STATUS OF THESIS

Title of thesis: A NEW ENERGY EFFICIENT ADAPTIVE HYBRID ERROR CORRECTION TECHNIQUE FOR UNDERWATER WIRELESS SENSORS NETWORKS

I AMMAR ELYAS BABIKER HASSAN

hereby allow my thesis to be placed at the Information Resource Center (IRC) of Universiti Teknologi PETRONAS (UTP) with the following conditions:

1. The thesis becomes the property of UTP.

2. The IRC of UTP may make copies of the thesis for academic purposes only.

3. This thesis is classified as

☐ Confidential

☑ Non-confidential

If this thesis is confidential, please state the reason:

____

The contents of the thesis will remain confidential for ___________ years.

Remarks on disclosure:

____

Endorsed by

______________________	______________________
Signature of Author	Signature of Supervisor
Permanent Address:	Name of Supervisor
NIC, Ministry of Information	Dr. Mohamed Nordin Bin Zakaria
and Communication	
Khartoum, Sudan	
Date: ______________	Date: ______________

UNIVERSITI TEKNOLOGI PETRONAS

A NEW ENERGY EFFICIENT ADAPTIVE HYBRID ERROR CORRECTION TECHNIQUE FOR UNDERWATER WIRELESS SENSORS NETWORKS

By

AMMAR ELYAS BABIKER HASSAN

The undersigned certify that they have read, and recommend to the Postgraduate Studies Programme for acceptance this thesis for the fulfillment of the requirements for the degree stated.

Signature: ______________________________

Main Supervisor: Dr. MOHAMED NORDIN BIN ZAKARIA

Signature: ______________________________

Co-Supervisor: Dr. HASSAN YOUSIF AHMED

Signature: ______________________________

Head of Department: Dr. MOHD FADZIL BIN HASSAN

Date: ______________________________

A NEW ENERGY EFFICIENT ADAPTIVE HYBRID ERROR CORRECTION TECHNIQUE FOR UNDERWATER WIRELESS SENSORS NETWORKS

By

AMMAR ELYAS BABIKER HASSAN

A Thesis

Submitted to the Postgraduate Studies Programme
as a Requirement for the Degree of

PhD

INFORMATION TECHNOLOGY

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SRI ISKANDAR

PERAK

SEPTEMBER 2011

DECLARATION OF THESIS

Title of thesis: A NEW ENERGY EFFICIENT ADAPTIVE HYBRID ERROR CORRECTION TECHNIQUE FOR UNDERWATER WIRELESS SENSORS NETWORKS

I AMMAR ELYAS BABIKER HASSAN

hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTP or other institutions.

Witnessed by

____________________	____________________
Signature of Author	Signature of supervisor
Permanent Address:	Name of Supervisor
National Information Center	Dr. Mohamed Nordin Bin Zakaria
Ministry of Communication and	
Information, Khartoum, Sudan	
Date: ____________________	Date: ____________________

To my father; Mother

Brothers and sister

Wife

Kids; Wasan, Mohamed and Leena

friends

ACKNOWLEDGEMENT

I thank God the Almighty, on giving me the strength as opportunity to achieve what had been done in this work. I would like to thank my supervisors Dr. Mohamed Nordin Bin Zakaria, and Dr Hassan Yousif for their help and supervision in conducting this research. I greatly appreciate their care, dedication and constructive criticism. I have truly benefited and enjoy working with them.

I would like to thank the management and authorities of Universiti Teknologi PETRONAS for the generous financial support, providing different administrative and facilities throughout my stay with Computer and Information Science Department.

I would like to express my sincere appreciation to my friends and my country mates for their support during the progress of this work.

I also would like to extend my appreciation to all of my family members for their understanding and inspiration for me to finish this project.

ABSTRACT

Underwater wireless sensors networks find many applications in today's life. However underwater sensors are still relatively expensive. They suffer from short lifetime which is limited by batteries lifetime as it is difficult to recharge or even replace batteries in harsh aquatic medium. When the battery is depleted the sensor is of no use anymore. So designing energy efficient communication protocols is an important issue for underwater sensors networks.

Underwater is characterized by variable channel conditions, whereas underwater sensors are mobile due to water currents leading to variable distances between sensors. This variability in channel conditions and distances between sensors leads to inefficiency in energy consumptions when using fixed type of error correction technique.

