach explores the use of LTDA-MAC in linear chain underwater acoustic networks comprising nodes with full-duplex capability, and show the performance gains that can be achieved through improved temporal re-use of an acoustic channel by switching on the full-duplex capabilities.
- A new full-duplex based MAC approach (FD-LTDA-MAC) has been developed in Chapter 5. This is designed to achieve further performance improvement which was not readily achievable by simply adapting LTDA-MAC in full-duplex network scenarios. This is achieved by re-developing the traditional LTDA-MAC protocol to fully exploit full-duplex capabilities and enhance spatial reuse for full-duplex underwater multi-hop chain networks. This approach is able to provide more efficient packet scheduling and reduced end-to-end packet delays in large scale scenarios compared with LTDA-MAC and LTDA-MAC with full-duplex enabled nodes. This results in higher monitoring rates for long range underwater pipelines using low cost, mid range, low rate and low power acoustic modems as presented in [150] and [154].

6.2.2. Evaluation Model related

- Full-duplex based network models developed in Chapter 3 are used to evaluate the MAC approaches in the thesis. This can be used to evaluate other MAC approaches.

- A unique channel model has been developed in Chapter 3 to provide a realisation of the underwater acoustic environment for the evaluation of the MAC approaches in this thesis. This model can be used to evaluate other network protocols.

6.3. Recommendations for Further Work

In this thesis the prospects of MAC approaches with full-duplex nodes have been investigated. Although the results showed that full-duplex based MAC approaches can provide significant network performance improvement, however, more approaches can be explored to further improve performance. This section provides further work that can be carried out. Useful further research includes the use of other optimisation algorithms in a bid to further shorten the frame durations produced by FD-LTDA-MAC. Also, redundancy in the links will be explored to solve the problem of failing nodes.

The greedy optimisation algorithm can further be extended to other optimisation algorithm such as epsilon-greedy to provide a better near optimal solution of transmit delays.

Due to failing nodes in real underwater network topologies, the network model could be extended to include redundant nodes. These redundant nodes would create alternative links for packet delivery in the case of failing nodes due to distance, power or other underwater environmental effect.

The acoustic modem employed in this work is low powered acoustic modem with low data rate. This research could be extended to use high power acoustic modems to provide more efficient packet schedules especially for very long pipeline models.

There is need to investigate more topologies that need bidirectional data flow which have a high potential for full-duplex exploitation. Additionally, analytical models of ALOHA are being researched in relation to various underwater chain network topologies, including half-duplex and full-duplex nodes. This establishes a foundation for computing fundamental gains from full-duplex underwater networks that employ contention-based MAC schemes.

The MAC approaches presented in this thesis were evaluated at simulation level. This can be extended by deploying the protocols on acoustic modems for real life experiments such as sea trials.

Glossary

ACK Acknowledgment

ARQ Automatic Repeat Request

ARS Adaptive Retransmission Scheme

AODV Ad hoc On-demand Distance Vector

BER Bit Error rate

cdf Cumulative Distribution Function

CDMA Code Division Multiple Access

CSMA Carrier-Sense Multiple Access

D2D Device to Device

DMAC Dynamic MAC

DSDV Destination-Sequence Distance-Vector

DSR Dynamic Source Routing

DSSS Direct-Sequence Spread-Spectrum

DTMAC Delay Tolerant MAC

E2E End-to-End

EC Electrical Conductivity

FD Full Duplex

FDD Frequency Division Multiplexing

FDR Full-duplex Relay

FD-LTDA-MAC Full Duplex Linear Transmit Delay Allocation MAC

FDMA Frequency Division Multiple Access

FEC Forward Error Correction

FDD Frequency Division Duplexing

FSK Frequency-Shift Keying

HC Horizontal Communication

HD Half Duplex

ISI Inter Symbol Interference

LLC Logical Link Control

LTDA-MAC Linear Transmit delay Allocation MAC

LUASN Linear Underwater Acoustic Sensor Networks

MAC Medium Access Control

M-FAMA Multi-sessions FAMA

MIMO Multiple-Input Multiple-Output

np-CSMA non-persistence CSMA

OFDM Orthogonal Frequency Division Multiplexing

OLSR Optimized Link State Routing

OOK On-Off Keying

PDR Packet Delivery Ratio

pH Potential of Hydrogen

PHY Physical

PSK Phase-Shift keying

QoE Quality of Experience

QAM Quadrature Amplitude Modulation

QoS Quality of Service

REQ Request

RF Radio frequency

R-MAC Reservation MAC

ROV Remotely Operated Vehicle

RTS/CTS request to send / Clear to send

RTT Round trip Time

SDMA Space Division Multiple Access

SDN Software Defined Network

S-FAMA Slotted Floor Acquisition Multiple Access

SI Self Interference

SINR Signal-to-Interference-plus-Noise Ratio

SNR Signal-to-Noise Ratio

SSP Sound Speed Profile

TDD Time Division Duplexing

TDMA Time Division Multiple Access

UAN Underwater Acoustic Network

UASN Underwater Acoustic Sensor Network

UAC Underwater Acoustic Communication

UUV Unmanned Underwater vehicle

UWA Underwater Acoustic

VC Vertical Communication

WHOI Woods Hole Oceanographic Institution

WSN Wireless Sensor Network

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