Interference Cancellation and Network Coding for Underwater Communication Systems

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Abstract

It is widely believed that wider access to the aquatic environment will enhance human knowledge and understanding of the world's oceans which constitute the major part of our planet. Hence, the current development of underwater sensing and communication systems will produce scientific, economic and social benefits. New applications will be enabled, such as deeper ocean observation, environmental monitoring, surveying or search and rescue missions.

Underwater communications differ from terrestrial communications due to the unpredictable and complex ocean conditions, relying on acoustic waves which are affected by many factors like large propagation losses, long latency, limited bandwidth capacity and channel stability, posing great challenges for reliable data transport in this kind of networks. The aim of this project is to design a future underwater acoustic communication system for dense traffic situations investigating the possibility of Medium Access with Interference Cancellation and Network Coding. The main efforts focus on reliability, low energy consumption, storage capacity, throughput and scalability.

Preface

The present report is written during the project period of the 10th semester at the Department of Communication Technology, Institute of Electronic Systems, Aalborg University.

This document aims to introduce the reader in the field of underwater communications looking at the history of development, underwater channel characteristics and applications. Furthermore, the report tries to be a sort of guide for the design of an underwater communication system focusing on different requirements, such as energy consumption, throughput and scalability. The main part concentrates on the evaluation of Medium Access with emerging concepts like Network Coding and Interference Cancellation.

The fundamentals of the project are based on many studies from different fields like underwater channel modelling, architecure for underwater networks, design and implementation of Underwater Sensor Networks, design considerations for an underwater transceiver and, underwater and terrestrial Medium Access Control schemes.

The contents of the project rely on a conceptual approach. Note that, the idea is to wonder what is necessary in order to understand the simulations and results which are shown at the end of the document. In other words, the explanations are devoted to define the basic ideas of the concepts involved in the document, thus, avoiding difficult mathematical equations. In this sense, the goal is to understand how ideas come to be.

Acknowledgements

I would like to thank Frank Fitzek and Janus Heide for helping me during the project period and for giving me the opportunity to learn such interesting topics as those involved in underwater communications.

Likewise, I would like to thank my family, girlfriend and friends for giving me so much support all the time, especially, my friend Bernardo, who has followed the development of the project since its beginnings.

Aalborg University, 3rd of June 2010

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Introduction

The new approach of long-lived, versatile and easily deployable underwater networks have high expectations to fuel revolutionary technological developments on wider access to the marine environment. So, in this sense, new generations of underwater networks will enhance deeper human knowledge and understanding of the world's oceans which constitute the major part of our planet. Furthermore, it is commonly thought that the undersea world holds ideas and resources which will have great impact on many areas of science, industry and government.

New applications will be enabled ranging from environmental monitoring to deeper ocean observation, and search and rescue missions. This means that while current applications include supervisory control of individual Autonomous Underwater Vehicles (AUVs), and telemetry of oceanographic data from bottom-mounted instruments, the vision of future consists of integrated networks of instruments, sensors, robots and vehicles operating together in a wide variety of underwater environments. However, any underwater operations are fraught with difficulty due to the absence of an easy way to collect and monitor data.

Since ocean conditions are complex and unpredictable, underwater communications pose many challenges to networking protocol design as compared with terrestrial radio networks. What is required is a low-cost, versatile, high quality, easily deployable and self-configurable platform that will automate data collection and scale-up in time and space, speed-up access to the collected data, ensure complete data retrieval with high probability by means of cooperative approach among nodes and achieve low energy consumption to prolong the network lifetime. Hence, the motivation of this project in studying new communication systems for future underwater networks in order to fulfill these requirements.

This project aims to be the basis of future research for the design and implementation of future underwater wireless networks relying on emerging concepts for Medium Access protocol design. Wireless Medium Access schemes, while successful in traditional radio communications, are prone to severe limitations in efficiency and scalability when deployed in the underwater environment posing many challenges to networking protocol design. In this sense, CSMA is widely used in wired and wireless radio communications. For this reason, CSMA is the lay out for implementing these new strategies in order to overcome the several constraints of the underwater channel.

The goal of this project is to design a future underwater wireless communication system for dense traffic situations investigating the possibility of Medium Access with Interference Cancellation and Network Coding modifying the CSMA standard. On the one hand, Network Coding will help to improve the throughput. On the other hand, mitigating the interference will help to increase the efficiency reducing the energy consumption of the network nodes.

As the design of any communication system involves many topics covering physical and networking capabilities, the main focuses are an overview of commercial underwater transceivers and suppliers, and suggestions for transceiver selection, as well as the design and performance evaluation of Medium Access with Interference Cancellation and Network Coding (main part). Thus, the contents of the document are organised as follows. In Chapter 1, some fundamentals of underwater communications are introduced. Chapter 2 presents the design criteria where the main design parameters are analysed, for instance the proposed scenario, some technical considerations and so forth. Likewise, Chapter 3 outlines the most relevant companies of underwater transceivers and their product range. After that, a transceiver selection is carried out. Chapter 4 presents the evaluation of Medium Access with Interference Cancellation and Network Coding. Finally, some conclusions are inferred.

Chapter 1

Underwater Communications

The aquatic environment has posed many challenges for feasible and successful undersea communications due to the dynamic and complex ocean conditions being generally very difficult to predict. In this sense, there are many issues affecting communication depending on the applied technology, such as large propagation losses and scattering issues.

This chapter will describe the history, development and characteristics of underwater communication, survey the trends and technology current in use and under development and then finish with a more specific description of emerging and enabled applications.

1.1 History of Development

The field of underwater acoustics can be traced back to Aristotle (384-322 BC). According to [1], Aristotle was among the first to note that sound could be heard in water as well as in air. Nearly 2000 years later, Leonardo da Vinci (1452-1519) observed that ships could be heard at great distances underwater. Almost 200 years after da Vinci's observation, the physical understanding of acoustical process was advancing rapidly with Marin Mersenne and Galileo whose researches are considered to provide the foundation for acoustics. Several decades later, in 1687, Sir Isacc Newton published the first mathematical theory of how sound moves, in his great work, Philosophiae Naturalis Principia Mathematica. Although Newton focused on sound in air, the same basic mathematical theory applies to sound in water.

The 1800s

In 1743, Abb J. A. Nollet conducted a series of experiments to settle a dispute about whether sounds could travel through water. During the 1800s, the first successful measurements of the speed of sound in water were carried out by several scientists of that time. In 1826 on Lake Geneva, Switzerland, Jean-Daniel Colladon, a physicist, and Charles-Francois Sturm, a mathematician, made the first recorded attempt to determine the speed of sound in water. At about this same time, scientists began to think about the practical applications of underwater sound. One of the first applications that scientists explored was to determine the depth of the sea by listening for echos. Several decades later, in 1877 and 1878, the British scientist John William Strut, also known as Lord Rayleigh, was the first to formulate the wave equation, a mathematical means of describing sound waves that is the basis for all work on acoustics.

From 1900s to 1930s

In the early 1900s, the development of the telegraph and telephone systems[1] fuelled the first practical uses of underwater acoustics. During the World War I (WWI), the use of submarines and underwater mines profoundly influenced the development of underwater acoustics. In 1917, Paul Langevin, a French physicist, used the piezoelectric effect, which had been discovered in 1880 by Paul-Jacques and Pierre Curie, to build an echo-ranging system. In 1918 for the first time, echoes were received from a submarine at distances as great as 1500 m. The period between WWI and World War II (WWII) was a time of increased discovery about underwater acoustics. Scientists were beginning to understand some fundamental concepts about sound propagation, and underwater sound was being used to explore the ocean and its inhabitants.

From 1941 to 1945

During WWII, progress in underwater acoustics, as in other areas like radar and weapons, was shrouded in secrecy. At the end of WWII, many research

[1] Telegraph patended by Samuel Morse, 1837. Telephone patented by Alexander Bell, 1876.

organisations, such as the National Defense Research Committee[2], pursued extensive underwater acoustic programs. The main efforts focused on making careful measurements of factors that affected the performance of echo ranging systems, which came to be called "sonars" late in WWII as an acronym for SOund Navigation And Ranging.

The development of underwater communications after WWII was still in its early beginnings and new innovations accompanied the availability of new technologies. A particular work [2] presents an overview of the developments in environmental acoustics research [3] and the resultant scientific progress from 1960 to 2000. In the same line, [3] reports an overview of many experimental results on communications performance and the state of the art from 1982 to 2000. Another work [4] reviews recent achievements on undewater acoustic technology from 1997-2007 and defines some trends and directions. Next lines summarises most relevant events and developments regarding underwater acoustics in accordance with [2],[3] and [4].

The 1960s and 70s

Several mathematical method improvements were made. At this time, use of the parabolic form of the wave equation allowed efficient numerical solutions for theoretical investigations and practical predictions in strongly range-dependent environments. Prior to the late 1970s, there were a few published attempts of acoustic modems. Analog systems were developed, which were essentially sophisticated loudspeakers, but they had no capability for mitigating the distortion introduced by the highly reverberant underwater channel. Paralleling the developments applied to the severely fading radio frequency atmospheric channels, the next generation of systems employed frequency-shift-keyed (FSK) modulation of digitally encoded data. The use of digital techniques was important in two respects. First, it allowed the use of explicit error-correction techniques to increase reliability of transmissions. Second, it permitted some level of compensation for the channel reverberation both in time (multipath) and frequency (Doppler spreading). The remainder of the decade saw steady improvements in these systems.

[2] NDRC Division. Other organisations include Woods Hole Oceanographic Institute and the MIT Radiation Laboratory.

[3] The field of environmental acoustics is concerned with the influence of the environment on sound propagation and scattering, and acoustic measurement of the environment, usually by so-called inverse methods.

The 1980s and 90s

The new methods and new computational resources provided new insights into the structure and stability of acoustic fields. The potential improvements in bandwidth efficiency (data rate/signal bandwidth) in the early 1980s stimulated researchers to design new modulation schemes which managed with the time variability and the dispersive multipath of the ocean, especially with the rapidly developing capabilities for high-speed digital signal processing. The early 1990s yielded a plethora of published coherent systems that moved acoustic telemetry into the horizontal ocean channel. Using quadrature phase-shift-keyed (QPSK) modulation, a data link of 1000 bit/s at 90 km was demonstrated [5][6]. Moreover, new oceanographic environmental sensors and vehicles were coming online, based in part on the same advances that led to the new acoustic systems, allowing more comprehensive experiments with better environmental measurements [7][8].

The 2000s: 1997-2007

Computers continued to improve. While systems were used aboard ships and in short-term moorings looking at shortperiod environmental effects [9], others were also deployed autonomously on the seafloor, fostering advances in studies of acoustic effects [10]-[14]. On the other hand, developments in transducers, hydrophones [4], arrays of these, and larger sonar systems are ongoing during this period. Likewise, new acoustic methods are being developed for the classification of zooplankton by means of scientific echo sounders operating at multiple ultrasonic frequencies [15], [16] and fish-tracking recording the position of fish echoes [17] or by passive acoustic receivers [18]. Finally, some developments have focused on modelling and prediction of ocean acoustic characteristics analysing how these properties affect propagation, scattering, and reverberation.

Trends and Directions

Marine mammals and other marine organisms are receiving increasing attention because of their innate and remarkable acoustic sensing capabilities and evident or potential sensitivity to sound, especially that from human

[4]Transducers that convert from an acoustic to an electrical signal for underwater communications

activities, e.g. geophysical explorations using seismic arrays; offshore oil, gas, and mineral extractions; shipping; and some sonar use.

The shallow-water zone defines much of the worldwide coastal zone. Understanding propagation and scattering of sound in shallow water is essential to many applications, including bathymetric mapping, underwater communications, and application of inverse methods to determine environmental properties both in the water column and in the sub-bottom.

Major advances have been made in the field of unmanned underwater vehicles over the past several decades, literally effecting a revolution in oceanographic measurement. As platforms for acoustic sensors, AUVs are supporting very high-resolution mapping operations, for instance, of the seafloor and hydrothermal vents, including their plumes.

Three prominent areas of neglect in this review, among others, are those of quality assurance of acoustic measurements, applications of image processing in acoustic detection and classification, and redundancy in acoustic measurement. There is no doubt that these and other important areas deserve explicit attention in future research.

1.2 Underwater Channel Characteristics

The underwater environment is a uniquely difficult one for communications. Water movements are never-ceasing, and conditions are always changing drastically depending on location, time of day and weather. Hence, the performance of any undersea communication can be unpredictable.

The physical signals that are used to carry digital information through an underwater channel are sound, radio and optical waves. While acoustic communications undergo large propagation losses, extended and variable propagation delays, strong multi-path signals, and limited bandwidth capacity and channel stability, underwater non-acoustic signalling methods also experience large propagation losses and scattering issues. As electromagnetic (EM) waves does not propagate well underwater over long distances, sound is mainly used as the communication medium. Thus, this section will describe the underwater acoustic channel and examine technical differences between underwater acoustics and terrestrial wireless communication.

1.2.1 Underwater Acoustic Channel Model

According to [19], the three distinguishing characteristics of this channel are frequency-dependent, propagation loss, severe multipath and low speed of sound propagation.

The underwater attenuation *A(l, f)* can be expressed as

$$A(l, f) = \left(\frac{l}{l_{ref}}\right)^{\alpha} a(f)^{l}, \tag{1.1}$$

where l is the distance between transmitter and receiver, and l_{ref} is a reference distance (typically 1 m). α is the counterpart of the path loss coefficient in terrestrial radio, and it is used to model the geometry of propagation. A practical value α=1.5 is usually adopted. The factor *a(f)* in (1.1) is called the absorption loss that depends on the frequency f: it models the conversion of acoustic pressure into heat, and can be approximated by Thorp's formula [20], [21]. This dependence severely limits the available bandwidth despite in practice it is limited by the transducer bandwidth.

Within this limited bandwidth, the signal is subject to multipath propagation, which is particularly pronounced on horizontal channels. In shallow water, multipath occurs due to signal reflection from the surface and bottom. In deep water, it occurs due to ray bending. The channel response varies in time, and also changes if the receiver moves. Regardless of its origin, multipath propagation creates signal echoes, resulting in intersymbol interference in a digital communication system.

The speed of sound underwater varies with depth and also depends on the environment, for instance local temperature, salinity and pressure in the medium [22], [23]. Its nominal value is only 1500 m/s, and this fact has a twofold implication on the communication system design. First, it implies long signal delay, which severely reduces the efficiency of any communication protocol that is based on receiver feedback, or hand-shaking between the transmitter and receiver. Secondly, low speed of sound results in severe Doppler distortion in a mobile acoustic system.

For further details about this topic, a particular work [24] describes more accurately the fundamentals of an underwater acoustic channel focusing on noise, capacity, transmission band, transmission power and distance of an underwater link.

1.2.2 Differences between Terrestrial and Underwater wireless communication

Unlike radio channel, the available bandwidth of the underwater acoustic channel is very limited dependent on both range and frequency, wheras the propagation speed is five orders of magnitude lower. This speed can vary considerably depending on pressure, water composition, and temperature [25]. Also huge propagation delay, noise power spectral density highly dependent on frequency, floating node mobility, and limited acoustic link capacity, are significantly different from ground-based wireless sensor networks [26]. The main discrepances between terrestrial and underwater networks can be outlined as follows in Table 1.1:

Environment / **Parameters**	**Underwater**	**Terrestrial**
Wave type	acoustic (commonly)	electromagnetic
Velocity	$1.500ms^{-1}$	$3.10^{-8}ms^{-1}$
Time of propagation		
Spatial Correlation	low	important
Spreading of sensors		
Bandwidth	0-400kHz	20kHz-300GHz
Required power Recuperation cost	important	low
Capacity of sensor storage	important (complex signal processing)	important(multimedia Application)
Receiver	Complex	Less complex
Numeric modulation type	M-PSK;M-FSK	M-QAM; M-PSK; M-FSK
Transducer	piezoelectric	electromagnetic

Table 1.1: Differences between terrestrial and underwater wireless communication. The data is taken from [27]

This comparative study explains that wireless underwater communication poses many challenges. Most commonly used methods, which are well established for digital communication in air, do not work in water. Besides, it should be pointed out that an underwater acoustic link combines in itself the worst aspects of radio channels: poor quality of a land-mobile link and high latency of a space link.

1.3 Current Technologies

Present underwater communication systems involve the transmission of information using acoustic, radio or optical techniques. Each of these physical methods has advantages and limitations depending on applications and design requirements. A particular paper work [28] reviews the physical fundamentals and engineering implementations for efficient information exchange via wireless communication using physical waves as the carrier among nodes in an underwater sensor network. The physical waves under discussion include sound, radio, and light. Next lines describes the most relevant physical properties and critical issues for each of the acoustic, radio, and optical wave propagations in underwater environments.

Acoustic Waves

Acoustic communication is the most versatile and widely used technique in underwater environments due to the low attenuation (signal reduction) of sound in water. This is especially true in thermally stable, deep water settings. On the other hand, the use of acoustic waves in shallow water can be adversely affected by temperature gradients, surface ambient noise, and multipath propagation due to reflection and refraction. The much slower speed of acoustic propagation in water, about 1500 m/s (meters per second), compared with that of radio and optical waves, is another limiting factor for efficient communication and networking. Nevertheless, the currently favorable technology for underwater communication is upon acoustics.

Radio Waves

On the front of using EM waves in radio frequencies, conventional radio does not work well in an underwater environment due to the conducting nature of the medium, especially in the case of seawater. Nevertheless, radio could work underwater over short distances. So, in this sense, its much faster propagating speed is definitely a great advantage for faster and efficient communication among nodes.

Despite its very few practical applications to date, there are some studies which reveal that radio signalling coupled with digital technology and signal compression techniques has many advantages that makes it suitable for some underwater applications. [29] describes the background physics and potential applications in the areas of underwater communications, sensing and navigation.

Optical Waves

Free-space optical (FSO) waves used as wireless communication carriers are generally limited to very short distances because of the severe water absorption at the optical frequency band and strong backscatter from suspending particles. Even the clearest water has 1000 times the attenuation of clear air, and turbid water has more than 100 times the attenuation of the densest fog. Even so, underwater FSO, especially in the blue-green wavelengths, offers a practical choice for high-bandwidth communication (10-150 Mbps, bits per second) over moderate ranges (10-100 meters). This communication range is much needed in harbour inspection, oil-rig maintenance, and linking submarines to land, just name a few of the demands on this front.

Summary

For a more intuitive comprehension, the most significant features of acoustic, radio and optical carriers for UnderWater Sensor Networks (UWSN) in seawater environments are outlined in Table 1.2.

Carriers / **Parameters**	**Acoustic**	**Radio**	**Optical**
Attenuation	low	high	high
Effective range	≈km	≈10m	≈10-100m
Propagation delay	high	low	low
Bandwidth	≈kHz	≈MHz	≈10-150MHz
Data Rate	up to 100kbps	up to 10Mbps	up to 1Gbps
Heavy constraints	bandwidth-limited, interference-limited	power-limited	environment-limited

Table 1.2: Comparison of Acoustic, Radio and Optical waves. The data is taken from [28]

As it can be observerd in Table 1.2, each of the three physical wave fields has its own advantages and disadvantages for acting as an underwater wireless communication carrier. Depending on the application, one of them will be more suitable than the others.

Up to date and extending to the near future, acoustic waves will be staying as the major carrier of wireless communication in UWSNs. For acoustic wave carriers, apparently the key challenges are in communication and networking.

1.4 Applications

The potential applications of wider access to the marine environment have pumped the development of new techniques, such as UWSNs, in the areas of underwater communications, water monitoring and navigation.