In this thesis, a mathematical energy efficiency derivations for the two main error correction techniques (Automatic Repeat request (ARQ) and Forward Error Correction (FEC)) in underwater environment has been done. The results from those derivations show that one technique is more energy efficient than the other below specific distance, where as the other is more energy efficient after this distance. This specific distance is found to be unfixed and varies with the variation in channel conditions and packet size. So using fixed error correction technique for specific distance is not accurate. Simulation has been done which validate the mathematical derivations.

Based on the above derivation results Adaptive Hybrid Error Correction (AHEC) technique which adaptively changes the error correction technique to the technique that gives the highest energy efficiency for the current channel conditions and distances has been proposed. The technique uses an adaptation algorithm which depends on a pre-calculated packet acceptance rate (PAR) ranges look-up table, current PAR, packet length and current error correction technique used. AHEC

technique has been found to have better energy saving compared with the techniques that depend on pure ARQ or FEC only. This saving ranges from 10 to 70 % in energy saving in ARQ case , and 7 to 10 % in energy saving in FEC case depending on current channel conditions and distance .It has also been compared with the technique that uses variable power supply in adaptation (Adaptive Variable Power Supply (AVPS)) and it achieves between 20 to 60 % in energy saving depending on current channel conditions and distance. It has also been compared with Adaptive Redundancy Reliable Transport Protocol (ARRTP), and it achieves between 10 to 80 % in energy saving depending on the current channel conditions and distance.

The adaptation algorithm which depends on PAR has also been applied in adaptation to the ARRTP which originally depends only on inter-node distance in adaptation. PAR take both of distance and channel conditions into consideration. This technique is called PAR-based ARRTP, and the results shows better adaptation than the basic ARRTP in variable channel conditions cases.

AHEC technique has also been applied with the bounded distance routing protocol to minimize the effects of variable channel conditions. Bounded distance routing protocol design depends on choosing specific number of relays between sender and receiver that minimize the total energy consumptions. This specific number of relays varies with the variation in channel conditions. The results show a deviation in number of relays from 6 when fixed error correction technique is used to only 2 when AHEC technique is used with it.

ABSTRAK

Jaringan sensor-sensor tanpa wayar bawah-air mempunyai banyak aplikasi di dalam kehidupan hari ini. Bagaimanapun, sensor-sensor bawah-air masih mahal secara relatif. Sensor-sensor ini dibebani dengan jangka hayat yang pendek kerana had pada jangka hayat bateri yang sukar untuk dicas semula atau di ganti dalam keadaan air yang bergelora. Apabila kehabisan bateri, sensor-sensor ini tidak lagi berguna. Oleh itu, rekabentuk protocol komunikasi yang cekap tenaga adalah isu yang penting untuk jaringan sensor-sensor bawah-air.

Bawah-air dicirikan berdasakan perubahan pada keadaan-keadaan saluran, di mana sensor-sensor bawah-air bergerak-gerak kerana arus air mengarah kepada perubahan jarak antara sensor-sensor. Perubahan pada keadaan saluran dan jarak antara sensor-sensor menyebabkan ketidak-cekapan dalam penggunaan tenaga apabila menggunakan teknik pembetulan ralat jenis tetap.

Di dalam tesis ini, kami telah menjalankan analisis terbitan kecekapan tenaga untuk dua teknik utama pembetulan ralat (Automatic Repeat Request (ARQ) dan Forward Error Correction (FEC)) di dalam persekitaran bawah-air. Keputusan menunjukkan satu teknik adalah lebih cekap tenaga berbanding yang lain dalam jarak yang tertentu, manakala teknik yang lain itu lebih cekap tenaga selepas jarak tersebut. Jarak yang tertentu tersebut didapati tidak tetap dan berubah dengan perubahan pada saluran dan saiz paket. Jadi, menggunakan teknik pembetulan ralat tetap untuk jarak yang tertentu adalah tidak tepat. Analisis simulasi telah dijalankan yang membuktikan Keputusan matematik.

Berdasarkan di atas hasil terbitan Adaptive Hibrid Ralat Pembetulan (AHEC) teknik yang adaptif perubahan teknik pembetulan kesilapan teknik yang memberi kecekapan tenaga tertinggi bagi keadaan saluran dan jarak semasa telah dicadangkan. Teknik menggunakan algoritma penyesuaian yang bergantung kepada

kadar pra-dikira penerimaan paket (PAR) adalah di antara melihat-up table, PAR semasa, panjang paket dan teknik pembetulan kesilapan semasa digunakan. AHEC teknik telah didapati mempunyai penjimatan tenaga yang lebih baik berbanding dengan teknik yang bergantung kepada tulen ARQ atau FEC sahaja. Ini menjimatkan rentang 10-70% penjimatan tenaga dalam hal ARQ, dan 7 hingga 10% penjimatan tenaga dalam hal FEC bergantung kepada keadaan saluran semasa dan jarak. Ia juga telah berbanding dengan teknik yang menggunakan bekalan kuasa yang berubah-ubah dalam penyesuaian (Adaptive Variable Bekalan Kuasa (AVPS)) dan ia mencapai antara 20 hingga 60% penjimatan tenaga bergantung kepada keadaan saluran semasa dan jarak. Ia juga telah dibandingkan dengan Adaptive Redundancy Dipercayai Transport Protocol (ARRTP), dan ia mencapai antara 10 hingga 80% penjimatan tenaga bergantung kepada syarat-syarat saluran semasa dan jarak. Algoritma penyesuaian yang bergantung kepada PAR juga telah digunakan dalam menyesuaikan diri dengan ARRTP yang asalnya hanya bergantung pada jarak antara nod dalam penyesuaian. PAR mengambil kedua-dua jarak dan syarat-syarat saluran kira. Teknik ini dipanggil ARRTP PAR-berasaskan, dan keputusan menunjukkan penyesuaian yang lebih baik daripada ARRTP asas dalam kes saluran syarat-syarat yang berubah-ubah. Teknik AHEC juga telah digunakan dengan jarak disempadani routing protokol untuk mengurangkan kesan keadaan saluran boleh ubah. Jarak disempadani laluan reka bentuk protokol bergantung kepada memilih nombor tertentu geganti antara pengirim dan penerima yang meminimumkan jumlah konsumsi tenaga. Bilangan tertentu lumba berganti-ganti ini berbeza dengan perubahan dalam keadaan saluran. Keputusan menunjukkan penyelewengan dalam beberapa geganti dari 6 apabila teknik pembetulan ralat tetap digunakan untuk hanya 2 apabila teknik AHEC digunakan dengan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATION

ACK	Acknowledgement
ADELIN	Adaptive rELIable traNsport protocol
AHEC	Adaptive Hybrid Error Correction
ARQ	Automatic Repeat reQuest
ARRTP	Adaptive Redundancy Reliable Transport Protocol
AUV	Autonomous Underwater Vehicle
AVPS	Adaptive Variable Power Supply
AWGN	Additive White Gaussian Noise
BCH	Bose, Chandhuri and Hocquenghem
BER	Bit Error Rate
CDMA	Code Division Multiple Access
CRC	Cyclic Redundancy Check
CS	Carrier Sensing
CUT-Lohi	Conservative Unsynchoronous TLohi.
DSP	Digital Signal Processing
DUCS	Distributed Underwater Clustering Scheme
ECC	Error Correcting Codes
ECT	Error Correction Techniques
FAMA	Floor Acquisition Multiple Access
FCS	Frame Check Sequence

FEC	Forward Error Correction
FSK	Frequency Shift Keying
HARQ	Hybrid Automatic Repeat reQuest
IR	Incremental Redundancy
ISI	Inter Symbol Interference
KHz	Kilo Hertz
Km/h	Kilometer Per Hour
Km/s	Kilometer Per Second
LEACH	Low- Energy Adaptive Clustering Hierarchy
MAC	Medium Access Control
NAC	Negative Acknowledgement
PAR	Packet Acceptance Rate
PER	Packet Error Rate
PSK	Phase Shift Keying
ROV	Remotely Operated underwater Vehicles
RSC	Recursive Systematic Convolutional
SR	Selective Repeat
SDRT	Segmented Data Reliable Transport protocol
ST-Lohi	Synchronous TLohi
TCP	Transport Control Protocol
UAC	Underwater Acoustic Communications
UAN	Underwater Acoustic Networks
UUV	Unmanned Undersea Vehicle
UT-Lohi	Unsynchronous TLohi
UWSN	Underwater Wireless Sensor Networks