There is a well established need for data transmission underwater. The most obvious application is surveying, which can involve data transmission for:

- Underwater vehicle control, either direct control of a ROV (Remotely Operated Vehicle), or management of an AUV (Autonomous Underwater Vehicle)
- Video images, to aid vehicle control, and to examine underwater structures (wrecks, pipelines, rock formations)
- Sonar data, for mapping, survey, fish detection, collision avoidance
- Transferring bulk data after geological survey or long term studies

There are also a number of potential military applications.

Regarding both long-term aquatic monitoring and short-term aquatic monitoring, the main potential applications summarised in [30] are: marine biology, deep-sea archaeology, pollution detection (chemical, biological and nuclear), ocean circulation modeling for improved understanding of climate systems, improved weather forecast, fish stock dynamics and spread of contaminants, monitoring of ocean currents and winds, detecting climate change, understanding and predicting the effect of human activities on marine ecosystems, disaster prevention distributed tactical surveillance, reconnaissance, targeting and intrusion detection systems, underwater natural resource discovery, distributed tactical surveillance, assisted navigation and mine reconnaissance, etc.

From the prospect of underwater communication and navigation, the most significant applications are outlined as follows:

- Real time control of Unmanned Undersea Vehicles (UUVs) from shore, submarines and surface vessels
- Real time transfer of sensor data from UUVs when submerged
- Communications between UUVs and sub sea sensors
- UUV distributed navigation systems for shallow harbours and ports
- Subsea navigation beacons; asset location and protection
- Diver communication (speech and texting)

To sum up, while current applications include supervisory control of individual AUVs, and telemetry of oceanographic data from bottom-mounted instruments, the vision of future is that of a "digital ocean" in which integrated networks of instruments, sensors, robots and vehicles will operate together in a variety of underwater environments. Examples of emerging applications include fleets of AUVs deployed on collaborative search missions, and ad hoc deployable sensor networks for environmental monitoring. Figure 1.1 shows a deployed network based on this approach.

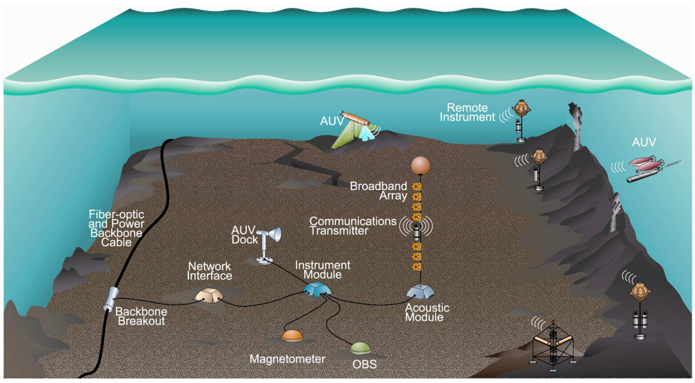

Figure 1.1: Deep-Sea Observatory with Acoustic Communications for AUVs and Instruments. Figure taken from Massachusetts Institute of Technology

Chapter 2

Design Criteria

The development of practical underwater networks is a difficult task that requires a broad range of skills. Not only must the physical layer provide reliable links in all environmental conditions, but there are a host of protocols that are required to support the network discovery and maintenance as well as interoperability, message formation, and system security.

As electromagnetic waves do not propagate well underwater, acoustics plays a key role in underwater communication. Due to significant differences in the characteristics of electromagnetic and acoustic channels, the design of feasible underwater networks needs to take into account a wide variety of different constraints.

The long delays, frequency-dependence and extreme limitations in achievable bandwidth and link range of acoustics should be of primary concern at an early design stage in addition to power and throughput efficiency, and system reliability. These factors make underwater networking a challenging and rewarding endeavour.

In this chapter, some significant aspects to be considered when designing an underwarter communication system are analysed. For example, the description of the environment where the network is supposed to be deployed, technical criteria and general assumptions.

2.1 Challenges

The design of underwater networks involves many topics covering physical and networking capabilities. As acoustic channels are commonly used for underwater communications, the main focuses in this project are the state-of-the-art analysis of commercial acoustic modems and suppliers as well as the design and possible implemention of Medium Access with Interference Cancellation and Network Coding (main part).

While some Medium Access schemes have been successful in traditional radio communications, they are prone to severe limitations in efficiency and scalability when employed in the underwater environment posing many challenges to networking protocol design. For example, in Medium Access Control (MAC) schemes which operate entirely in the time domain (for instance, TDMA and CSMA), these disadvantages are primarily because of the very large propagation delays [31]. Therefore, new strategies are needed in order to account the specific features of underwater propagation.

Some design challenges for reliable data transport in UWSNs [32] could be as follows:

1. *End-to-End approach does not work well due to the high channel error probability and the low propagation speed of acoustic signals*
2. *Half-Duplex acoustic channels limit the choice of complex ARQ protocols*
3. *Too many feedback from receivers are not desirable in terms of energy consumption*
4. *Very large bulk data transmission is not suitable in mobile UWSNs because of the limited communication time between any pair of sender and receiver, the low bandwidth and the long propagation delay*

2.2 Assumptions

The main goal of this project is to investigate how Medium Access with Interference Cancellation and Network Coding perform regarding data dissemination as compared with employed MAC techniques underwater. In this sense, some tests are conducted in order to evaluate the performance.

Consequently, general assumptions should be stated to understand how the tests are carried out.

In this project, an underwater network is simply defined as a set of nodes which communicate using acoustics waves. The nodes are fixed and the distance among them is considered in the long range; a typical range between emitter and receiver could be 1 km. Despite being a stationary network, mobile scenarios where nodes can passively float with water currents are also taken into account for explanations.

The coverage range of a node is one hop. This means that the level of signal which is received by next hop node is very high, otherwise, is very low. Typical values used in mobile communications systems are 90% and 10%, respectively. So, it is assumed that the signal from a source node will not be received by nodes whose range is higher than one hop.

Likewise, regarding the sound propagation speed, its nominal value 1500 m/s is used for calculations.

Another rellevant aspect which should be assumed in the performance evaluation of Medium Access schemes is the packet length. Hence, the packet size is set basing on two approaches. First, the transmission capacity of nodes is considered without data redundancy. Second, the packet transmission time is equals to the propagation delay depending on the distance between sender and receiver.

On the other hand, it should be mentioned that the node with greater impact on the network is supposed to implement Interference Cancellation and Network Coding whereas the other nodes are in charge of data packet retransmission using Interference Cancellation. Besides, a two-way communication (upstream and downstrem flows), unlimited storage capacity of terminals and no packet erasures are assumed to conduct the experiments.

Finally, the dissemination process is completed when the target nodes have received all the requested packets.

2.3 Target Scenario

The tests have been conducted over two scenarios:

- **Scenario 1: Line-up network.** *The goal is to investigate how* *the data is disseminated through nodes and how many time the data dissemination process takes*

- **Scenario 2: Meshed network.** *The aim is to analyse the performance of proposed MAC methods in such common topologies: dense traffic situations in large-scale networks*

2.3.1 Line-up Network

This scenario consists of 5 nodes which are aligned either vertically or horizontally. They are named and organised from left to right as "NODE X". Each node is logically linked with its upstream and downstrem nodes. Figure 2.1 shows the horizontal deployment of the line-up network.

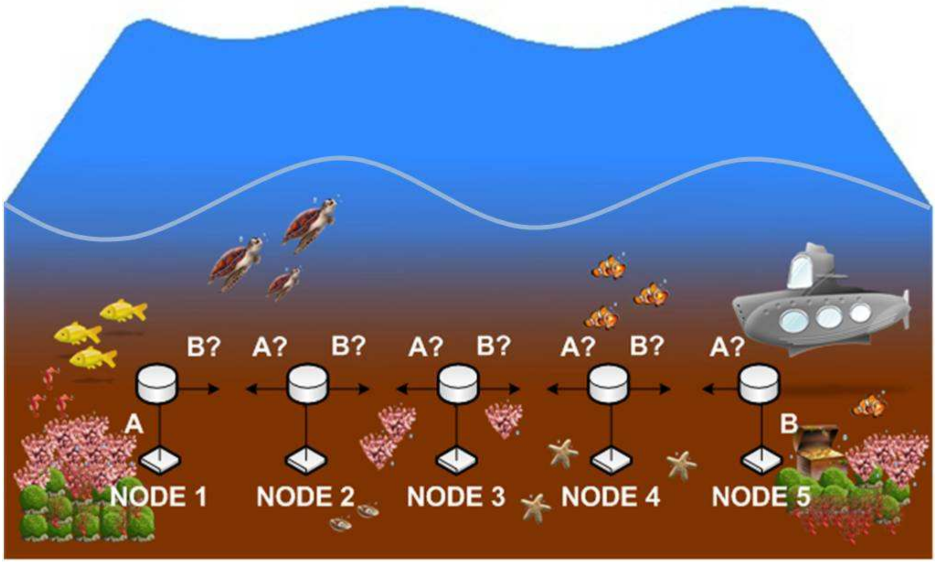

Figure 2.1: Line-up network in horizontal deployment

Its working principle is based on disseminating data packets among nodes. Thus, two information flows, A and B, are disseminated through the network. While flow A is trasmitted upstream by NODE 1, flow B is sent downstream by NODE 5. Note that all nodes want both data flows. So, this scenario is an easy way to evaluate the performance of proposed and existing MAC techniques in terms of data dissemination process.

2.3.2 Meshed Network

As in the previous scenario, the network comprises 5 nodes in a meshed topology. However, its purpose and behaviour are quite different.

In this particular case, nodes are linked logically building a meshed network with some single properties. Despite being a meshed network, it works through two axes, x and y. The performance focuses on two data flows, A and B, which are transmited in paralell. Flow A is transmitted through x-axis by NODE 2 whereas flow B is sent through y-axis by NODE 3. Note that now NODE 4 and 5 wants the data flows A and B, respectively. Also, NODE 2 and 3 broadcast their corresponding data flows as well as NODE 1, which is in charge of broadcasting both data flows to the rest of nodes as its the core of the network. This means that other nodes around will received both data flows even though they are not interested. Figure 2.2 depicts a possible deployment of the meshed network.

This scenario is intended for describing a typical situation in present meshed networks which is faced poorly efficient by current employed MAC methods due to the underwater channel constraints. Consequently, it is a good chance to find out how proposed MAC techinques performs in this common environment.

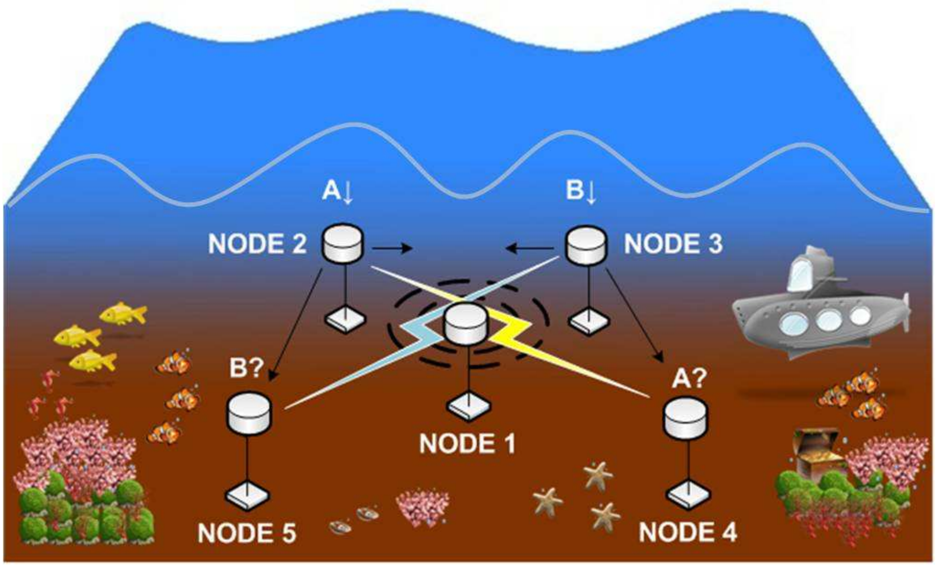

Figure 2.2: Meshed network deployment

2.4 Technical Criteria

From the engineering point of view, several desirable requirements should be aimed at when designing an underwater communication system. They can vary depending on the deployment environment and the applications. Such crucial issues can be power consumption, throughput, reliability and scalibility. In this section, some design factors for underwater networks will be stated.

Signal Communication

According to previous statements, the most convenient technology for underwater communication is upon acoustics in spite of its limiting factors. So, its channel effects should be taken into account at an early design stage evaluating how they affect to the design requirements. Note that range and data rate plays a key role in the selection of the communication carrier.

Type of Cells

Depending on the environment and the distribution of nodes, omnidirectional or directional antennas should be chosen for the design.

- **OMNIDIRECTIONAL:** *Suitable for dynamic topologies where nodes are mobile and the communication time between sender and receiver is limited*
- **DIRECTIONAL:** *Appropiated for stationay communications where nodes are fixed. In this scenario, the objective is to concentrate all the energy on a particular area*

In this project, the nodes are supposed to transmit with omnidirectional antennas though the scenarios to conduct the tests are static, thus, the broadcast nature can be exploited.

Coverage Levels

As in each wireless communication system, the coverage study is a significant factor to determine the system efficiency. It should fulfill the BER and SNR requirements at the receiver to correctly demodulate the data packets. This analysis should also consider the limiting factors of underwater propagation, sensitivity at the receiver, transmission power and all those factors which are included in the power balance. The passive sonar equation [33] characterises the signal to noise ratio (SNRU) of an emitted underwater signal at the receiver.

Underwater Deployment

The medium has strong influence on the deployment of an underwater network. In this sense, performance varies drastically depending on depth, type of water and weather conditions which affect seriously any underwater communications. To combat this unpredictability, some underwater communications systems are designed for reliability even when operating in harsh conditions and these configurations lead to sub-optimal performance when good propagation conditions exist. Part of the challenge in optimising performance is to predict which environmental factors have the greatest impact. A key element to predicting channel characteristics is correctly estimate the multipath and this is possible only if the properties of the boundaries are carefully modelled with simulation tools or channel measurements when possible.

Energy Consumption

Energy efficiency is always a major concern to prolong the network time. As nodes are battery-powered, recharging or replacing node batteries is difficult, especially in hard-to-access areas such as the underwater environment.

In order to cope this constraint there are two solutions: the first is energetic based on the finding of optimal frequency for underwater communication, the second solution is formal based on the choice of MAC protocols essentially these of routing. That second approach is the basis of this project in investigating the viability of proposed MAC techniques in underwater networks.

NB. Another approach in order to optimise energy utilisation which is gaining more and more attention in sensor networks is the power-sleeping mode, where devices alternate between active and sleep mode. There is proved that the combination of both radio off and microcontroller power down mode can significantly increase the network lifetime. A particular work [34] proposes a cooperative mechanism for data distribution that increases system reliability, and at the same time keeps the memory consumption for data storage low on each device using previous approach.

Bandwidth

It is well known that the frequency-dependency of the acoustic path loss imposes a bandwidth limitation on an underwater communication system. As sound waves are much slower than the electromagnetic the latency in communication is typically much higher. Due to the multi-path propagation and ambient noise, the effective data rates are lower and packet loss rate is usually much greater.

There are several approaches to improve the bandwidth efficiency. One way to achieve high throughputs over band-limited underwater acoustic channels could be to improve the receivers by using optimal modulation and coding techniques. Many research focus on the PSK (Phase Shift Keying) modulation, which are a viable way of achieving high speed data transmission [35][36]. This topic is also included in this project as an important research task. For this reason, the state-of-the-art analysis of current commercial acoustic modems will be discussed later.

Reliability

The need for reliable underwater communications is a difficult task when there are limitations in energy consumption and storage capacity of nodes. Some critical applications can demand data retrieval with high probability but assuring low energy consumption.

On possible approach is temporally distribute the date to be stored cooperatively on many nodes of the network. Data replication can also be applied to increase reliability of data retrieval process. Some paper works which are referred to this topic are [32], [34] and [37].

Scalability

As previous design factors, scalability is a desirable property of a network. Underwater sensor networks have recently received growing interest for aquatic applications. In near future, the deployment of underwater networks could be extensively done. So, scalability issues should be taken into account to comply with the design requirements when scaling-up in time and space.

Chapter 3

Underwater Wireless Transceiver

Evolutionary processes have shaped acoustic communication behaviours of remarkable complexity. Thus, numerous researches have led to the development of innovative receiver structures for robust underwater acoustic communication as consequences of advances in electronics and computer technology.

Due to the underwater acoustic channel constraints, some issues like attenuation, low power consumption, Bit Error Rate, error coding and alternative modulation strategies should be considered in the proposition of the transceiver structure and its design. The values of these parameters mentioned above are crucial to improve the wireless underwater communication.

Although the aim of this chapter is to describe the state-of-the-art of commercial acoustic modems, it is also desirable to introduce some design considerations for underwater wireless communication transceivers.

3.1 Design Considerations

As acoustic carriers are used for communications, signals are distorted by a variety of factors; the major contributors are absorption, refraction and reflection (reverberation). Through these three factors, the signals picked up by receivers are duplicated forms of the original, of varying levels of strength and distorted by spreading or compression.

Large delays between transactions can reduce the throughput of the system considerably if it is not taken into account. Also, the battery-powered network nodes limit the lifetime of the proposed transceiver. Therefore, advanced signal processing is very important and required to make optimum use of the transmission capabilities.

To overcome these difficulties, different modulations techniques and signalling encoding methods might provide a feasible means for a more efficient use of the underwater acoustic channel bandwidth. In fact, the values of the transmission loss, transmission distance and power consumption, should be optimised to improve the wireless underwater communication and the transceiver performance [27].

An important concern regarding wireless transceiver for the underwater communication is its requirement of a transducer at the transmitter side. This transducer allows to transform electrical waves into sound waves and inversely.

3.2 Commercial Acoustic Modems

This overview of commercial underwater acoustic modems highlights the main companies and products which have been found during the searching period. The objective is to check the state-of-the-art technology of acoustic modems in terms of transmission capacity, power efficiency, operating depth and range, and networking capabilities. Besides, a comparison study is presented in order to hypothetically purchase a versatile acoustic modem for a wide variety of applications and future research in underwater communications by AAU Department of Telecommunication Technology.

From the research, it is inferred that many advances and improvements have been carried out during the last years though much remains to be done. Next lines describe some well-known companies and their products in the field of technological solutions for underwater operations.

Teledyne Benthos

Benthos was founded in 1962 by Samuel O. Raymond in North Falmouth, Massachusetts, a few miles from the research facilities at Woods Hole Oceanographic Institution. In 2006, Benthos was acquired by Teledyne

Technologies Incorporated and the company is now known as Teledyne Benthos. Among its numerous contributions to underwater research, Benthos imaging and acoustic equipment was used by a Woods Hole Oceanographic Institution team to discover the sunken remains of the Titanic.

This company offers a wide variety of underwater equipment, for instance acoustic modems, Original Equipment Manufacturer (OEM) options, acoustic releases and SMART products. The focus is on acoustic modems. Anyway, it should be mentioned that surface units can be needed for topside control over the subsea devices. In this sense, Smart Modem Acoustic Release Technology (SMART) is a unique concept from Teledyne Benthos that combines the proven technology of an underwater acoustic release with the reliable undersea communications functionality of an acoustic modem.

While conventional acoustic modems requiere surface units to communicate, Benthos offers some smart acoustic modems with networking capabilities for water monitoring. Table 3.1 summarises the most important characteristics of both conventional and smart acoustic modems. Further information can be found in [38].