WSN	Wireless Sensor Networks
VBF	Vector-Based forwarding
VLSI	Very Large Scale Integration
VSAT	Very Small Aperture Terminal

CHAPTER 1

INTRODUCTION

1.1 Introduction

Water covers more than 70% of the planet [1-2], these large areas of water are so rich of natural resources which need to be explored, characterized by disasters to be prevented, and some useful data to be collected [1, 3]. Underwater Wireless Sensors Networks (UWSN) are the means to achieve all those applications.

As in terrestrial sensor networks; in most applications, reliable data transport is demanded in underwater wireless sensors networks [4]. Forward Error Correction (FEC) and Automatic Repeat reQuest (ARQ) are the two main error correction techniques that guarantee the reliability of data transmission in underwater acoustic links , 5-6].

To design a good reliable data transport protocol, a traditional concern is the energy efficiency issue, since many applications require nodes to operate underwater for long periods without recharging their batteries. It is also hard to recharge or replace batteries in most aquatic environments [4, 7].

Underwater channels are characterized by variable channel conditions, while underwater sensors are characterized by variable distances due to water currents. This Variability in channel conditions and distances leads to energy inefficient transmission.

The main purpose of this research is to propose an energy efficient error correction technique for underwater wireless sensor networks. This technique is based on a mathematical derivation and simulation for the energy efficiencies of the main error correction techniques in underwater environment. Based on the results of this derivation an Adaptive Hybrid Error Correction (AHEC) technique is proposed. After that AHEC technique is applied to solve variable channel conditions problem in some communications protocols. This chapter describes an overview about UWSNs, Underwater Acoustic Communications (UAC), and Error Correction Techniques (ECT). It outlines the problem statements, research objectives, methodology, scope of works, contribution and novelty and thesis overview.

1.2 Underwater Wireless Sensors Networks

Sensors are used in underwater instead of manned exploration which is difficult due to water pressure, unpredictable activities, and large size of underwater areas. Sensors are deployed locally instead of remote exploration which is difficult in underwater conditions. Without networking data collected by sensors are assembled by recovering instruments which has the following disadvantages [8]:

* No real time monitoring: the recorded data cannot be accessed until recovering instruments which may take months.

* It is impossible to detect failure until the instrument is recovered.

* No ability to reconfigure instruments during the mission.

* Limited storage capacity: monitoring mission is limited by the capacity of the storage device.

Interconnecting those sensors in a wireless manner solves those problems; add the capability of self-configuration, real time monitoring, instantaneous failure detection and limited storage capacity needed.

As in Figure1.1, underwater sensors devices are usually consist of a main controller/CPU, sensor, memory, power supply, acoustic modem and interface circuitry. Data are collected by sensors, stored on onboard memory, processed by the controller, and transmitted to the network by the acoustic modem. All those devices are power supplied by the power supply [4].

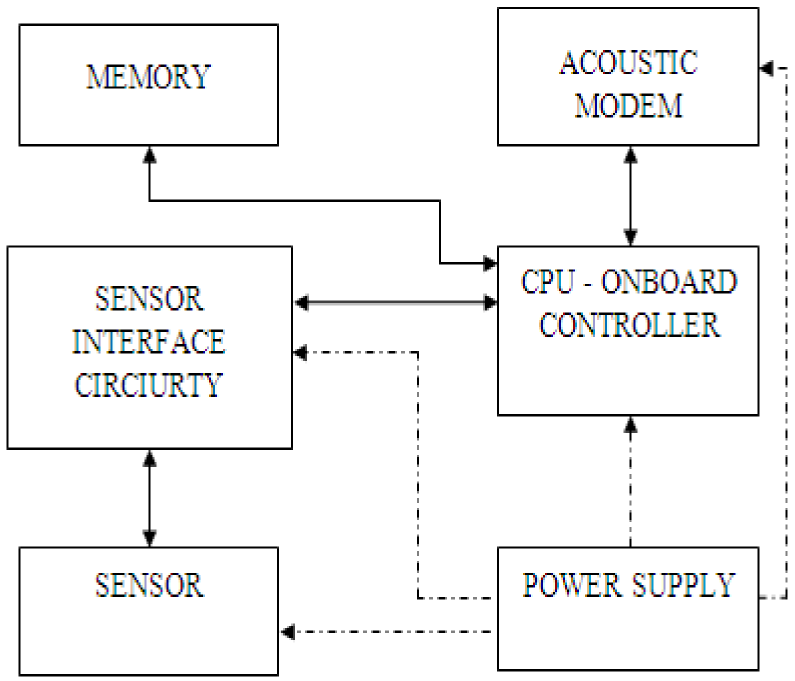


Figure 0.1: Internal Construction of Underwater Sensor

1.3 Underwater Acoustic Communication

Acoustic is the typical technology in underwater communications as electromagnetic waves do not propagate well at high frequencies [5-7]. Electromagnetic wave propagates at long distances only at low frequencies (30- 300 Hz) [8-9], which need large antenna and high transmission power. Optical waves are also not suitable in underwater as it is affected by scattering and require high precision in pointing laser beams.

In general Underwater Acoustic Networks (UAN) are characterized by [8-11] :

* Limited bandwidth which is strongly dependent on distances, frequencies and channel conditions.

* Path loss: it is due to two factors; the first one is the spreading of sound energy as wave propagates forward. The spreading is either spherically where the wave propagates in all direction as in deep water, or cylindrically where the wave is limited by the top and bottom surface of the water as in shallow water. Spreading

losses is function of distances only. The other factor is attenuation which is the absorption of energy due to conversion into heat. This attenuation is mainly function of distance and frequency and partially caused by scattering, reflection and refraction of acoustic waves in ocean surface and bottom as in Figure 1.2 [7].

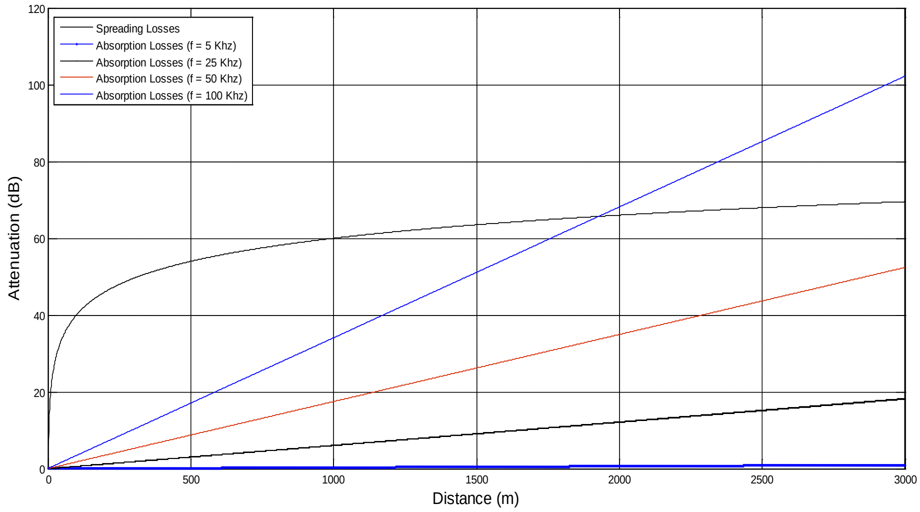


Figure 0.2: Acoustic Signal Attenuation versus Distance [7]

* Noise: there are two types of noise source; the first one is made by human machinery and shipping activities. The other source of noise is ambient noise caused by movement of water currents, storms, wind and thermal noise.

* Multipath: it causes Inter Symbol Interference (ISI) which cause severe degradation of the acoustic communication signal. This multipath is clearer in horizontal link than in vertical link.