Product	**Depth**	**Power**	**Data Rate**	**BER**	**Range**
ATM-885[1]	2000 m	378 W·Hr internal batteries (can also be powered by external source)	140-15,360 bps	$< 10^{-7}$	2-6 km[5]
ATM-886[1]	2000 m	No internal batteries. 12-48 VDC external power required	140-15,360 bps	$< 10^{-7}$	2-6 km[5]
ATM-887[1]	6000 m	588 W·Hr internal batteries (can also be powered by external source)	140-15,360 bps	$< 10^{-7}$	2-6 km[5]
SR-100[2]	6000 m	Up to 2 years, Alkaline 588 W·Hr	140-15,360 bps	$< 10^{-7}$	max. 10 km
SR-50[3]	300 m	Up to 2 years, Alkaline 588 W·Hr	140-15,360 bps	$< 10^{-7}$	max. 10 km
SM-75[4]	6700 m	Up to 2 years, Alkaline 588 W·Hr	140-15,360 bps	$< 10^{-7}$	max. 10 km

Table 3.1: Commercial acoustic modems offered by Teledyne Benthos

1. *Can work Low frequency 9-14 kHz or Mid frequency 16-21 kHz. The transducer can be Omnidirectional (180 beam) or Directional (60 beam). Equipped with 704 Kbyte for Data Storage and with Data redundancy, 1/2 rate convolutional coding mulitpath guard period selection MFSK and PSK modulation schemes.*

2. *Can be connected tounderwater sensors or other devices. It can then acoustically transfer data from the device to the surface or to another subsea unit.*

3. *Obtain real-time data, get battery information, check on a deployment, and then use the acoustic release function to return the entire package to the surface.*

4. *It may operate independently or can function as a node in a small network. Can be fix or mobile.*

5. *Greater distances are possible, +20 km available using repeater functionality.*

LinkQuest

LinkQuest Inc. is a leading manufacturer of precision acoustic instruments for offshore and oceanographic applications, which is located in San Diego, California. Since 1998, LinkQuest's products have been extensively deployed all over the world for offshore oil exploration, construction, drilling, survey, environmental study and other oceanographic applications.

Among its numeorus technological solutions for a wide range of applications, FlowQuest Acoustic Current Profilers and NavQuest Doppler Velocity Logs provide highly competitive solutions for current profiling or precision underwater navigation applications. But, crucially, LinkQuest offers sophisticated underwater acoustic modems and tracking systems. While TrackLink systems provides solutions for underwater tracking and communication, underwater acoustic modems are the focus of this study.

LinkQuest's extensive line of underwater acoustic modems can provide feasible solutions for near-vertical, horizontal and extreme horizontal underwater environments. In addition, they provide a completely transparent wireless RS-232 connection between two end equipments as if they were directly connected through an RS-232 cable. This ensures seamless integration with underwater instruments and surface units, such as a computer. This products does not seem to allow networking capabilities or mobile wireless communications. Table 3.2 describes the most important characteristics of LinkQuest's acoustic modems. Further information can be found in [39].

Product	Depth	Power	Data Rate	BER	Range
UWM 1000[1,2]	2000 m	12-24 V	9600 to 19200 bps	$< 10^{-9}$	350 m
UWM 2000[1,2]	2000 or 4000 m	12-24 V	19600 to 19200 bps	$< 10^{-9}$	1200 or 1500 m[7]
UWM 2200[3]	1000 or 2000 m	12-24 V	19200 to 38400 bps	$< 10^{-9}$	1000 m
UWM 2000H[1,4]	2000 m	9-24 V or 12-24 V[9]	300 to 1200 bps	$< 10^{-9}$	1200 or 1500 m[7]
UWM 3000[2,5]	2000, 4000 or 7000 m	18-28 V	2500 to 5000 bps	$< 10^{-9}$	3000 or 5000 m[8]
UWM 3000H[4,5]	2000, 4000 or 7000 m	18-28 V	80 to 320 bps	$< 10^{-9}$	3000 or 6000 m[8]
UWM 4000[6]	3000 or 7000 m	18-28 V	4800 to 9600 bps	$< 10^{-9}$	3000 or 6000 m[7]
UWM 10000[2,5]	2000, 4000 or 7000 m	18-28 V	2500 to 5000 bps	$< 10^{-9}$	7000 or 10000 m[7]

Table 3.2: Commercial acoustic modems offered by LinkQuest Inc.

1. *Works from 26.77 to 44.62kHz. The transducer can be 120 degrees (wide beam) or 210 degrees (omni-directional) or 70 degrees (narrow beam) depending on model.*

2. *Equipped with 900 Kbyte for Data Storage.*

3. *Performs from 53.55 to 89.25 kHz. The transducer can be 90 degrees.*

4. *Equipped with 500 Kbyte for Data Storage.*

5. *Operates from 7.5 to 12.5 kHz. The transducer can be 70 (narrow beam) or 210 degrees (omni-directional) depending on model. Equipped with 900 Kbyte for Data Storage.*

6. *Runs from 12.75 to 21.25 kHz. The transducer can be 70 degrees (narrow beam) or 210 degrees (omni-directional) depending on model.*

7. *With omnidirectional or directional transducer, respectively.*

8. *Using high power option.*

DSPCOMM

DSPCOMM's modems could be another option to deploy an underwater wireless communication system. In spite of providing an smaller range of solutions as compared with the previous companies, this company offers underwater wireless products which might fulfill the requirements for underwater research applications at AAU. DSPCOMM provides with two sorts of underwater wireless modems:

- **AquaComm** *Available in 100 bit/sec and 480 bit/sec versions and in two forms:*
  - OEM: AquaComm modem module for integrating into an OEM's housing
  - Encased: AquaComm modem module encased in AquaCase
- **AquaNetwork** *Underwater wireless modem with networking capability that includes all the features of AquaComm. It offers a broad set of networking capabilities, such as addressing, parallel links, unicast or broadcast and many easy-configurable items.*

In addition, there are some extra equipment which are designed to improve the modems' capabilities, such as:

∗ **AquaCase** *Underwater housing purpose built for harsh underwater environment*

∗ **AquaBase** *Plug-and-play base unit for the surface platform*

∗ **AquaTrans** *Underwater acoustic hydrophone transducer tailored for use with the modems*

∗ **AquaStore** *Add-on board to AquaComm that provides data logging capability as well as extended sleep modes. Able to register measurements from different sensors.*

The focus of this study is in AquaNetwork despite it depends on AquaComm and possibly on the rest of products. The main parameters of DSPCOMM solutions are outlined in Table 3.3. Further information can be found in [40].

Product	Depth	Power	Data Rate	BER	Range
AquaNetwork[1]	200 m[2]	5 to 9V[3]	100 or 480 bps[4]	$< 10^{-6}$	3 km[5]

Table 3.3: Wireless underwater communication modem offered by DSPCOMM

1. *Works from 16KHz to 30KHz Broadband operation. The transducer is omnidirectional according to AquaCase and AquaTrans.*
2. *Standard 200m depth (on request, customised housings capable of deeper depths up to 3000m are available).*
3. *Power supply input voltage. Standard housing either with external source or extra internal battery packs.*
4. *Host communications: 9600 baud (default),1 start bit, 1 stop bit, no parity 4800, 2400 or 1200 baud programmable.*
5. *Tested. Longer ranges are possible.*

Summary

Choosing a suitable underwater acoustic modem will depend on the underwater environment and the applications. The modem is supposed to be chosen for building small networks either static or dynamic in shallow waters for underwater networking research. Consequently, the main features to be considered when selecting an underwater wireless modem are:

- **Easy configurable platform with many networking capabilities and setting options** *Programming modems for specific applications or evaluating networking protocols and tests.*
- **High data rates** *Generate dense traffic. Different data packets: streaming, images and so forth.*
- **Battery powered** *Evaluate the performance of the deployed network along the time.*
- **Versatile** *To build stationary or mobile communciations systems.*
- **Storage Capacity** *To assess different scenarios where nodes should share data in cooperative approach, for example.*

Other aspects, for instance, range and depth are not so important since the network is supposed to work in reduced environments.

Despite deeper studies should be carried out to determine which modems are more suitable according to specifications, AquaNetwork from DSPCOMM and SM-75 from Teledyne Benthos seem to meet most requirements a priori.

Table 3.4 summarises the strengths and weaknesses of each underwater wireless modem in line with the selection criteria stated above.

Product	**Network Capability**	**Battery Powered**	**Data Rate**	**Versatile**	**Storage Capacity**
AquaNetwork	Important[1]	Possible[2]	low	Possible	Yes
SM-75	Low[3]	Yes[4]	high	Yes	Possible

Table 3.4: Comparison between AquaNetwork and SM-75

1. *Offers a broad set of networking capabilities, such as addressing, parallel links, unicast or broadcast and many easy-configurable items*
2. *Standard housing either with external source or extra internal battery packs.*
3. *May operate independently or can function as a node in a small network*
4. *Up to 2 years*

While AquaNetwork stands out for its wide range of networking capabilites, SM-75 offers high data rates. Consequently, AquaNetwork could be the best choice since it offers an easy-configurable platform for networking protocol design which is the most relevant issue when investigating new networking approaches.

Chapter 4

Interference Cancellation and Network Coding

The long latency and limited bandwidth of acoustic communications pose great challenges in underwater MAC protocol design. In this line, terrestrial MAC protocols become either unpractical or not energy efficient when deployed directly in the underwater environment.

Due to the dense network deployment and the shared communication medium, an efficient MAC protocol is very important to the final performance of wide underwater networks. One of the most important goals of the MAC design for dense traffic situations is to resolve data packet collision efficiently in terms of energy consumption as nodes are battery-powered. Other properties such as end-to-end latency, throughput and channel utilization are also desirable. As a result, new strategies are needed to face the underwater channel effects.

Interference Cancellation and Network Coding appear as emerging concepts for Medium Access protocol design aiming to cope with the underwater channel contraints in order to improve the system efficiency.

Currently, one of the most prominent wireless MAC protocols is the CSMA standard as it is widely implemented in traditional wireless communications. However, the simple principle of CSMA is severely compromised in terms of efficiency and scalability due to the long propagation delays of the underwater acoustic channel. Hence, CSMA is tested to be the lay out for implementing these new concepts.

This chapter is devoted to examine how Medium Access with Interference

Cancellation and Network Coding perform regarding data dissemination as compared with CSMA. Besides, general considerations are proposed in order to modify the CSMA standard for the implementation of each new concept.

The remainder of the chapter is organised as follows. First, an overview of underwater MAC techniques is introduced. Then, CSMA, Interference Cancellation and Network Coding are described. Finally, some tests and results are presented.

4.1 MAC Protocols

It is well known that the bandwidth allocation is a significant factor to determine the system efficiency in any given network. So, in this sense, the access to the resources must be regulated efficiently.

In terrestrial wireless networks, methods for channel sharing are based on scheduling or on contention. Scheduling, or deterministic multiple-access, includes frequency, time and code-division multiple-access (FDMA, TDMA and CDMA) as well as a more elaborate technique of space-division multiple access (SDMA). Contention-based channel sharing does not rely on an a-priori division of channel resources; instead, all the nodes contend for the use of channel. In other words, they are allowed to transmit randomly at will, in the same frequency band and at the same time, but likewise they must follow a protocol for medium-access control to ensure that their information packets do not collide. An example of contention methods is the Carrier-Sense Multiple Access (CSMA) scheme.

While previous MAC protocols have succeeded in traditional radio communications, they are unpractical and ineffcient when employed directly in underwater acoustic networks. Orthogonal MAC schemes such as FDMA are not suitable for underwater networks due to the narrow bandwidth in underwater channel, and the vulnerability of limited band systems to fading. On the other hand, TDMA requires precise time synchronization and long guard time. Furthermore, orthogonal MAC schemes have scalability problems when some nodes join or leave a network. Note that a method for channel sharing is scalable if it is equally applicable to any number of nodes in a network of given density. For example, TDMA is not scalable, since it rapidly looses efficiency on an underwater channel because of the increasing propagation delay with the area of coverage.

All types of multiple-access are being considered for the underwater acoustic systems. Experimental systems during these years have favoured either TDMA or Multiple-Access Collision Avoidance (MACA) based on a hand-shaking contention procedure that requires an exchange of requests and clearances to send (RTS/CTS). However, they present drawbacks in terms of system efficiency and scalability. Hence, intelligent collision avoidance appears to be necessary in an underwater channel, where the simple principle of CSMA is severely compromised due to the long propagation delays (the fact that the channel is sensed as idle at some location does not guarantee that a data packet is not already in transmission at a remote location).

Strong efforts in research have fuelled the development of new MAC protocols for underwater communications. A particular work [41] proposes a new multiple access protocol for underwater acoustic network, which uses a kind of special-designed combined synchronization header to identify different users and process user's data. By using the CDMA technology, the combining design of different synchronization header and parallel processing of the received collided packet data, the scheme can not only improve the throughput of the network, but also solve the collision problem.

Another paper work [42] introduces and studies the MACA for Underwater (MACA-U) protocol, which is an adaptation of terrestrial MACA for multi-hop underwater networks. From the simulation results, they show that MACA-U achieves a stable throughput, and it is a suitable candidate for dense underwater multihop networks. Their future work for MACA-U includes an investigation of unfairness in the backoff algorithm, as well as a theoretical analysis of the throughput and delay characteristics.

On the other hand, [43] proposes a reservation-based MAC protocol, called R-MAC. Focusing on energy efficiency and fairness, R-MAC schedules the transmissions of control packets and data packets to avoid data packet collision completely. The scheduling algorithms not only save energy but also solve the exposed terminal problem[1] inherited in RTS/CTS-based protocols. By simulations, they show that R-MAC is an energy efficient and fair MAC solution for underwater sensor networks.

[1]Occurs when a node is prevented from sending packets to other nodes due to a neighbouring transmitter

4.2 CSMA

Carrier Sense Multiple Access (CSMA) is a widely used MAC protocol in wired and wireless communications in which a node verifies the absence of other traffic before transmitting on a shared transmission medium.

In wireless communications, pure CSMA does not work very well since the wireless medium is highly location-dependent, i.e. the channel state might be different at the receiver from what is estimated at the transmitter. This gives rise to the so-called hidden terminal problem, where two nodes that do not hear each other transmit packets to a common receiver, and packets collide at the receiver. Hence, CSMA with Collision Avoidance (CSMA/CA) is used as a modification of the CSMA standard.

CSMA/CA improves the performance of CSMA by using collision avoidance schemes, such as RTS/CTS handshakes, thus, reducing the probability of collisions on the channel. A node that has a packet to send checks to be sure that the channel is clear (no other node is transmitting at the time). If the channel is free, then the packet is sent. If the channel is sensed busy, the node waits for a randomly chosen period of time, and then checks again to see if the channel is clear. This period of time is called the backoff timer, and is counted down by a backoff counter when the channel is free. If the channel is clear when the backoff counter reaches zero, the node transmits the packet. If the channel is not clear when the backoff counter reaches zero, the backoff timer is set again, and the process is repeated.

CSMA/CA does not guarantee that the receiver can hear the transmision just because the transmitter has obtained the medium. Distributed Foundation Wireless MAC (DFW MACIEEE 802.11) tries to solve this problem by using an RTS/CTS exchange to better handle situations such as the hidden node problem in wireless networking.

In RTS/CTS access mode, as soon as a source node receives a packet that is to be sent, it contends for channel reservation by sending a short Request-To-Send (RTS) control packet to the destination node. Upon receiving the RTS, the destination node immediately replies a short Clear-To-Send (CTS) or Receiver-Busy, try again later (RxBUSY) control packet back to the source node. After receiving the CTS, the source node immediately sends data to the destination node. If the destination node receives the data packet correctly, it replies with an ACK message. Otherwise, it replies a NAK message as the frame is corrupted. Then, the source node sends again the data packet. This procedures is repeated a certain number of times until a successful transmission of data frame. Note that, any neighboring node that overhears a control packet that is intended for another node (xRTS or xCTS) will defer its transmission for a random period of time.

Although RTS/CTS messages tries to solve the hidden node problem, the exposed terminal problem remains inherited in modern RTS/CTS-based protocols where ACKs are included. This approach is taken into account when conducting the tests.

In wireless networks, the exposed node problem occurs when a node is prevented from sending packets to other nodes due to a neighbouring transmitter. Consider an example of 4 nodes labeled R1, T1, T2, and R2, where the two receivers are out of range of each other, yet the two transmitters in the middle are in range of each other. Here, if a transmission between T1 and R1 is taking place, node T2 is prevented from transmitting to R2 as it concludes after carrier sense that it will interfere with the transmission by its neighbour T1. However note that R2 could still receive the transmission of T2 without interference because it is out of range from T1 [44]. Figure 4.1 depicts this example.

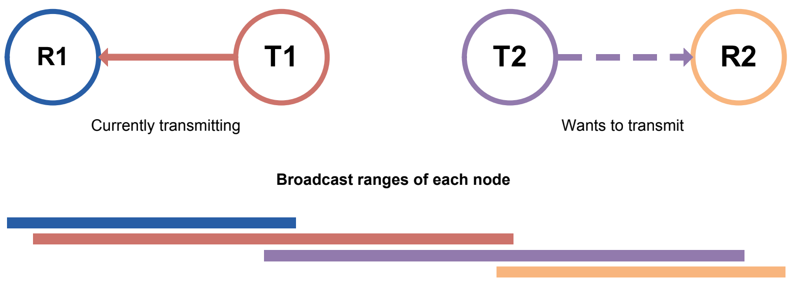

Figure 4.1: Exposed Terminal Problem

Finally, a practical example of CSMA/CA implementation for WLANs is described. IEEE 802.11 standard for WLAN defines a distributed coordination function (DCF) for sharing access to the medium based on the CSMA/CA protocol [45]. DCF consists of a basic access mode as well as an optional RTS/CTS access mode.

In basic access mode, the node senses the channel to determine whether another node is transmitting before initiating a transmission. If the medium is sensed to be free for a DCF inter-frame space (DIFS) time interval the transmission will proceed. If the medium is busy the node defers its transmission until the end of the current transmission and then it will wait an additional DIFS interval and generate a random backoff delay uniformly chosen in the range [0,W - 1] where W is called the backoff window or contention window (CW).

The backoff timer is decreased as long as the medium is sensed to be idle for a DIFS, and frozen when a transmission is detected on the medium, and resumed when the channel is detected as idle again for a DIFS interval. If the channel is clear when the backoff counter reaches zero, the node transmits the packet.

The initial CW is set to W = 1, if two or more nodes decrease their backoff timer to 0 at the same time a collision occur, at this situation the CW is doubled for each retransmission until it reaches a maximum value. Figure 4.2 shows the working principle. Note that, the different IFS intervals provide different channel access priorities.

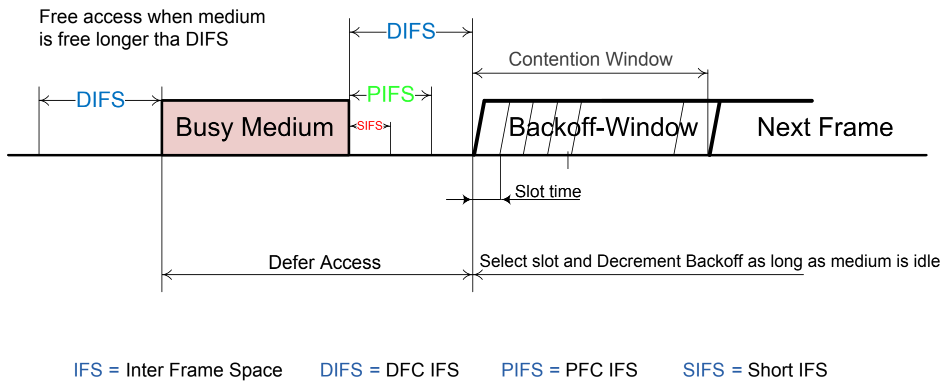

Figure 4.2: CSMA/CA performance for WLANs

Optionally, but almost always implemented, an IEEE 802.11 RTS/CTS exchange can be required. Figure 4.3 shows the RTS/CTS mechanism in a succesfull data transmission.