* High delay and delay variance: acoustic waves are characterized by a very low propagation speed. This propagation speed is not fixed in underwater and varies with the variation of temperature, depth, and salinity which cause delay variations

1.4 Error Correction Techniques

The above characteristics of underwater acoustic channel introduce challenges in designing networks protocols. Protocol designed for terrestrial networks cannot be directly applied in underwater [12-14]. Among networking protocols transport protocols are especially different due to the high Bit Error Rate (BER) and large propagation delay. Generally there are two approaches for reliable data transport; the first one is the end to end approach, which is found to be unsuitable for Wireless Sensors Networks (WSN). In underwater end to end approach is more unsuitable due to the large propagation delay which encounters management difficulties, and the high error rate which makes the probability of successfully transmitting data from end to end approach zero [15-16]. The second approach is the hop by hop approach which achieves reliability either by retransmitting the error packet using some kind of ARQ, or by redundancy which use some kinds of FEC techniques. Conventional ARQ is found to be unsuitable for underwater due to the large propagation delay. Pipelined ARQ protocols, such as Go-Back-N and Selective Repeat (SR) can significantly improve channel utilization. FEC consumes more energy in transmitting redundancy which is not necessary all the times [17].

Wireless sensors nodes are usually equipped with small batteries which can afford only small capacity [18-21]. It is also difficult to replace or recharge batteries due to the difficulties in recollecting spaced and large number of sensors. In underwater this is more difficult due to the harsh aquatic medium and more sparely distributions of sensors, so an energy efficient error correction technique is required.

1.5 Problem Statement

As UWSNs applications grown rapidly in the last two decades, reliable and efficient data communications between sensors are demanded. Data reliability is usually attained by using error correction techniques, whereas energy efficiency is most important issues in UWSNs.

Using acoustic waves in underwater instead of radio waves for terrestrials impose additional problems to the reliable data transfer for UWSNs. The acoustic propagation speed in underwater is 1.5×10^3meter per second (m/s) which is too lower compared with speed of 3×10^8(m/s) for radio waves [6, 22]. The path losses due to spreading and absorption, noise due to wind, shipping, turbulence and thermal effects, signal reflection and refraction, and Doppler spread. All those factors cause high error probability which needs some kind of reliability. Generally there are two kinds of reliability solutions; end to end solution like Transport Control Protocol (TCP), and this have been shown to be unsuitable for terrestrial WSNs [3, 22], for underwater this is justified more by the large propagation delay which makes it difficult to manage data transmission from end to end. Also the high error probability makes the probability of successfully transmitting data from end to end approach zero. The other kind of reliability solutions is hop to hop solution, which is achieved either by feedback or redundancy. Conventional ARQ which is a feedback based technique causes very low channel utilization due to the long propagation delay of acoustic waves, whereas forward error correction technique (redundancy based) introduces additional computation and packet overhead irrespective of channel conditions, and this consumes more energy. So an error correction technique which makes a tradeoff between channel utilization and energy consumption is needed for UWSNs.

Regarding energy efficiency issue, sensors networks are number one application cited in this context [23]. This is due to two reasons; the first one is that the sensor nodes have small batteries which can only afford small capacities. The second reason is that it is so difficult to recharge or replace batteries for scattered and large number of sensors. In underwater this is more difficult due to the harsh aquatic medium where it is not easy to access nodes position when it is depleted of energy, so the node will die and disconnect from the network. Also underwater sensors are very expensive compared with terrestrials one, so increasing their lifetime by reducing power consumption is an important issues which have been addressed in many aspects [18]. Thus energy efficient error correction techniques for UWSNs are very important.

In typical underwater conditions, the majority of sensor nodes are mobile, this mobility is due to water current which has speed of 3- 6Kilometer Per Hour (k/h)[6-7], and due to other underwater activities; this mobility has no specific direction, so it makes distances between sensor nodes unfixed and varying with time. Underwater is also a dynamic and complicated medium; it depends on environmental conditions (proximity, roughness, motion of scattering surfaces, speed of sound profile), positioning of nodes and ambient noise. All those factors change rapidly and continuously with time. For this variable distances between nodes and variable channel conditions, using one type of error corrections is energy inefficient, so different error correction techniques are required for variable distances and variable channel conditions.

1.6 Objectives

Energy efficiency is the main efficient factor for underwater wireless sensors networks, whereas error correction is main tools for reliable communications. The main objective of this research is to develop an efficient energy error correction technique for underwater wireless sensors networks. This objective can be summarized as follows:

* To do mathematical energy efficiency derivation for the main error correction techniques in underwater environments. Simulation study will be done to validate the mathematical derivation results.

* To develop an energy efficient error correction technique based on the results of the derivation done above.

* To apply this technique to reduce the effects of variable channel conditions on choosing the optimum number of relays in designing energy efficient routing algorithm in underwater wireless sensors networks, and to apply our new adaptation algorithm idea in ARRTP instead of the inter-node distance based-ARRTP.

1.7 Methodology

This section provides all the sequence steps that have been followed in order to satisfy the research objectives. In general this research can be divided into three stages.

In the first stage, a mathematical derivation for the two main error correction techniques (ARQ and FEC) energy efficiencies is done in underwater environment. Variable channel conditions are achieved using variable wind speeds and variable shipping factors. Whereas variable distances are used from half to double the designed distances for the modem used. A simulation study using MATLAB is done to validate the mathematical derivation results.

In the second section, an Adaptive Hybrid Error Correction (AHEC) technique is proposed. This technique is a hybrid of ARQ and FEC using convolutional codes with different code rates. Different code rates are achieved using puncturing techniques. An adaptation algorithm is developed which gives maximum energy efficiency in a wide range of distances and variable channel conditions. This adaptation algorithm is based on current PAR, current error correction techniques used, and a pre-calculated PAR ranges look-up table. Based on this adaptation algorithm the receiver determines which error correction technique is most energy efficient for the current conditions and distances and sends this in a feedback to the sender. The proposed technique is compared with the pure ARQ, pure FEC, Adaptive Variable Power Supply (AVPS) and Adaptive Redundancy Reliable Transport Protocol (ARRTP)/Adaptive rELIable traNsport protocol (ADELIN) in terms of energy efficiency and packet probability of success (PAR) in a wide range of distances and variable channel conditions to validate it is effectiveness..

In the third section, the proposed technique discussed in section two is applied to solve the problem of determining the optimum number of relays between nodes in a bounded distance routing protocol. This optimum number of relays is only suitable for a specific channel conditions. If the channel conditions change, it will not be the optimum number anymore. Applying our proposed technique as the error correction technique will solve this problem. We shall also apply our adaptation algorithm idea which accounts for both distance and channel conditions variations in ARRTP instead of only inter-node distance in which the protocol depends on in adaptation.

1.8 Scope of Works

The scope of this research is about energy efficiency of error correction techniques. We focus on solving the effect of variable underwater channel conditions and variable distances between sensors on energy efficiencies for the error correction techniques. For energy efficiency it depends on two factor; the first one is the packet format of the error correction technique used, and the second one is the PAR. Whereas for PAR; it depends on two factors also, the first one is the BER, and the second one is packet length. For BER, it depends on the type of error correction technique used and the SNR. For SNR, it depends on transmit power, distance between nodes and channel conditions. Based on this derivation a new adaptive hybrid error correction technique is proposed to give maximum energy efficiency in a wide range of distances and channel conditions. Adaptation is mainly based on current PAR, current error correction technique used and a pre-calculated PAR ranges look-up table.

1.9 Contribution and Novelty

In this thesis a mathematical derivation for energy efficiencies of the two main error correction techniques in underwater environment has been done. The impact of channel conditions, distances between nodes, and packet size of each error correction technique were studied. In a good channel conditions and short distances retransmission technique (ARQ) is more energy efficient than redundancy based (FEC) error correction techniques, while in bad channel conditions and long distances the reverse is true. A simulation study is done which verified the mathematical derivation study.

Based on the mathematical derivation and simulation for the energy efficiencies derivation done above, a new Adaptive Hybrid Error Correction (AHEC) technique for UWSN has been developed. The technique overcome the problem of variable channel conditions and variable distances between sensors by adaptively changes the error correction techniques from pure ARQ in good channel conditions and short distances to a hybrid of ARQ and FEC with variable rates in a bad channel conditions and long distances. The technique depends on an adaptation algorithm which periodically calculates the current Packet Acceptance Rate (PAR) which is a function of current bit error rate and packet size, current error correction technique used, and a pre-calculated PAR range look-up table which depends on the modem parameters and the packet format for each error correction technique. Based on this adaptation algorithm the receiver determines which error correction technique is most suitable for the current channel conditions and distance, and then sends a 3 bit feedback to the sender stating which error correction technique to use. In this technique PAR is taken as a measure of channel conditions and distances between nodes.