In CSMA/CA for WLANs, there are several inter-frame spacing which give grades of priority to different transmissions. Despite they are implemented in real wireless communications systems, they are not considered to conduct the experiments since the increase of time would be constant thus, not affecting to the results.

- **DIFS: DCF Inter Frame Space** *If the medium is sensed to be free for a DFIS time interval, the transmission will proceed.*
- **SIFS: Short Inter Frame Space** *It is used to give priority access to ACK packets.*

- **EIFS: Extended Inter Frame Space** *If the source node does not receive an ACK due to collision or transmission errors it reactivates the backoff algorithm after the channel remains idle for EIFS interval.*

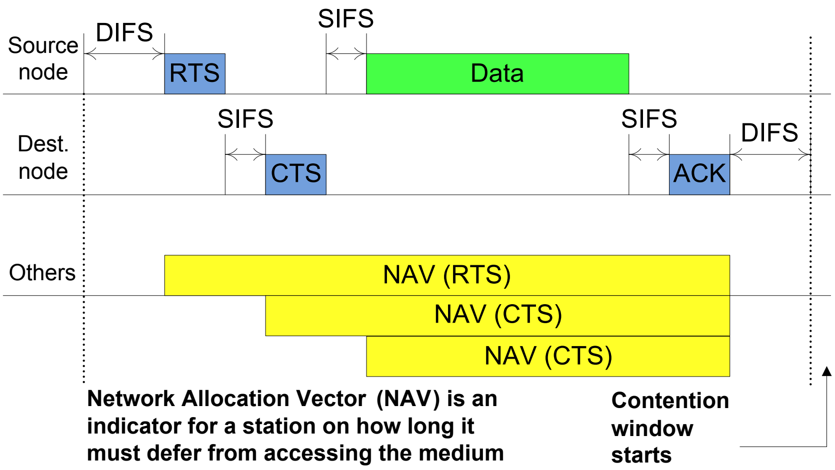

Figure 4.3: RTS/CTS mechanism for WLANs

While successful in traditional radio communications, CSMA is severly limited in terms of system efficiency and scalability when deployed in the underwater environment. Such disadvantages are mainly because of the large propagation delays of the underwater acoustic channel. CSMA works well only if the propagation time on the channel is much smaller than the duration of a data packet transmission: in typical underwater scenarios, with the long propagation delays cited before, this is usually not the case. Improving CSMA with collision avoidance schemes, such as RTS/CTS handshakes, is prone to the same inefficiency that affects CSMA [46]: again, long delays make collisions between packets more likely and frequent. This may lead to prefer simpler protocol. Hence, the motivation in investigating new strategies, such as Interference Cancellation and Network Coding approaches in simple and practical implementations for underwater networks.

4.3 Interference Cancellation

In terrestrial wireless communications, for instance IEEE 802.11, each node that has a packet to send announces its intention to transmit before acting in order to avoid collisions among data packets. This procedure is common in wireless networks as they do not have a practical way to transmit and receive simultaneously. However, in underwater environments where the underwater channel propagation makes unfeasible any traditional radio communications, new strategies are needed.

The concept of Interference Cancellation tries to cope with this issue providing, somehow, with a simple and practical way to transmit and receive simultaneously, not in physical layer but modifying the traditional MAC protocols.

The idea of Interference Cancellation lies in the knowledge of the propagation delay between a pair of nodes. If a source node could determine the propagation delay with respect to the destination node and the other way around, they would set the packet transmission time equals to the propagation delay taking advantage of the maximal packet length for this pair of nodes. Then, if both nodes had packets to send, they would transmit their packets during the propagation delay and after that, they would start receiving. For more intuitive comprehension, Figure 4.4 shows an example.

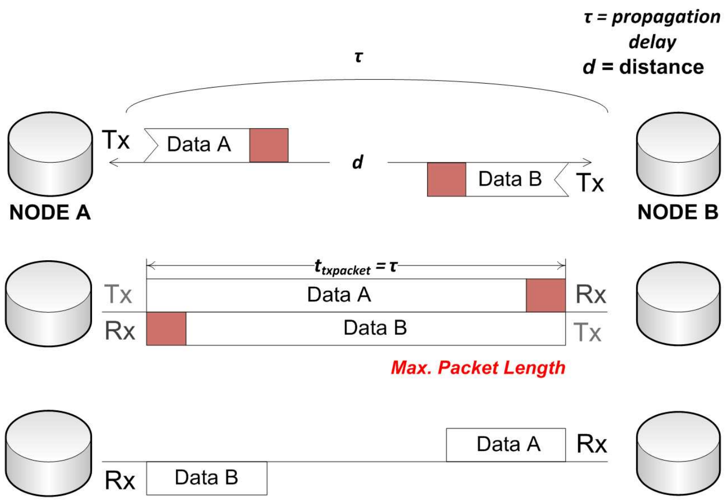

Figure 4.4: Interference Cancellation

In this example, a transmission of data packets between two nodes, A and B, is displayed. As nodes are supposed to be fixed, the propagation delay is constant. So, they set the maximal packet length according to their transmssion capacities and the propagation time between each other. The transmission comprises three steps. First, both nodes start sending their packets, Data A and B, respectively, to one another. After that, the data is being transmitted until the maximal packet size is achieved. At this same time, both nodes have just transmitted their packets and start receiving immediately the data from each other. Finally, nodes are rerceiving simlutaneously until the reception process is succesfully completed.

As a first aproximation, Interference Cancellation is intended for stationary networks where nodes are fixed and the propagation delay is constant. This way, the difficulty of implementation is reduced as compared with dynamic scenarios where nodes can passively float with water currents and propagation delays among nodes are variable. Nevertheless, it can be also assumed that nodes move very slowly.

Its benefits can be extended to many areas of wireless networks, especially, underwater networks, improving considerably the system efficiency. In this sense, Interference Cancellation can enhance the energy efficiency of nodes and prolong the network lifetime. As nodes are battery-powered, the implementation of Interference Cancellation might be an interesting approach to be tested in underwater networks.

A possible implementation of Interference Cancellation could be based on modifying the CSMA/CA MAC protocol. In this sense, some design considerations are proposed for future researh, so that, Interference Cancellation might be feasible in underwater acoustic networks.

On the one hand, CSMA/CA is an RTS/CTS-based protocol which has proved inefficient and unpractical when deployed directly in underwater networks due to the very long propagation delays of the underwater acoustic channel. This means that the channel utilization is inefficient as the bandwidth is used for signalling instead of useful data too much time. Therephore, RTS/CTS messages are unsuitable for underwater networks and new strategies are needed in order to improve the system efficiency but ensuring reliable data transport.

Interference Cancellation could enhance the system efficiency. However, its accomplishment can be fraught with difficulty due to the complexity of a practical way to implement this concept without RTS/CTS approach. Some considerations could be as follows.

- A set of additional functionalities should be added to the performance of nodes in the network so that the propagation delay could be calculated for every pair of nodes.
- Synchronisation is an important requirement as nodes end their

transmissions and start receiving packets simultaneously. A practical way to reduce synchronisation dependence could consist of adding a stuff bits sequence at the beggining and at the end of the packets.

- Reliability is a relevant factor since RTS/CTS messages are avoided. Some approaches could be considered in order to fulfil this requirement.
  - **Master-Slave** *A master node is in charge of network management whereas slave nodes follow its rules. This way, master node gives different grades of priority to each node and signalling might be reduced as compared to RTS/CTS approach. A drawback is the energy consumption of the master node so, this fact can lead to prefer dynamic master-slave architectures where nodes alternate between master/slave roles*
  - **Frequency reuse** *A node has two frequencies, one to transmit and the other to receive. Neighbouring nodes alternate the frequencies in order to avoid interferences. Some disadvantages are energy consumption and inefficiency. One way to improve them is adding sleeping modes where nodes alternate between on and off modes*
  - **Data and Control Plane** *Consists of estrategic frequency reuse where nodes have resources for data transmission, data plane, and for signalling, control plane. While nodes transmit and receive packets in the data plane, signalling is carried out over the control plane. As a drawback, this approach needs more resources and is more complex.*
  - **TX/RX alternation** *A node alternates between transmission and reception modes.*

4.4 Network Coding

Nowadays, behind the operation of all networks, the data is transported separately as independent information streams. This is the working principle of all network functions, especially, these of routing.

Network Coding, pioneering work [47], make the simple but important observation that in communication networks, nodes cannot only forward but also process the incomming independent information flows. In other words, data streams that are independently originated and consumed do not necessarily need to be kept separate when they are transported throughout the network: there are ways to combine and later extract independent information. This new approach has the promise of revolutionising the management and operation of networks [48].

According to previous statements, Network Coding can be defined as a particular in-network data processing technique which exploits the characteristics of the wireless medium (in particular, the broadcast communication channel). Network Coding promises to offer benefits in different areas of communication networks, such as throughput, wireless resources, security, complexity, and resilience to link failures.

There are several possible approaches to Network Coding. Nevertheless, this project focuses on linear and physical-layer network coding.

4.4.1 Linear Network Coding

In linear network coding [49], the output flow at a given node is obtained as a linear combination of its input flows. The coefficients of the combination are, by definition, selected from a finite field. The combination is obtained as an XOR function of incoming streams. This is a linear code because the encoding and decoding schemes are linear operations. Specifically, when two different flows of information are about to reach a given node, the procedure is as follows. First, the node receives one flow. Then, the node receives the other flow. Finally, the node broadcasts the linear combination of both flows over its outputs. At the reciever, the node decodes the information by applying XOR, extracting the useful information. For more intuitive comprehension, Figure 4.5 depicts this approach in a meshed scenario.

In the meshed network, there is a source (at the top of the picture), which have knowledge of packets b_1 and b_2. There are two destination nodes (at the bottom), which are interested in both b_1 and b_2. The transmission of packets follows several steps. First, the source node broadcasts its packets. Once Nodes A and B have received b_1 and b_2, respectively, they broadcast the data directed to Node C and receivers 1 and 2. Using linear network coding, Node C combines linearly both packets and send the XOR of b_1 and b_2 on the middle link. When Node D has received the XOR of both packets, it broadcasts the XOR over its links. Finally, both destination nodes can substract the packet which is left in each receiver by using XOR.

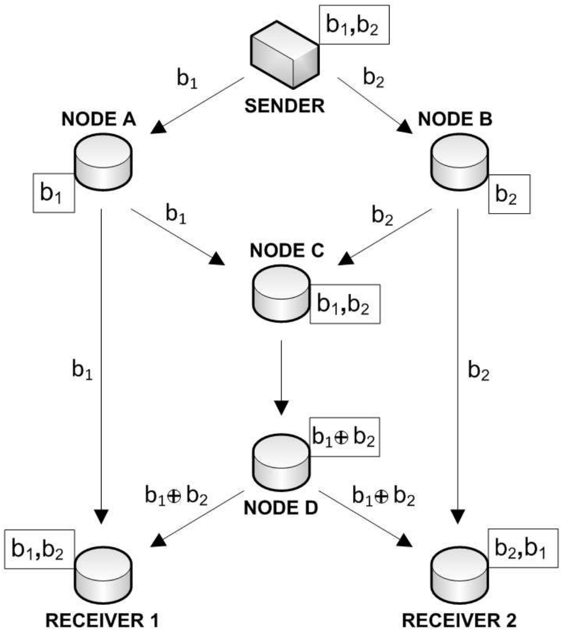

Figure 4.5: Linear network coding in a meshed network

4.4.2 Physical-layer Network Coding

Wireless communications differ from wired networks in many senses. A main distinguishing feature lies in its broadcast nature, where the signal transmitted by a node might reach several other nodes, and a node might receive signals from several other nodes simultaneously. Rather than an advantage, this feature is treated as an interfering nuisance in most wireless networks today (e.g. IEEE 802.11). Thus, the concept of Network Coding can be applied at the physical layer to turn the broadcast property into a capacity improvement in wireless ad hoc networks [50]. This approach is known as Physical-layer Network Coding (PNC).

Unlike linear network coding which performs coding arithmetic on digital bit streams after they have been received, PNC makes use of the additive nature of simultaneously arriving EM waves for equivalent coding operation, i.e. the idea of PNC is similar to that of network coding, but at the lower physical layer dealing with EM signal reception and modulation. PNC can yield higher capacity than linear network coding when applied in wireless networks. Opening up a whole new research because of its implications and new design requirements for the different network layers, PNC might lead to a revolutionary new model for wireless ad hoc networking.

In PNC, a node receives two different streams of information simultaneously. After that, it broadcasts the collision over its outputs as the combination of both flows by modualtion schemes. In contrast with NC, the node which implements PNC is not able to store data since packets collide. However, PNC is more efficient since it takes less time to combine two different flows. Figure 4.6 shows an example where the core node implements PNC.

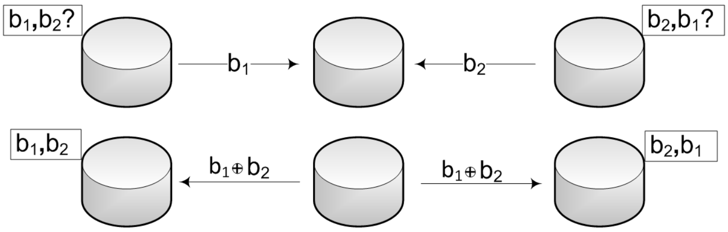

Figure 4.6: Physical-layer Network Coding in a line-up network

In this example, a transmission of data packets between two end nodes is shown. While left-end node has knowledge of b_1 and is interested in b_2, right-end node has knowledge of b_2 and is interested in b_1. First, both end nodes send their packets to the core node. At this same moment, the core node receives simultaneously both packets and broadcasts the collision as the physical mix of them by modulation schemes. Finally, each end node extract the packet which is left, respectively, by demodulation schemes.

Challenges

The deployment of Network Coding is a challenging task. Nodes are supposed to have a set of additional funcionalities and it leads to more complex networks. Furthermore, the integration of Network Coding with the existing network architecture can be fraught with difficulty. However, the implemention of Network Coding with other MAC considerations, such as modifying CSMA/CA MAC protocol by removing RTS/CTS messages, can improve the performance of wireless networks, especially, in underwater environments where network resources are quite limited.

4.5 Evaluation

The main work of this project focuses on investigating the possibility of Medium Access mixing Interference Cancellation (IC) and Network Coding (NC) concepts for data dissemination in underwater wireless networks.

The experiments have been conducted over two scenarios, line-up and meshed networks (further detalis in sections 2.3.1 and 2.3.2, respectively). The main task is to evaluate the performance of CSMA/CA, IC, NC and mix of IC and NC for data dissemination in different topologies. Note that, PNC is also considered.

There have been two sorts of tests relying on different approaches. Their differences lie basically on the MAC constraints. While the first test is more conservative with respect to existing MAC protocols, the second one aims to improving MAC protocol design. The goal is to observe if there are significant differences in the way of transmission regarding the dissemination time. Both tests are described as follows.

- **Test 1: Minimal Modified CSMA/CA** *Keeps the MAC Constraints of CSMA/CA where RTS/CTS approach is considered. However, the increase of time due to these messages is not counted.*
- **Test 2: Improved MAC Protocol Approach** *Refers to next generation MAC protocol design where RTS/CTS approach is supposed not to be required. Then, the broadcast coverage of a given node does not affect to the neighbouring nodes in the same way as before.*

Some premises have been stated to conduct the tests as for each topic:

- **CSMA/CA** *A node cannot transmit and receive simultaneously.*
- **IC** *A node can transmit and receive simultaneously if propagattion delay is constant and packet length is fixed.*
- **NC** *A node is able to combine two different flows but cannot transmit and receive simultaneously.*
- **PNC** *A node is able to combine two different flows which are received simultaneoulsy but cannot store them and cannot transmit and receive simultaneosuly.*

- **Mix of IC and NC** *A node can transmit and receive simultaneously, if propagattion delay is constant and packet length is fixed, and is able to combine two different flows.*
- **Mix of IC and PNC** *A node can transmit and receive simultaneously, if propagattion delay is constant and packet length is fixed, and is able to combine two different flows which are received simultaneously but cannot store them.*
- **Other considerations** *Unlike PNC and mix of IC and PNC, a node cannot receive simultaneously.*

Besides, different number of packets are set to be disseminated through the network. The aim is to investigate how many time slots the dissemination process takes to be completed and its behavior (linear or variable) in both scenarios according to each technique. In this sense, two streams, A and B, are defined for each kind of network. Therefore, the tests are carried out for 1, 2, 4, 6 and 8 packets per flow.

As specific assumptions, some rules which have been followed to conduct the tests are presented so as to ensure the repeatability of the experiments. These rules are the basis to understand how results have come to be.

- Flow A has priority with respect to B when a transmission decision must be taken between them.
- During the dissemination process, fairness is required in order to achieve a balanced transmission between both data flows.
- Outgoing packets from a source node must be received according to their transmission order at the receiver. In other words, a_1 takes preference over a_2.
- The data packets transmission must be carried out strictly following the working principle of each MAC method applied for every particular case.

Finally, the propagation delay has been taken into account in order to quantify roughly the dissemination time in each particular case. As in both scenarios nodes are supposed to be fixed, some parameters are given in Table 4.1. Note that, the packet transmission time is equals to the propagation delay between a pair of nodes. Thus, the maximal packet length (headers are not included) is achieved for Interference Cancellation.

Parameters	Quantity	Magnitude
Data Rate	9600	bps
Length of Links	1000	m
Speed of Sound	1500	m/s
Propagation Delay	$666,\hat{6}$	ms
Packet Size	1800	bytes
Packet Transmission Time	$666,\hat{6}$	ms
RTS packet size	20	bytes
CTS packet size	14	bytes
RTS packet Transmission Time	$16,\hat{6}$	ms
CTS packet Transmission Time	$11,\hat{6}$	ms

Table 4.1: Underwater Design Parameters

4.5.1 Line-up Network

This particular scenario presents its own characteristics and shapes the performance of MAC techniques under evaluation, when conducting the tests. Remember that the goal is to investigate how the data is disseminated through nodes and how many time the data dissemination process takes. For this reason, some explanations should be devoted to describe how each MAC technique performs according to the proposed experiments.

Next, the different topics are described for every test. In each example, two packets per flow are supposed to be inserted in the network. At the end of each part, the results from tests conducted over this scenario are presented.

Test 1: Minimal Modified CSMA/CA approach

As it was mentioned previously, RTS/CTS acces mode is considered. This means that the general constraints of CSMA/CA are assumed. In this sense, the broadcast channel of a node affects considerably the rest of nodes in the network. For this reason, a node that has a packet to transmit is prevented from sending due to a neighbouring transmitter. So, the main rule is to determine the remoteness of the current transmitter. If the node which wants to transmit is further than two hops from the current transmission, the node is allowed to send the packet.

As a general description for the line-up scenario, Node 1 and Node 5 have the information, a_1 and a_2, and b_1 and b_2, respectively. All nodes want all the information, so the data is disseminated through the network from Node 1 and 5. Below each node, there is a box which refers to the data stored on it at a given time. The data is organised by incoming order. At the right of the figure, the time of the overall transmition is counted in time slot units.

CSMA/CA. All nodes are supposed to implement this standard. In CSMA/CA, a node cannot transmit and receive simultaneously. Figure 4.7 shows an example.

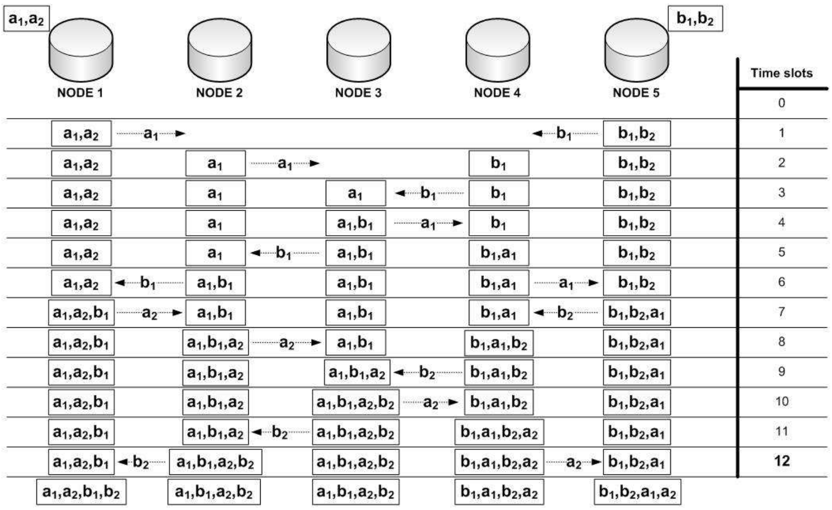

Figure 4.7: Line-up CSMA/CA example

In this example, packet a_1 is sent from Node 1 to Node 2 and simultaneously Node 5 transmits b_1 to Node 4 since both transmissions are out of range and will not interfere each other. After that, a_1 can be only sent from Node 2 to Node 3 because it has priority, and no other neighbouring transmissions are allowed in order to avoid collisions as RTS/CTS approach is assumed in this test (note that simultaneous transmissions are permitted, provided that the receivers are further than two bounds free of transmsssion). Then, b_1 is transmitted from Node 4 to Node 3 as fairness is one of the assumptions. Next, a_1 is sent from Node 3 to Node 4. After that, b_1 is transmitted from Node 3 to Node 2. Finally, b_1 and a_1 are sent simultaneously from Node 2 and 4 to Node 1 and 5, respectively. The process is repetead for a_2 and b_2, and so on.

NC. While Node 3 is supposed to implement Network Coding, all nodes work according to CSMA/CA standard. In NC, a node is able to combine two different flows. Figure 4.8 shows an example.

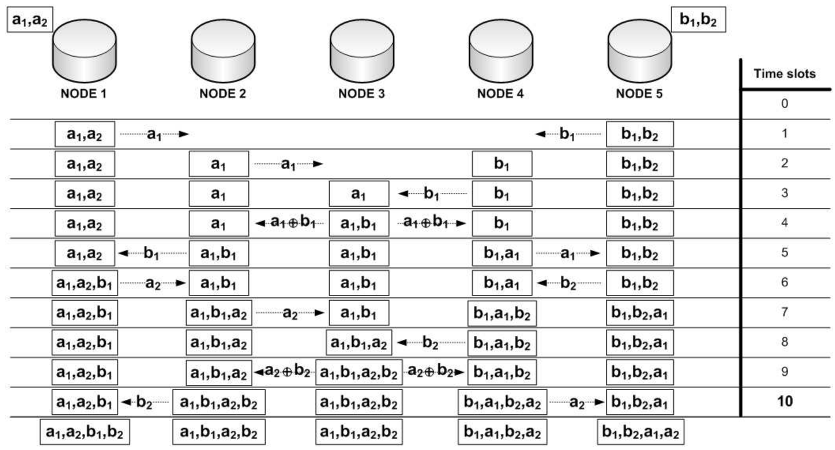

Figure 4.8: Line-up NC example for Minimal Modified CSMA/CA

In this simulation, packet a_1 is sent from Node 1 to Node 2 and simultaneously Node 5 transmits b_1 to Node 4 since both transmissions are out of range and will not interfere each other. After that, a_1 can be only sent from Node 2 to Node 3 because it has priority, and no other neighbouring transmissions are allowed in order to avoid collisions as RTS/CTS approach is assumed in this test (note that simultaneous transmissions are permitted, provided that the receivers are further than two bounds free of transmssion). Then, b_1 is transmitted from Node 4 to Node 3 as fairness is one of the assumptions. Next, Node 3 combines a_1 and b_1 by applying XOR and broadcasts the XOR of both packets to Node 2 and Node 4. Later, Node 2 and 4 extract the remaining packet, respectively, by XOR and finally send b_1 and a_1 simultaneously to Node 1 and 5, respectively. This way, the process is repetead for a_2 and b_2, and so on.

PNC. Node 3 is supposed to implement Physical-layer Network Coding whereas all nodes implement CSMA/CA. In PNC, a node is capable of combining two different flows which are received simultaneously. Figure 4.9 depicts an example.

Despite these tests focus on Minimal Modified CSMA/CA approach, PNC is considered as a special case aiming to compare its performance with the rest of MAC techniques [2]. As such, this scenario is quite different. While Node 1 and Node 5 have the information, a_1 and a_2, and b_1 and b_2, respectively, they want the information of each other, so the data is transmitted through the network from Node 1 and 5.

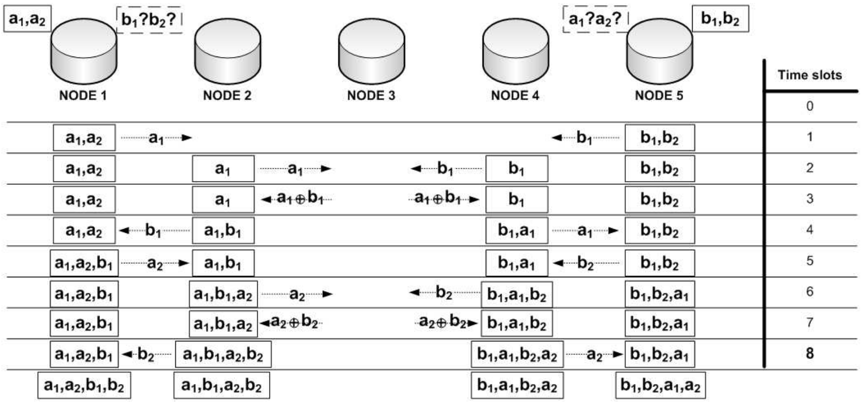

Figure 4.9: Line-up PNC example for Minimal Modified CSMA/CA

In this test, packet a_1 is sent from Node 1 to Node 2 and simultaneously Node 5 transmits b_1 to Node 4. After that, a_1 and b_1 are sent from Node 2 and 4, respectively, to Node 3. Then, upon receiving both physical information carriers, Node 3 broadcasts the collision of a_1 and b_1 to Node 2 and Node 4 as the physical combination of them by modulation schemes (Node 3 does not store the data since packets have collided). Later, Node 2 and 4 extract the remaining packet, respectively, by demoluation schemes and finally send b_1 and a_1 simultaneously to Node 1 and 5, respectively. This way, the process is repetead for a_2 and b_2, and so on.

IC. All nodes are supposed to implement this concept. In IC, a node can transmit and receive simultaneously. Figure 4.10 shows an example.

Here, packet a_1 is sent from Node 1 to Node 2 and simultaneously Node 5 transmits b_1 to Node 4 since both transmissions are out of range and will not interfere each other. After that, a_1 can be only sent from Node 2 to Node 3 because it has priority, and no other neighbouring transmissions are allowed in order to avoid collisions as RTS/CTS approach is assumed in this test (note that simultaneous transmissions are permitted, provided that the

[2] Note that PNC should be only placed in Test 2: Improved MAC protocol Approach as it needs to modify CSMA/CA MAC protocol considerably in order to achieve its real performance.

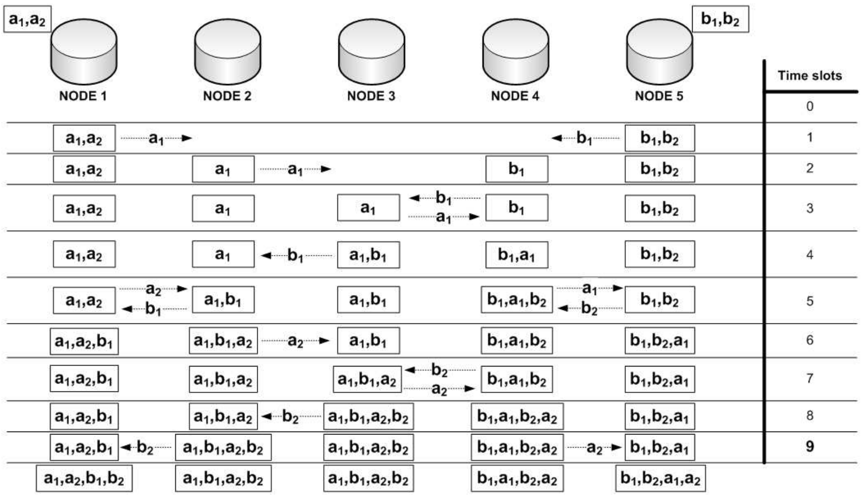

Figure 4.10: Line-up IC example for Minimal Modified CSMA/CA

receivers are further than two bounds free of transmssion). Then, a_1 and b_1 are transmitted simultaneously from Node 4 to Node 3 and viceversa taking advantage of IC properties. Later, b_1 is sent from Node 3 to Node 2 as fairness is one of the assumptions. Finally, b_1 and a_1 are sent simultaneously from Node 2 and 4 to Node 1 and 5, respectively. In addition, while Node 1 and 5 are receiving b_1 and a_1, a_2 and b_2 are transmited at the same time due to the IC properties. This way, the process is repetead for a_2 and b_2, and so on.

IC and NC. While all nodes are supposed to implement Interference Cancellation, Node 3 implements Network Coding. In mix of IC and NC, a node can combine two different flows and, transmit and receive simultaneously. Figure 4.11 presents an example.

In this simulation, packet a_1 is sent from Node 1 to Node 2 and simultaneously Node 5 transmits b_1 to Node 4 since both transmissions are out of range and will not interfere each other. After that, a_1 can be only sent from Node 2 to Node 3 because it has priority, and no other neighbouring transmissions are allowed in order to avoid collisions as RTS/CTS approach is assumed in this test (note that simultaneous transmissions are permitted, provided that the receivers are further than two bounds free of transmssion). Then, b_1 is transmitted from Node 4 to Node 3 as fairness is one of the assumptions. Next, Node 3 combines a_1 and b_1 by applying XOR and broadcasts the XOR of both packets to Node 2 and Node 4. Later, Node 2

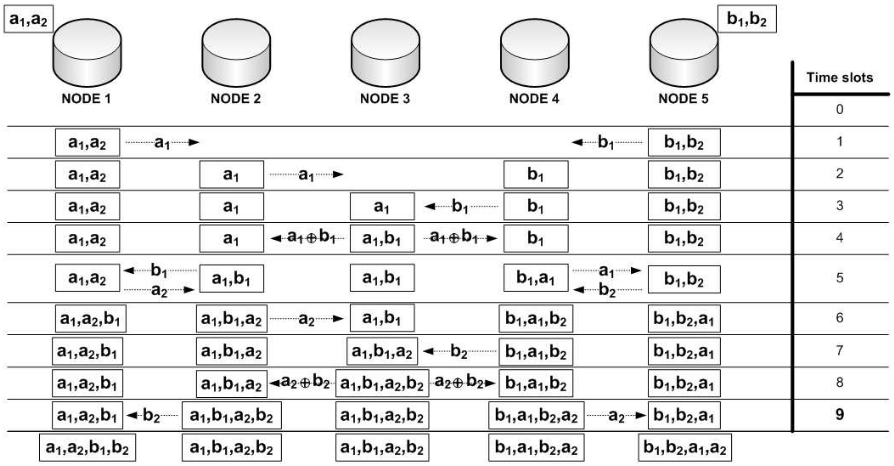

Figure 4.11: Line-up IC and NC example for Minimal Modified CSMA/CA

and 4 extract the remaining packet, respectively, by XOR and finally send b_1 and a_1 simultaneously to Node 1 and 5, respectively. Likewise, while Node 1 and 5 are receiving b_1 and a_1, a_2 and b_2 are transmited at the same time because of the IC properties. This way, the process is repetead for a_2 and b_2, and so on.

IC and PNC. While all nodes are supposed to implement Interference Cancellation, Node 3 implements Physical-layer Network Coding. In mix of IC and PNC, a node is able to combine two different flows which are received simultaneously and, transmit and receive simultaneously. Figure 4.12 displays an example.

In this test, packet a_1 is sent from Node 1 to Node 2 and simultaneously Node 5 transmits b_1 to Node 4. After that, a_1 and b_1 are sent from Node 2 and 4, respectively, to Node 3. Then, upon receiving both physical information carriers, Node 3 broadcasts the collision of a_1 and b_1 to Node 2 and Node 4 as the physical combination of them by modulation schemes (Node 3 does not store the data since packets have collided). Later, Node 2 and 4 extract the remaining packet, respectively, by demoluation schemes and finally send b_1 and a_1 simultaneously to Node 1 and 5, respectively. In addition, while Node 1 and 5 are receiving b_1 and a_1, a_2 and b_2 are transmited at the same time due to the IC properties. This way, the process is repetead for a_2 and b_2, and so on.

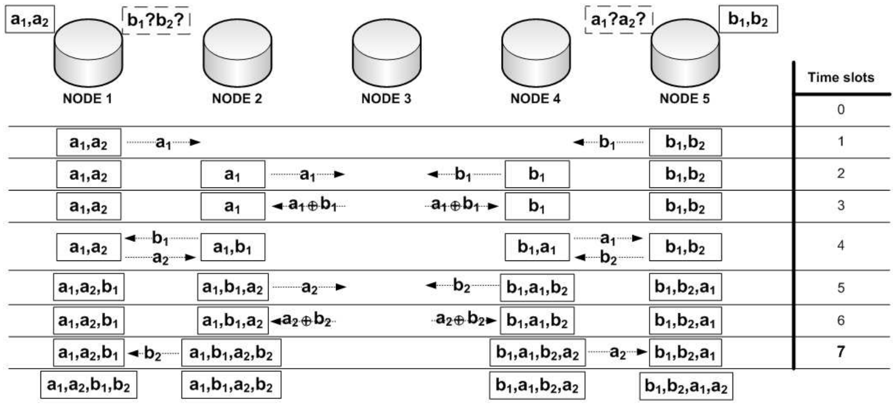

Figure 4.12: Line-up IC and PNC example for Minimal Modified CSMA/CA

Results

This section is organised as follows. First, some conclusions are inferred for every MAC method. Then, propagation delays are applied so as to observe the efficiency in transmission time of every technique. Thus, the improvements of new concepts are pointed out.

Figure 4.13 presents the performance evaluation of analysed MAC techniques in terms of data dissemination process.

- **CSMA/CA** *Presents a linear behaviour given by 3N* [3]*. This means that when a packet is sent through the network the overall dissemination time is increased three time slots.*
- **NC** *Shows a linearity in steady state modelled by 2,5N, where N≥4 packets disseminated through the network (2 packets per flow). This is because NC is not linear when less than four packets are transmitted in the network. Improves CSMA/CA in two time slots less every two packets, one packet per flow.*
- **IC** *Undergoes a linear behaviour in the long term featured by 2N+1, where N≥4 packets. IC increases NC efficiency according to the dissemination time in one time slot less every two packets, one packet per flow.*

[3] N is the number of packets disseminated through the network

- **Mix of IC and NC** *Is linear in steady state shaped by 2N+1. As IC and NC are not liner for less than 4 packets, mixing of IC and NC is not linear as well. Mix of IC and NC does not improve IC. In fact, both show the same efficiency.*

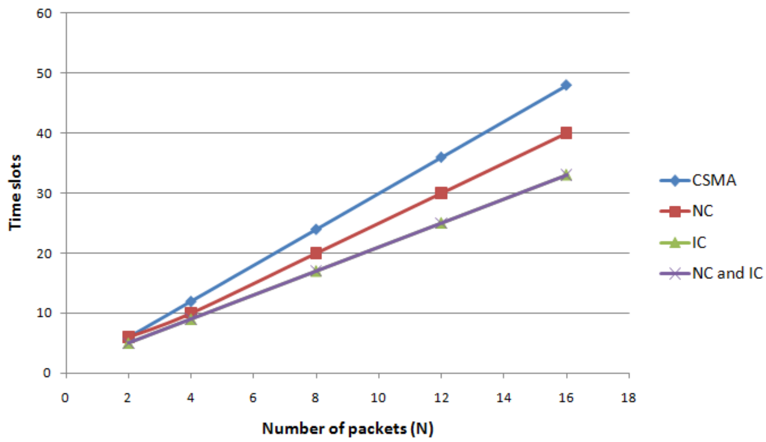

Figure 4.13: Line-up performance evaluation for Minimal Modified CSMA/CA

Previous statements are summarised in Figure 4.13. As a conclusion, there are some evidences that IC and NC concepts could enhance considerably the system efficiency for data dissemination as compared with CSMA/CA. Focusing on the results, IC performs better than NC. Despite this fact, the combination of IC and NC does not seem to improve the system efficiency as expected a priori. Actually, the mix of IC and NC achieves the same performance as just IC.

In contrast with NC, PNC can improves the performance since it is more efficient than NC. Note that, PNC enhances NC efficiency in two time slots less every two packets, one packet per flow. However, PNC is not useful for data dissemination as the node which implements PNC cannot store the data. Figure 4.14 shows its benefits for other applications, for instance end nodes in the line-up network demand flows A and B, respectively. Thus, mix of IC and PNC would be better than mix of IC and NC.

Propagation Delays

Up to now, each MAC technique has been compared with one another in terms of time slots. This concept refers to the data packets transmission

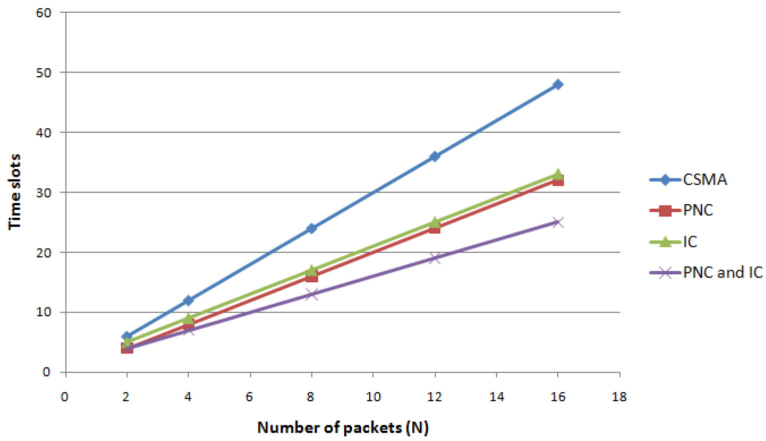

Figure 4.14: Line-up PNC performance evaluation for Minimal Modified CSMA/CA

time, i.e, the packets which are transmitted during the propagation time. In order to quantify the overall dissemination time, the propagation delay is considered. So, in this sense, one time slot is the sum of packets transmission and propagation times, both are 666,$\hat{6}$ms (See Table 4.1). That is to say, one time slot is equivalent to 1,$\hat{3}$s. Note that, RTS/CTS messages are considered despite the contribution in time is not counted. This fact will increase the dissemination time considerably due to the long propagation delays.

Table 4.2 shows how many time each MAC method takes according to the number of packets transmitted through the line-up network. This way, it is easy to see which offer better transmission times.

Number of Packets	Overall Dissemination Times (s)					
	CSMA/CA	**NC**	**PNC**	**IC**	**IC and NC**	**IC and PNC**
4	16	13,$\hat{3}$	10,$\hat{6}$	12	12	9,$\hat{3}$
8	32	26,$\hat{6}$	21,$\hat{3}$	22,$\hat{6}$	22,$\hat{6}$	17,$\hat{3}$
12	48	40	32	33,$\hat{3}$	33,$\hat{3}$	25,$\hat{3}$
16	64	53,$\hat{3}$	42,$\hat{6}$	44	44	33,$\hat{3}$

Table 4.2: Line-up Packets Dissemination Times for Minimal Modified CSMA/CA

As a result, the best choices for data dissemination would be mix of IC and NC or just IC taking 44 seconds for disseminating 16 packets of 1800 bytes per unit, in contrast with CSMA/CA which is the worst with 64 seconds. Besides, think of implementing IC and PNC, which takes over 33 seconds, for other applications could offer better results than IC and NC or just IC.

Test 2: Improved MAC Protocol approach

In contrast with the previous test, an advanced MAC protocol design is assumed where RTS/CTS approach is not required. Consequently, some improvements could be achieved. As RTS/CTS messages are not considered, the broadcast channel constraints are reduced. In this sense, this approach allows to have simultaneous transmissions between different pair of nodes if the range is longer than one hop. This means that if the node which wants to transmit is further than one hope from the current transmission, the node sends the packet.

CSMA/CA. All nodes are supposed to implement this standard. In CSMA/CA, a node cannot transmit and receive simultaneously. Figure 4.15 shows an example.

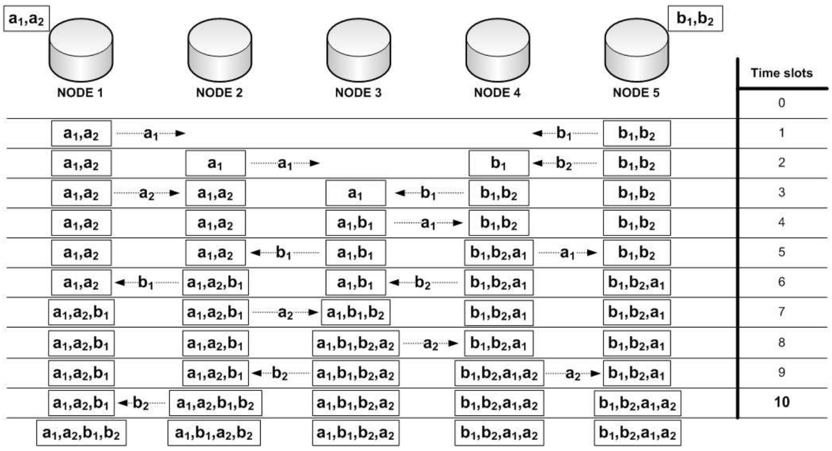

Figure 4.15: Line-up CSMA/CA example for Improved MAC protocol

In this example, packet a_1 is sent from Node 1 to Node 2 and simultaneously Node 5 transmits b_1 to Node 4 since both transmissions are out of range and will not interfere each other. After that, a_1 is sent from Node 2 to Node 3 because it has priority, and at the same time b_2 is transmitted from Node 5 to Node 4 as it is the single possible additional transmission (note that simultaneous transmissions are permitted, provided that the receivers are further than one bound free of transmssion when RTS/CTS messages are not required). Then, b_1 is transmitted from Node 4 to Node 3 as fairness is one of the assumptions (b_1 is sent before b_2 as it has preference), and simultaneously, a_2 is sent from Node 1 to Node 2. Next, a_1 is sent from Node 3 to Node 4 (Note that, if Node 1 had an additional packet to send, it would transmit the packet at this same time). After that, b_1 is transmitted from Node 3 to Node 2, and a_1 is sent simultaneoulsy from Node 4 to Node 5. Later, b_1 is transmited from Node 2 to Node 1 wheras b_2 is sent from Node 4 to Node 3. Afterwards, a_2 is sent from Node 2 to Node 3 (Note that, if Node 5 had an additional packet to send, it would transmit the packet at this same time). From now on, the process is repetead from Time Slot 4 for a_2.

NC. While Node 3 is supposed to implement Network Coding, all nodes work according to CSMA/CA standard. In NC, a node is able to combine two different flows. Figure 4.16 shows an example.

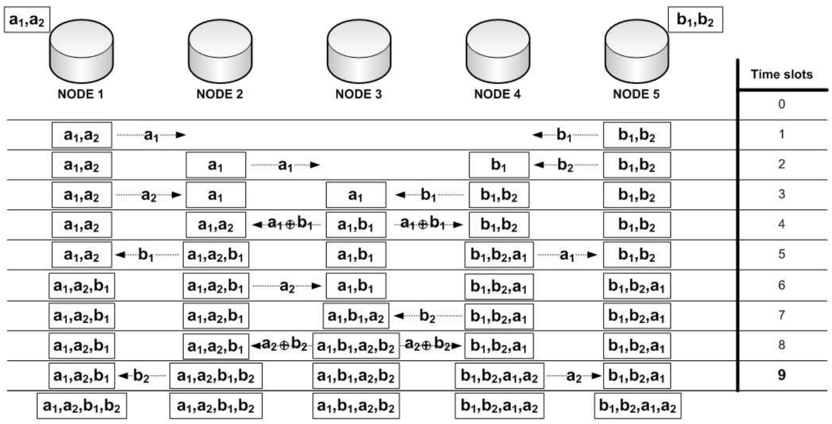

Figure 4.16: Line-up NC example for Improved MAC protocol

In this simulation, packet a_1 is sent from Node 1 to Node 2 and simultaneously Node 5 transmits b_1 to Node 4 since both transmissions are out of range and will not interfere each other. After that, a_1 is sent from Node 2 to Node 3 because it has priority, and at the same time b_2 is transmitted from Node 5 to Node 4 as it is the single possible additional transmission (note that simultaneous transmissions are permitted, provided that the receivers are further than one bound free of transmssion when RTS/CTS messages are not required). Then, b_1 is transmitted from Node 4 to Node 3 as fairness is one of the assumptions (b_1 is sent before b_2 as it has preference), and simultaneously, a_2 is sent from Node 1 to Node 2. Next, Node 3 combines a_1 and b_1 by applying XOR and broadcasts the XOR of both packets to Node 2 and Node 4. Later, Node 2 and 4 extract the remaining packet, respectively, by XOR and finally send b_1 and a_1 simultaneously to Node 1 and 5, respectively. From now on, the process is repetead from Time Slot 2 for a_2. Then, where a_2 and b_2 have been considered, new packets from both source nodes, 1 and 5, will be transmitted.

PNC. Node 3 is supposed to implement Physical-layer Network Coding whereas all nodes implement CSMA/CA. In PNC, a node is capable of combining two different flows which are received simultaneously. Figure 4.17 depicts an example.

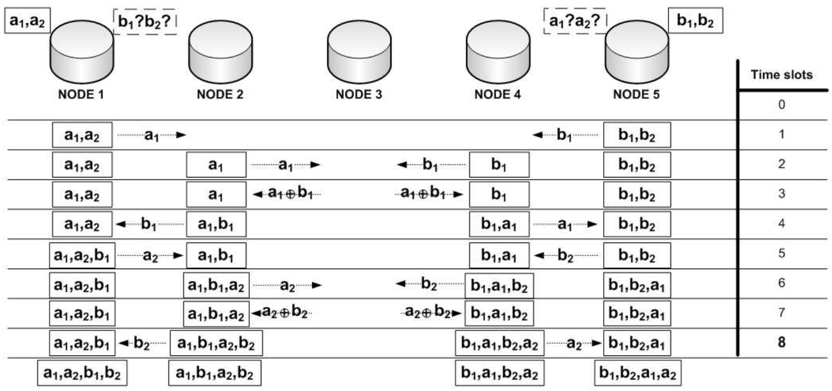

Figure 4.17: Line-up PNC example for Improved MAC protocol

In this test, packet a_1 is sent from Node 1 to Node 2 and simultaneously Node 5 transmits b_1 to Node 4. After that, a_1 and b_1 are sent from Node 2 and 4, respectively, to Node 3. Then, upon receiving both physical information carriers, Node 3 broadcasts the collision of a_1 and b_1 to Node 2 and Node 4 as the physical combination of them by modulation schemes (Node 3 does not store the data since packets have collided). Later, Node 2 and 4 extract the remaining packet, respectively, by demoluation schemes and finally send b_1 and a_1 simultaneously to Node 1 and 5, respectively. This way, the process is repetead for a_2 and b_2, and so on.

IC. All nodes are supposed to implement this concept. In IC, a node can transmit and receive simultaneously. Figure 4.18 shows an example.

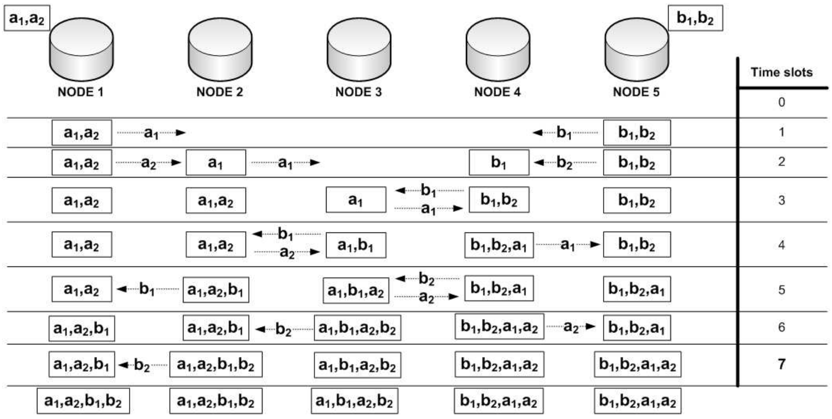

Figure 4.18: Line-up IC example for Improved MAC protocol

Here, packet a_1 is sent from Node 1 to Node 2 and simultaneously Node 5 transmits b_1 to Node 4 since both transmissions are out of range and will not interfere each other. After that, a_1 is sent from Node 2 to Node 3 because it has priority, and at the same time b_2 is transmitted from Node 5 to Node 4 as it is the single possible additional transmission (note that simultaneous transmissions are permitted, provided that the receivers are further than one bound free of transmssion when RTS/CTS messages are not required). Also, a_2 can be sent from Node 1 to Node 2 at the same time taking advantage of IC properties. Then, a_1 and b_1 are transmitted simultaneously from Node 4 to Node 3 and viceversa taking advantage of IC properties (b_1 is sent before b_2 as it has preference), note that if Node 1 had packets to send, it would transmit them at this time. Later, b_1 and a_2 are sent from Node 3 to Node 2 as fairness is one of the assumptions. At the same time, a_1 is transmitted from Node 4 to Node 5 (if Node 5 had packets to send, it would transmit them at this time due to IC properties). Afterwards, b_1 is transmitted from Node 2 to Node 1 (f Node 1 had packets to send, it would transmit them at this time due to IC properties) whereas a_2 and b_2 are sent simultaneously from Node 3 to Node 4 and viceversa due to IC properties. From now on, the process is repetead from Time Slot 4 for a_2 and new packets.

Mix of IC and NC. While all nodes are supposed to implement Interference Cancellation, Node 3 implements Network Coding. In mix of IC and NC, a node can combine two different flows and, transmit and receive simultaneously. Figure 4.19 presents an example.

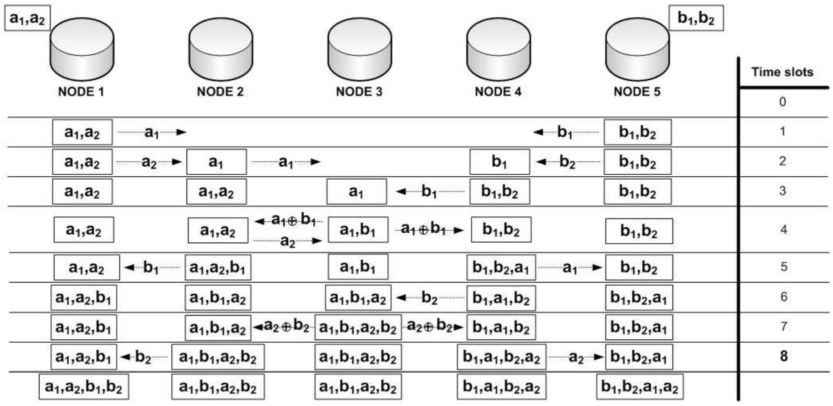

Figure 4.19: Line-up IC and NC example for Improved MAC protocol

In this example, packet a_1 is sent from Node 1 to Node 2 and simultaneously Node 5 transmits b_1 to Node 4 since both transmissions are out of range and will not interfere each other. After that, a_1 is sent from Node 2 to Node 3 because it has priority, and at the same time b_2 is transmitted from Node 5 to Node 4 as it is the single possible additional transmission (note that simultaneous transmissions are permitted, provided that the receivers are further than one bound free of transmssion when RTS/CTS messages are not required). Also, a_2 can be sent from Node 1 to Node 2 at the same time taking advantage of IC properties. Then, b_1 is transmitted from Node 4 to Node 3 as fairness is one of the assumptions (b_1 is sent before b_2 as it has preference), note that if Node 1 and 5 had more packets to send, they would transmit them at this time simultaneously. Next, Node 3 combines a_1 and b_1 by applying XOR and broadcasts the XOR of both packets to Node 2 and Node 4. Simultaneously, a_2 is send from Node 2 to Node 3. Later, Node 2 and 4 extract the remaining packet, respectively, by XOR and finally send b_1 and a_1 simultaneously to Node 1 and 5, respectively. If Node 1 and 5 had more packets to send, they would transmit them at this time by IC properties. From now on, the process is repetead from Time Slot 2 for a_2. Then, where a_2 and b_2 have been considered, new packets from both source nodes, 1 and 5, will be transmitted.

Mix of IC and PNC. While all nodes are supposed to implement Interference Cancellation, Node 3 implements Physical-layer Network Coding. In mix of IC and PNC, a node is able to combine two different flows which are received simultaneously and, transmit and receive simultaneously. Figure 4.20 displays an example.

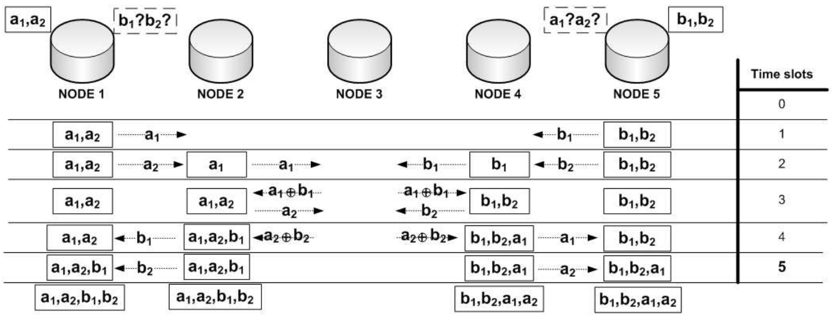

Figure 4.20: Line-up IC and PNC example for Improved MAC protocol

In this simulation, packet a_1 is sent from Node 1 to Node 2 and simultaneously Node 5 transmits b_1 to Node 4 since both transmissions are out of range and will not interfere each other. After that, a_1 and b_1 are sent from Node 2 and 4, respectively, to Node 3, and at the same time a_2 is transmitted from Node 1 to Node 2 as well as b_2 can be sent from Node 5 to Node 4 taking advantage of IC properties. Then, upon receiving both physical information carriers, Node 3 broadcasts the collision of a_1 and b_1 to Node 2 and Node 4 as the physical combination of them by modulation schemes (Node 3 does not store the data since packets have collided). Simultaneously, a_2 and b_2 are transmitted from Node 2 and 4, respectively, to Node 3 taking advantage of IC properties. Later, Node 2 and 4 extract the remaining packet, respectively, by demoluation schemes and send b_1 and a_1 simultaneously to Node 1 and 5, respectively. At this same time, Node 3 broadcasts the collision of a_2 and b_2 to Node 2 and Node 4 due to IC properties. Finally, Node 2 and 4 extract the remaining packet, respectively, by demoluation schemes and send b_2 and a_2 simultaneously to Node 1 and 5, respectively. If Node 1 and 5 had more packets to send, they would transmit them at this time by IC properties. From now on, the process is repeated for new packets.

Results

This section is organised as follows. First, some conclusions are inferred for every MAC method. Then, propagation delays are applied so as to observe the efficiency in transmission time of every technique. Thus, the improvements of new concepts are pointed out.

From Figure 4.21, it is inferred that the behaviour of MAC methods considering this approach is quite different from that observed in the previous test.

- **CSMA/CA** *Presents a linear behaviour in the long term modelled by 2N+2. This means that when a packet is sent through the network the overall dissemination time is increased two time slots.*

- **NC** *Shows a linearity in steady state shaped by 2N+1. Improves CSMA/CA in one time slot less every four packets. Therefore, NC performs less efficiently as compared with the rest when advanced MAC protocol design is considered. This is basically due to its broadcast properties as it cannot take advantage of Improved MAC properties whereas CSMA/CA or IC, as follows, does do it.*

- **IC** *Undergoes a linear behaviour in the long term featured by N+3. IC increases considerably NC efficiency according to the dissemination time. In fact, IC achieves one time slot less every packet inserted in the network as compared with NC.*

- **Mix of IC and NC** *Is linear in steady state given by 1,5N+2. As NC performs quite inefficient when Improved MAC Protocol Approach is assumed, IC and NC does not improve IC effciency. Nevertheless, mix of IC and NC performs better than just NC.*

Looking at Figure 4.21, there is no doubt that analysed MAC techniques take less time for data dissemination when Improved MAC Protocol Approach is considered as compared with Minimal Modified CSMA/CA. This fact is because RTS/CTS approach which is considered in the first test affects directly to the behaviour of nodes when they have a packet to sent. Remember that nodes are prevented from sending packets due to a neighbouring transmitter. So, nodes have to wait and the overall dissemination time is increased regardless of the MAC method.

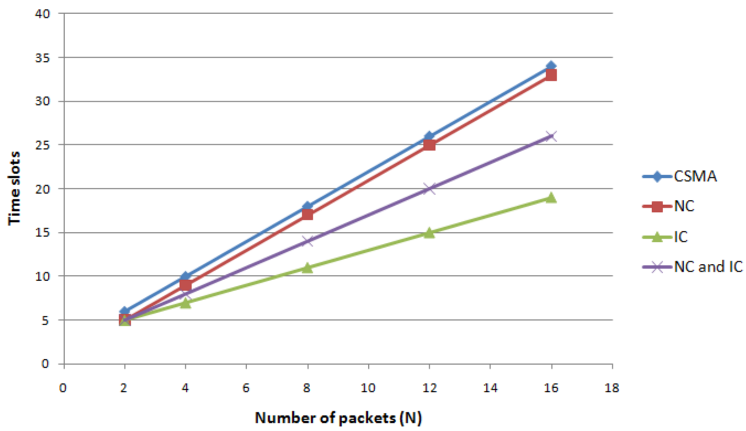

Figure 4.21: Line-up performance evaluation for Improved MAC Protocol

Focusing on the results, some observations are presented. On the one hand, it is observed that IC undergoes the best performance when an advanced MAC protocol design is assumed. On the other hand, the mix of IC and NC performs worse than IC due to the NC working principle in the line-up network. In NC, it is not possible to take advantage of the new conditions when the Improved MAC protocol approach is taken into account due to the structure of the network (five line-up nodes). Possibly, the results would be different if the line-up network consisted of more nodes. In this particular case, NC does not work very well as compared with IC or mix of IC and NC despite it is more efficient than CSMA/CA.

Unlike NC, PNC can improve again the performance since it is more efficient than NC. Note that, while NC has to receive the two flows separately and then, combines and broadcasts them, PNC receives both flows simultaneously and then, combines and broadcasts them. Thus, mix of IC and PNC can work properly in this kind of scenarios being more efficient than just IC. Nevertheless, remember that PNC is not suitable for data dissemination as the node which implements PNC cannot store the data.

Figure 4.22 shows its benefits for other applications, for instance end nodes in the line-up network demand flows A and B, respectively. This way, mix of IC and PNC would be better than just IC.

As it can be seen, there are significant differences when IC properties are combined with PNC.

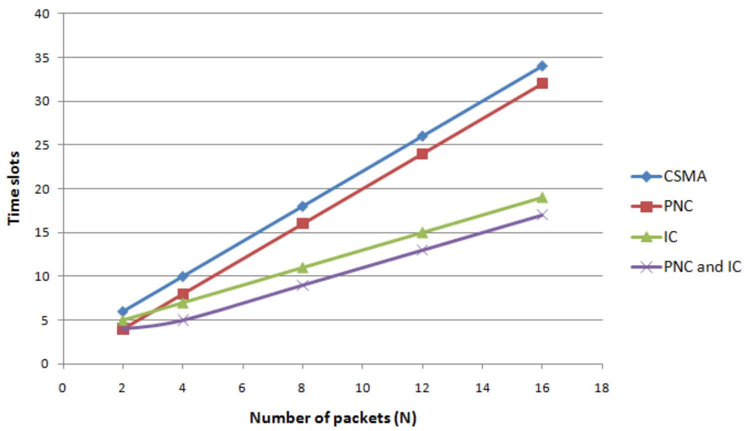

Figure 4.22: Line-up performance PNC evaluation for Improved MAC Protocol

Propagation Delays

Considering propagation delays, Table 4.3 show how many time each MAC method takes according to the number of packets transmitted through the line-up network. As it was stated in previous sections, this test has shown less overall dissemination times as compared with the previous test. This fact is summarised in Table 4.3.

Number of Packets	Overall Dissemination Times (s)					
	CSMA/CA	**NC**	**PNC**	**IC**	**IC and NC**	**IC and PNC**
4	$13,\hat{3}$	12	$10,\hat{6}$	$9,\hat{3}$	$10,\hat{6}$	$6,\hat{6}$
8	24	$22,\hat{6}$	$21,\hat{3}$	$14,\hat{6}$	$18,\hat{6}$	12
12	$34,\hat{6}$	$33,\hat{3}$	32	20	$26,\hat{6}$	$17,\hat{3}$
16	$45,\hat{3}$	44	$42,\hat{6}$	$25,\hat{3}$	$34,\hat{6}$	$22,\hat{6}$

Table 4.3: Line-up Packets Dissemination Times for Improved MAC Protocol Approach

From Table 4.3, it is inferred that the best choice for data dissemination would be IC taking over 25 seconds for disseminating 16 packets of 1800 bytes per unit, in contrast with CSMA/CA which is the worst with more than 45 seconds. Besides, think of implementing IC and PNC, which takes over 23 seconds, for other applications could offer better results than just IC.

4.5.2 Meshed Network

Unlike the line-up network, this scenario aims to analyse the performance of proposed MAC methods in such common topologies: dense traffic situations in large-scale networks. This way, it is possible to identify the benefits of new concepts, such as Network Coding and Interference Cancellation, as compared with successful MAC schemes in wireless communications like CSMA/CA. Likewise, it should be remarked that special attention is given to PNC since this network is not intended for data dissemination but the transmission of two parallel flows.

This particular scenario presents its own characteristics and shapes the performance of MAC techniques under evaluation, when conducting the tests. For this reason, some explanations should be devoted to describe how each MAC technique performs according to the proposed experiments. In this case, just the Improved MAC Protocol test is run because of the meshed topology. As all nodes are in range of one hop, all of them are equally affected by the broadcast channel of a given node in the network. That is why Minimal Modified CSMA/CA approach is not applicable in this scenario.

Next lines are devoted to show an example of every MAC tehnique in order to explain its working principle. Next, the different topics are described. In each particular case, one packet per flow are supposed to be inserted in the network. But first, some statements are presented as before for every technique.

- **CSMA/CA** *All nodes implement it.*
- **PNC** *Node 1 is supposed to implement Physical-layer Network Coding whereas all nodes behave as CSMA/CA standard.*
- **NC** *Node 1 is supposed to implement Network Coding whereas all nodes behave as CSMA/CA standard.*
- **IC** *All nodes are supposed to implement this concept.*
- **Mix of IC and PNC** *All nodes are supposed to implement Interference Cancellation whereas Node 1 implements Physical-Layer Network Coding.*
- **Mix of IC and NC** *While all nodes are supposed to implement Interference Cancellation, Node 1 implements Network Coding.*

As a general description for the meshed scenario, Node 2 and Node 3 have the information, a_1 and b_1, respectively. While Node 4 is interested in a_1, Node 5 wants b_1. The box next to each node refers to the data which is stored on it at a given time. The data is organised by incoming order. At the right of figure, there is a legend describing the evolution of the network along the time. Each color identifies the transmissions in the network for every time. Time 0 defines the initial conditions.

CSMA/CA. Nodes cannot transmit and receive simultaneoulsy. Figure 4.23 presents an example of CSMA/CA over the meshed topology.

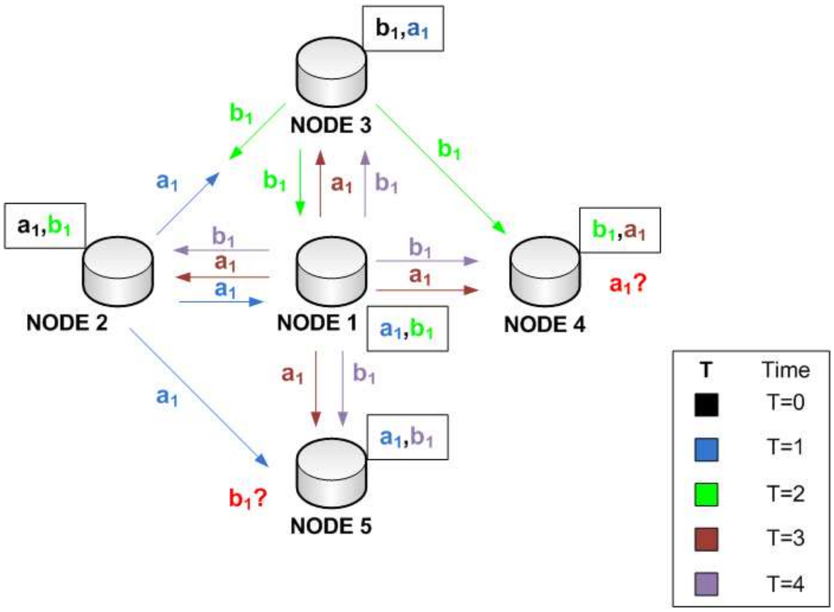

Figure 4.23: Meshed CSMA/CA example for Improved MAC protocol

In this example, the evolution of the network is described as follows. In T=1, packet a_1 is broadcasted from Node 2 to Nodes 3, 1 and 5 as it has preference with respect to b_1 in order to avoid collisions. In T=2, b_1 is sent from Node 3 to Nodes 2, 1 and 4 as fairness is one of the assumptions. In T=3, Node 1 broadcasts a_1. Finally, Node 1 broadcasts b_1 in T=4. The process is repeated for next packets.

IC. In order to understand the working principle of IC in the meshed scenario, it is necessary to run an example with an addition of one packet per flow. In this sense, IC performs as CSMA/CA for the first packets and then it behaves as follows. Note that, Figure 4.24 is the continuation of Figure 4.23. In IC, a node can transmit and receive simultaneously.

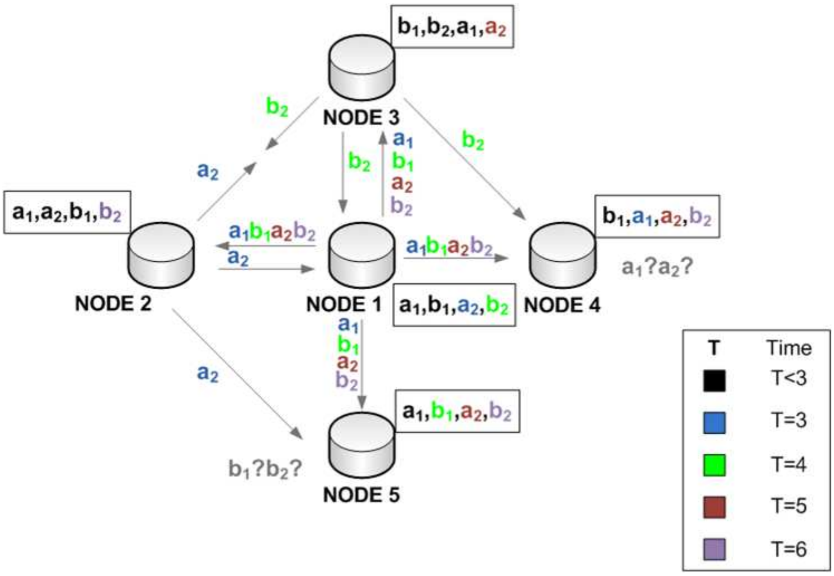

Figure 4.24: Meshed IC example for Improved MAC protocol

In this figure, $T < 3$ means previous times' transmissions. In T=3, while a_1 is being broadcasted by Node 1, Node 2 sends a_2 taking advantage of IC. Despite packets a_1 and a_2 collide at Nodes 3 and 5, Node 4 receives a_1. In T=4, b_1 is broadcasted by Node 1 whereas Node 3 transmits b_2 simultaneously due to IC properties. Although b_1 and b_2 collide at Nodes 2 and 4, Node 5 receives b_1. In T=5, a_2 is sent by Node 1 (If Node 2 had more packets to send, it would transmit them at this time). Finally, b_2 is broadcasted by Node 1 (If Node 3 had more packets to transmit, it would send them at this moment). From now on, the process is repeated for next packets.

PNC. Figure 4.25 displays and example of PNC over the meshed scenario. In PNC, a node is capable of combining two different flows which are received simultaneously.

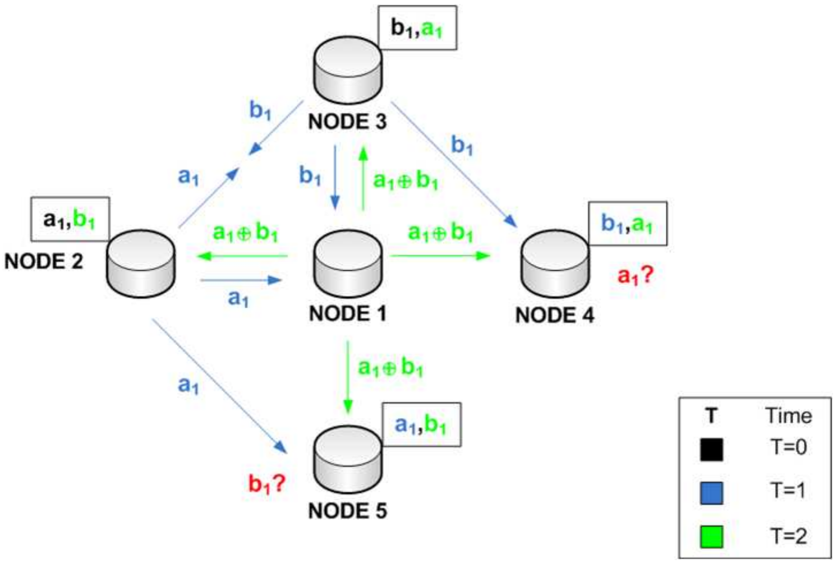

Figure 4.25: Meshed PNC example for Improved MAC protocol

In this simulation, the evolution of the network is described as follows. In T=1, Node 2 and 3 transmit a_1 and b_1, respectively. In T=2, upon receiving both physical information carriers, Node 1 broadcasts the collision of a_1 and b_1 as the physical combination of them by modulation schemes (Node 3 does not store the data since packets have collided). Finally, as Node 4 and 5 have received a_1 and b_1 in T=1,respectively, they are able to substract the packet which is left by demodulation schemes. The process is repeated for next

Mix of IC and PNC. A node is able to combine two different flows which are received simultaneously and, transmit and receive simultaneously. As just IC, an example with an addition of one packet per flow is needed aiming to understand how the mix of IC and PNC works. In this sense, Figure 4.26 is the next step with respect to Figure 4.25.

Figure 4.26 needs further explanations to be understood. This figure shows a particular feature when properties of IC are added to the performance of PNC.

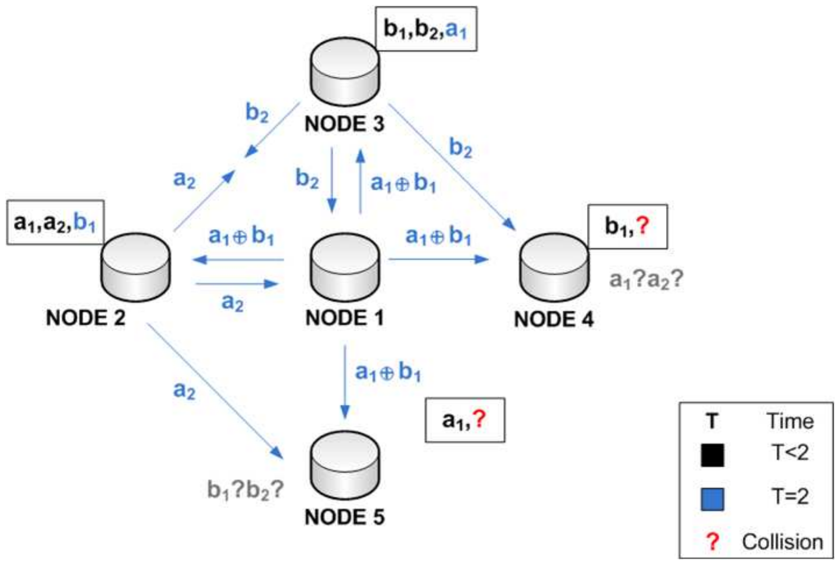

Figure 4.26: Meshed Mix of IC and PNC example for Improved MAC protocol

Once NODE 2 and 3 has sent packet a_1 and b_1, respectively, NODE 1 broadcasts the combination of a_1 and b_1. In this same moment, taking advantage of Interference Cancellation NODE 2 and 3 could transmit packet a_2 and b_2, respectively. Here, there is a burning issue as packets will collide in NODE 4 and 5. So, NODE 2 and 3 will have to wait for the next time slot to transmit their packets in order to avoid collisions. Thus, mix of IC and PNC works as just PNC.

NC. Figure 4.27 depicts and example of NC over the meshed scenario. In NC, a node is able to combine two different flows.

In this simulation, the evolution of the network is described as follows. In T=1, Node 2 transmitd a_1. In T=2, b_1 is transmitted by Node 3. In T=3, Node 1 combines a_1 and b_1 by applying XOR and broadcasts the XOR of both packets. Finally, as Node 4 and 5 have received a_1 and b_1 in T=1 and T=2,respectively, they are able to substract the remaining packet, respectively, by XOR. The process is repeated for next packets.

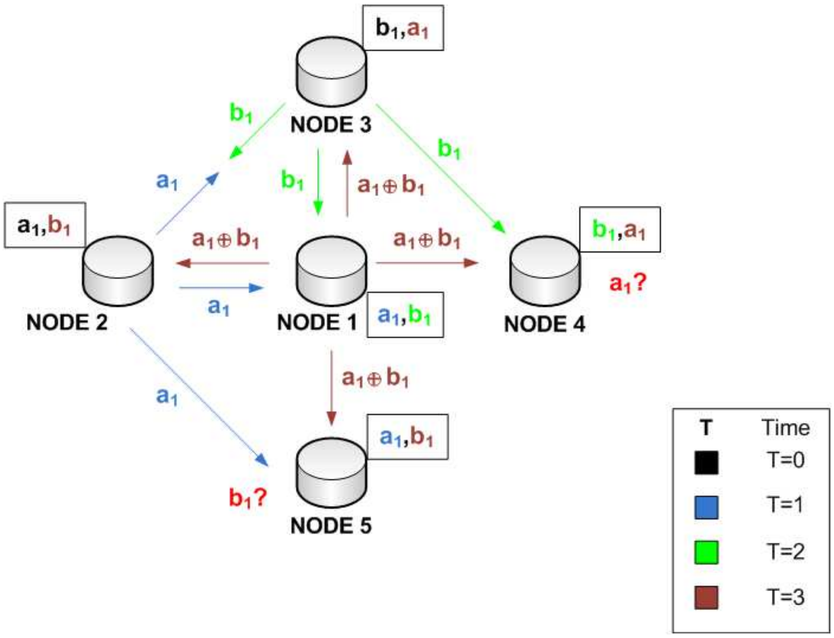

Figure 4.27: Meshed NC example for Improved MAC protocol

Mix of IC and NC. A node can combine two different flows and, transmit and receive simultaneously. As mix of IC and PNC, an example with an addition of one packet per flow is needed aiming to understand how the mix of IC and NC works. In this sense, Figure 4.28 is the continuation of Figure 4.27.

Figure 4.28 needs further explanations to be understood. Despite mix of IC and NC has similarities to mix of IC and PNC, the performance when adding IC is a bit different. Again, a single feature is pointed out when properties of IC are combined with NC.

Once NODE 2 and 3 has sent packet a_1 and b_1, respectively, through their links, NODE 1 broadcasts the mix of a_1 and b_1. In this same moment, taking advantage of Interference Cancellation NODE 2 could transmit packet a_2 over their links. Here, there is a burning issue again as packets will collide in NODE 5. So, NODE 2 will have to wait for the next time slot to transmit their packets in order to avoid collisions. Thus, mix of IC and NC works as just NC.

Finally, it should be mentioned that flow A would not be affected by this sort of problem and Node 4 would be able to extract a_1 and a_2.

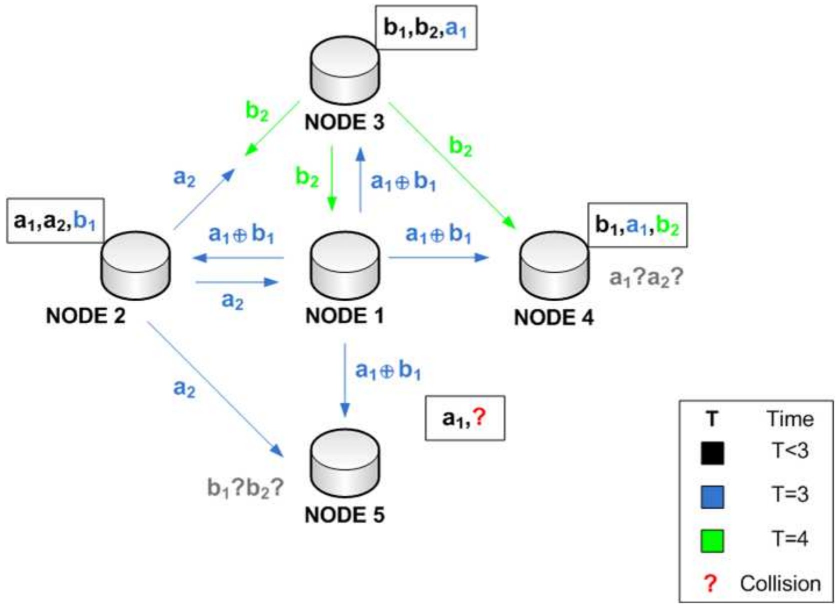

Figure 4.28: Meshed Mix of IC and NC example for Improved MAC protocol

Results

As the line-up network, this scenario has proved some benefits from the new concepts. The analysis of results are based on the Improved MAC Protocol Approach according to previous statements. Next, some conclusions are inferred for every MAC method.

Figure 4.29 presents the performance evaluation of analysed MAC techniques in terms of data transmission process.

- **CSMA/CA** *Presents a linear behaviour modelled by 2N. This means that when a packet is sent through the network the overall dissemination time is increased two time slots.*
- **IC** *Undergoes a linear behaviour in the long term featured by N+2, where N≥4 packets disseminated through the network (2 packets per flow). This is because IC is not linear when less than four packets are transmitted in the network. Increases considerably CSMA/CA efficiency according to the packets transmission time in one time slot less every packet inserted in the network.*
- **PNC** *Shows a linearity shaped by N. Does not improve IC in terms*

of less time slots when a packet is transmitted through the network. However, PNC is quicklier than IC when starting. So, it ends the transmission process two time slots earlier than IC.

- **Mix of IC and PNC** *Follows the same linearity as PNC, N. Performs as just PNC since the properties of Interference Cancellation cannot be exploited.*

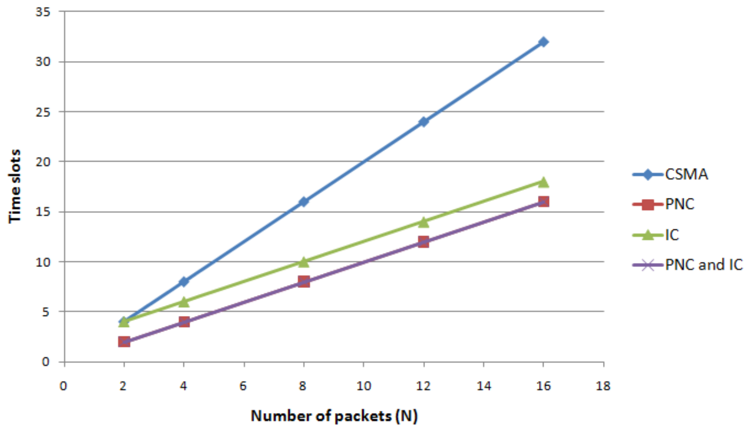

Figure 4.29: Meshed performance evaluation for Improved MAC Protocol

According to the results shown in Figure 4.29, there are some evidences that IC and NC concepts could enhance considerably the system efficiency for these common topologies, dense traffic situations in large-scale networks, as compared with CSMA/CA.

Analysing the results, it is observed that PNC and mix of IC and PNC undergo the best performance when an advanced MAC protocol design is assumed. This means that both take less time for data transmission in contrast with CSMA/CA or IC in spite of IC performs better than CSMA/CA. In addition, it should be commented that mix of IC and PNC does not improve PNC efficiency as the advantages of applying IC are not reflected in the better performance of the data transmission streams due to the meshed nework topology. As a result, mix of IC and PNC is as efficient as just PNC.

Apart from this, it should be remarked that NC cannot improve the system efficiency as it takes more time than PNC for the data packets transmission. Nevertheless, this approach is shown in Figure 4.30 since it could be suitable if the goal is to disseminate data packets through all the nodes of the network where IC would be the best option. As before, mix of IC and NC does not improve NC and IC efficiency because properties of IC cannot be exploited again when combined with NC.

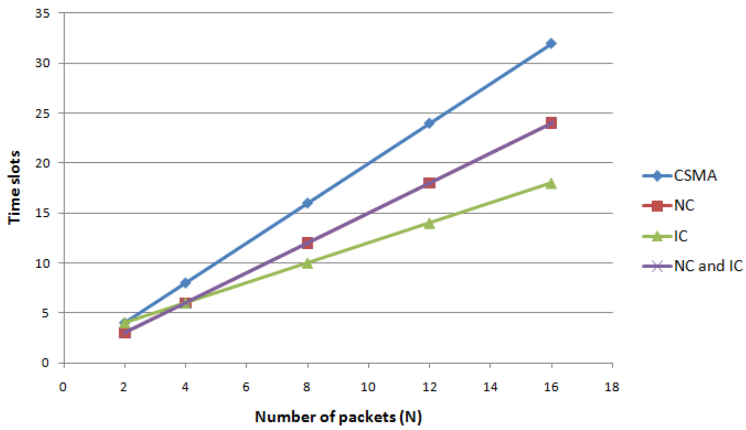

Figure 4.30: Meshed NC performance evaluation for Improved MAC Protocol

Propagation Delays

Up to now, each MAC technique has been compared with one another in terms of time slots. In order to quantify the overall transmission time, the propagation delay is considered. So, in this sense, one time slot is equivalent to 1,$\hat{3}$s. Table 4.4 shows the overall dissemination time for each MAC method when Improved MAC Protocol Approach is assumed. This way, it is easy to see which offer better transmission times.

Number of Packets	Overall Dissemination Times (s)					
	CSMA/CA	NC	PNC	IC	IC and NC	IC and PNC
4	10,$\hat{6}$	5,$\hat{3}$	8	8	5,$\hat{3}$	8
8	21,$\hat{3}$	10,$\hat{6}$	16	13,$\hat{3}$	10,$\hat{6}$	16
12	32	16	24	18,$\hat{6}$	16	24
16	42,$\hat{6}$	21,$\hat{3}$	32	24	21,$\hat{3}$	32

Table 4.4: Meshed Packets Transmission Times for Improved MAC Protocol Approach

As a conclusion, the best choice for data transmission would be mix of IC and PNC or just PNC taking over 21 seconds for transmitting 16 packets of 1800 bytes per unit, in contrast with CSMA/CA which is the worst with more than 42 seconds. Besides, think of implementing IC, which takes 24 seconds, for data dissemination could offer better results than CSMA/CA or NC.

Conclusions

In this project, the basis for the design and possible implementation of an underwater acoustic communication system have been stated. The project have covered different topics ranging from history, characteristics and applications of underwater communications to design factors and the analysis of existing and improving MAC protocol design, tests and results. Specifically, the main focuses have been the analysis of commercial acoustic modems and suppliers as well as the design and performance evaluation of Medium Access with Interference Cancellation and Network Coding (main part).

The underwater environment is a uniquely difficult one for communications. Water movements are never-ceasing, and conditions are always changing drastically depending on location, time of day and weather. In this sense, underwater communications differ from terrestrial communications by many factors. Acoustic waves are used as the signal carrier since radio and optical waves only propagate well over very short distances. Large propagation losses, long latency, limited bandwidth capacity and channel stability are the main channel effects. Therefore, underwater communications pose many challenges to networking protocol design as compared with terrestrial radio networks.

While some Medium Access schemes have been successful in traditional radio communications, they are prone to severe limitations in efficiency and scalability when deployed directly in the underwater environment. That is the case of CSMA/CA, widely implemented in wireless communications, which relies on RTS/CTS handshakes for collision avoidance. Such disadvantages are primarily because of the large propagation delays of the underwater acoustic channel. As a result, new strategies are needed to face the underwater channel effects.

Interference Cancellation and Network Coding appear as emerging concepts for Medium Access protocol design aiming to cope with the underwater channel contraints in order to improve the system efficiency. The goal has been to investigate the possibility of Medium Access with Interference Cancellation and Network Coding modifying the CSMA/CA MAC protocol.

The concept of Interference Cancellation (IC) refers to the simultaneous transmission and reception of information basing on the knowledge of the propagation delay. In stationary networks where nodes are fixed or move very slowly, the propagation delay between a pair of nodes is almost constant. If a node could determine it easily, it would set the maximal packet length. Then, when neighbouring nodes had packets to send to each other, they would be able to transmit them and start receiving inmediately, thus, enhancing the system efficiency.

The idea of Network Coding (NC) lies in the combination of independent flows when they are transported throughout the network. Two different possible ways to Network Coding have been considered: linear and physical-layer network coding. While linear network coding consists of the XOR combination of two independent flows received separately, Physical-layer Network Coding (PNC) makes use of the additive nature of simultaneously arriving EM waves for equivalent coding operation, i.e. the idea of PNC is similar to that of network coding, but at the lower physical layer dealing with EM signal reception and modulation. Among the benefits of Network Coding, throughput is remarked.

In order to evalute the performance of Medium Access with previous concepts, several tests over different scenarios have been conducted. In this sense, two sorts of scenarios have been described: Line-up and Meshed networks. The line-up network aims to investigate how the data is disseminated through nodes and how many time the data dissemination process takes, whereas the meshed topology focuses on the performance of proposed MAC methods in such common topologies: dense traffic situations in large-scale networks. Specifically, the performance evaluation consists of the analysis of CSMA/CA, IC, NC and mix of IC and NC for data dissemination according to the tests run over the different topologies. Note that, PNC is also considered.

Regarding the tests, two experiments have been considered: Minimal Modified CSMA/CA and Improved MAC Protocol Approach. Whilst Minimal Modified CSMA/CA keeps the MAC Constraints of CSMA/CA where RTS/CTS messages are considered, Improved MAC Protocol Approac refers to next generation MAC protocol design where RTS/CTS approach is supposed not to be required. Then, the broadcast coverage of a given node does not affect to the neighbouring nodes in the same way as before.

Focusing on the results, both tests conducted over the line-up network have shown the benefits of new concepts. In Minimal Modified CSMA/CA, IC and mix of IC and NC have taken the least time to disseminate all the packets through the network, followed by NC. Likewise, PNC would be the best option for end to end transmissions. In this sense, mix of IC and PNC has proved the best efficiency. In Improved MAC Protocol Approach, all MAC techniques have shown less overall dissemination times in contrast with the previous test. IC performs better as compared to the rest, followed by mix of IC and NC. In the same line, PNC has undergone the best performance when combined with IC for end to end transmissions. However, just PNC performs as efficient as mix of IC and NC. As the line-up network, the experiment run over the meshed scenario has proved some benefits from the emerging concepts. In this case, special attention is given to PNC as it performs well for end to end transmissions. For this reason, PNC and mix of IC and PNC have shown the best efficiency, followed by IC. In addition, IC would be the best option to disseminate data through the meshed network.

According to the results, in the line-up scenario, mix of IC and NC does not improve the performance of just IC though it enhances considerably NC efficiency. On the contrary, mix of IC and PNC always improves the performance of either IC or PNC depending on the test. In the meshed scenario, mix of IC and NC does not improve the performance of IC or NC. In contrast, mix of IC and PNC does not improve PNC efficiency despite it enhances IC efficiency.

As a conclusion, there are some evidences that prove the feasiblilty of Interference Cancellation and Network Coding for data dissemination improving the throughput and avoiding collisions as compared with CSMA/CA MAC protocol. Thus, the system efficiency may be enhanced.

This new approach can be very useful to be applied in underwater wireless networks where resources are quite limited depending on the long propagation delays and frequency-dependence of the underwater channel. Future research should focus on the practical implementation of these concepts over the principle of CSMA/CA in underwater acoustic networks. For this reason, an overview of commercial underwater acoustic modems, main companies and products have been carried out. The objective has been to check the state-of-the-art technology of acoustic modems in terms of transmission capacity, power efficiency, operating depth and range, and networking capabilities. Besides, a comparison study has been presented in order to hypothetically purchase a versatile acoustic modem for a wide variety of applications. The modem is supposed to be chosen for building small networks either static or dynamic in shallow waters for networking research in underwater communications by AAU Department of Telecommunication Technology.

References

[1] *History of Underwater Acoustics. http://www.dosits.org/people/history/.*

[2] Timothy F. Duda and Allan D. Pierce. *History of Environmental Acoustics, 1960s to 2000s.* 2008.

[3] D.B. Kilfoyle and A.B. Baggeroer. The state of the art in underwater acoustic telemetry, January 2000.

[4] Kenneth G. Foote. *Underwater acoustic technology: review of some recent developments.* 2008.

[5] J. A. Catipovic M. Stojanovic and J. G. Proakis. *Adaptive multi-channel combining and equalization for underwater acoustic communications.* 1993.

[6] *Phase-coherent digital communications for underwater acoustic channels.* 1994.

[7] T. E. Ewart. *Acoustic fluctuations in the open oceanA measurement using a fixed refracted path.* 1976.

[8] T. E. Ewart and S. A. Reynolds. *The Mid-Ocean Acoustic Transmission Experiment, MATE.* 1984.

[9] C.-F. Huang and W. S. Hodgkiss. *Matched-field geoacoustic inversion of low-frequency source tow data from the ASIAEX East China Sea experiment.* 2004.

[10] A. E. Newhall L. Wu T. F. Duda, J. F. Lynch and C.-S. Chiu. *Fluctuation of 400-Hz sound intensity in the 2001 ASIAEX South China Sea experiment.* 2004.

[11] C. W. Miller J. F. Lynch T. F. Duda C.-S. Chiu, S. R. Ramp and T.-Y. Tang. *Acoustic intensity fluctuations induced by South China Sea internal tides and solitons.* 2004.

[12] P. C. Mignerey and M. H. Orr. *Observations of matched-field autocorrelation time in the South China Sea.* 2004.

[13] S. N. Wolf J. F. Lynch T. Schroeder M. H. Orr, B. H. Pasewark and C.-S. Chiu. *South China Sea internal tide/internal waves impact on the temporal variability of horizontal array gain at 276 Hz.* 2004.

[14] A. E. Newhall J. F. Lynch T. F. Duda C.-S. Liu R.-C. Wei, C.-F. Chen and P.-C. Lin. *A preliminary examination of the low-frequency ambient noise field in the South China Sea during the 2001 ASIAEX experiment.* 2004.

[15] M. C. Benfield D. G. Mountain P. H. Wiebe, T. K. Stanton and C. H. Greene. *High-frequency acoustic volume backscattering in the Georges Bank coastal region and its interpretation using scattering models.* 1997.

[16] P. H. Wiebe L. V. Martin Traykovski, T. K. Stanton and J. F. Lynch. *Model-based covariance mean variance classification techniques: algorithm development and application to the acoustic classification of zooplankton.* 1998.

[17] C. Schell and S. P. Linder. *Experimental evaluation of tracking algorithms used for the determination of fish behavioral statistic.* 2006.

[18] M. Obara P. Kasturi H. T. Rossby G. Fischer, S. Lee and C. W. Recksiek. *Tracking fishes with a microwatt acoustical receiver an archival tag development.* 2006.

[19] Milica Stojanovic. *Underwater Wireless Communications: Current Achievements and Research Challenges.* 2006.

[20] L. Berkhovskikh and Y. Lysanov. *Fundamentals of Ocean Acoustics. Springer.* 1982.

[21] M. Stojanovic. *On the relationship between capacity and distance in an underwater acoustic communication channel.* 2007.

[22] Michael B. Porter Martin Siderius and Paul Hursky. *Measurements and Modeling Comparisons of Underwater Communications Performance at three Shallow-Water Sites.* 2003.

[23] Abdennaceur KACHOURI Mahmoud ABDELLAOUI Nejah NASRI, Helmi BEN HNIA and Mounir SAMET. *Modulation/Demodulation Techniques With FPGAs Architecture to improve OFDM Wireless Underwater Communication Transceiver*. 2006.

[24] Muriel MEDARD Daniel E. LUCANI and Milica STOJANOVIC. *A Lower Bound to Transmission Power for Multicast in Underwater Networks using Network Coding*. 2008.

[25] Jun-Hong Cui and all. *Challenges: Building Scalable and Distributed Underwater Wireless Sensor Networks (UWSNs) for Aquatic Applications*. 2005.

[26] Ian F. Akyildiz and all. *Underwater acoustic sensor networks: research challenges*. 2005.

[27] Laurent ANDRIEUX Nejah NASRI, Abdennaceur KACHOURI and Mounir SAMET. *Design Considerations For Wireless Underwater Communication Transceiver*. 2008.

[28] Shengli Zhou Lanbo Liu and Jun-Hong Cui. *Prospects and Problems of Wireless Communication for Underwater Sensor Networks*.

[29] Mark Rhodes. *Electromagnetic Propagation in Sea Water and its value in Military Systems*.

[30] Alessandro Ghio Davide Anguita, Davide Brizzolara and Giancarlo Parodi. *Smart Plankton: a Nature Inspired Underwater Wireless Sensor Network*. 2008.

[31] Paolo Casciaro Nicola Baldo, Paolo Casari and Michele Zorzi. *Effective Heuristics for Flexible Spectrum Access in Underwater Acoustic Networks*.

[32] Peng Xie and Jun-Hong Cui. *An FEC-based Reliable Data Transport Protocol for Underwater Sensor Networks*. 2007.

[33] R. J. Urick. *Principles of Underwater Sound. Mcgraw-Hill*. 1983.

[34] Achuthan Paramanathan Janne Dahl Rasmussen Tatiana K. Madsen Anders Grauballe, Mikkel Gade Jensen and Frank Fitzek. *Implementation of Cooperative Information Storage on Distributed Sensor Boards*. 2008.

[35] A.Bouzoualegh. *tude et proposition dun rseau local acoustique aquatique*. 2006.

[36] Proakis. J. *Coded modulation for digital communication over Rayleigh fading channels*. 1991.

[37] Mikkel Gade Jensen Achuthan Paramanathan Janne Dahl Rasmussen Tatiana K. Madsen, Anders Grauballe and Frank Fitzek. *Reliable Cooperative Information Storage in Wireless Sensor Networksk*. 2008.

[38] Teledyne Benthos. *http://www.benthos.com/*.

[39] LinkQuest Inc. *http://www.link-quest.com/*.

[40] DSPCOMM. *http://www.dspcomm.com/*.

[41] Zhang Yonghuai Fan Guanghui and Sun Haixin. *A new Code-D i vis ion Mu It i pie Access Protoco I for Underwater Acoustic Network*.

[42] Mehul Motani Hai-Heng Ng, Wee-Seng Soh. *MACA-U: A Media Access Protocol for Underwater Acoustic Networks*. 2008.

[43] Peng Xie and Jun-Hong Cui. *R-MAC: An Energy-Efficient MAC Protocol for Underwater Sensor Networks*. 2007.

[44] Vaduvur Bharghavan. *MACAW: A Media Access Protocol for Wireless LAN's*. 1993.

[45] Dr. Todor Cooklev. *Wireless Communications Standards: A Study of IEEE 802.11, 802.15 and 802.16*. 2004.

[46] Jose dos Santos Coelho. *Underwater acoustic networks: evaluation of the impact of media access control on latency in a delay constrained network*. 2005.

[47] S.-Y. R. Li R. Ahlswede, N. Cai and R.W. Yeung. *Network information flow*. 2000.

[48] Christina Fragouli and Emina Soljanin. *Network Coding Fundamentals*. 2007.

[49] R. W. Yeung S.-Y. R. Li and N. Cai. *Linear network Coding*. 2003.

[50] Soung-Chang Liew Shengli Zhang and Patrick P.Lam. *Physical-Layer Network Coding*. 2006.