Then, we apply the proposed AHEC technique to solve the problem of determining the optimum number of relays between nodes which gives energy efficient routing technique in underwater. The optimum number of relays varies with the variation of channel conditions, so it is difficult to determine the number of relays specifically needed. Applying our proposed AHEC technique solves this problem and gives minimum energy consumptions irrespective of the channel conditions variations. We also apply our adaptation algorithm for ARRTP instead of using inter-node distance in adaptation.

1.10 Thesis Overview

This thesis contains six chapters. Chapter one is an introductory chapter which gives a background about UWSNs, UACs, and ECTs. Then the problem is stated, and the objectives are laid down. Contributions are detailed and methodology is mentioned. Scope of work is defined and at last thesis layout is presented.

In chapter 2, UWSNs applications are given in details, then UACs theory is given and compared with terrestrial radio waves networks, error correction techniques are presented, the theory of convolutional coding is presented; puncturing technique which is used as a way of changing the code rate is explained in details, then related work which was done in this field is presented.

In chapter 3, Underwater channel model is presented, and a mathematical derivations for the energy efficiencies of both ARQ and FEC is laid out. A simulation procedure to validate the mathematical derivations results is laid out. Results for the mathematical and simulations analysis are given, and at last the chapter is concluded.

In chapter 4, and based on chapter three results, an AHEC technique is proposed. The proposed AHEC technique energy efficiency results are presented and compared with the pure ARQ, FEC, Adaptive Variable Power Supply (AVPS), ARRTP previously known as ADELIN in a variable channel conditions and variable distances. In chapter 5, AHEC technique and its adaptation algorithm has been applied to solve variable channel conditions effects on bounded distance routing protocol and ARRTP.

Chapter 6 present the conclusion for this work, and some recommendations for future research direction that can be extended based on this research work.

Chapter 2

LITERATURE REVIEW

2.1 Background

The idea of transmitting information underwater is dated back to the time of Leonardo Da Vinci, who used a long tube submerged underwater to detect a distant ship [9]. By the Second World War, underwater communication began to develop for mil itary reasons. An underwater telephone was developed in 1945 in the United States for communicating with submarines. This telephone uses an amplitude modulation in a frequency range of 8-11 KHz [4], and sends acoustic signals over several kilometers distances. With the development of Very Large Scale Integration (VLSI) technology, a new generation of underwater acoustic communication system began to appear.

In the last few years, Underwater Acoustic Communication (UAC) systems have developed quickly in terms of operation range and data throughput. The scope of applications continues to grow, the need for real time communication in commercial and military arises, and underwater network emerged.

Underwater acoustic channel differs from terrestrial networks in many aspects; the main difference is that it uses acoustic waves instead of electromagnetic waves. This difference is the reason for large propagation delay, half-duplex communications, and low bandwidth capacity. Moreover underwater acoustic channel are affected by high path loss, noise, multipath and Doppler effects. All those factors cause high error probability. For such situations reliable and efficient communication data transport is needed [4].

Reliability problem in wireless sensor networks is not a new issue, it has been addressed by many existing work for terrestrial wireless networks [22-23], but as the radio communication is replaced by acoustic communications, which has low propagation speed, limited transmission range and frequency dependent bandwidth, those techniques cannot be directly applied to Underwater Wireless Sensor Networks (UWSNs).

For reliability there are generally two approaches:

1. End-to-end approach which is not suitable in underwater due to the large propagation delay and high error probability. Long propagation delay makes it so difficult to manage data transmissions in a timely manner, and high error probability makes it impossible to successfully transmit data from end to end.

2. Hop-to-hop approach, which is suitable for underwater communications.

In general Automatic Repeat request (ARQ) and Forward Error Correction (FEC) are the two main error correction techniques that guarantee reliability in underwater environment [5], and most of the error correction techniques proposed in underwater lay in some way under those two techniques. Conventional ARQ which is a feedback-based protocol is not suitable for underwater acoustic communication, and this is mainly due to the long propagation delay and high error probability. Improved versions of ARQ like selective repeat and Go-Back-N protocols solve this problem especially when the error rate is not high. FEC which is redundancy-based protocols suffer from energy wastage due to the need to add parity, which is not always needed especially in a good channel conditions.

For efficiency; energy is the most important issue in a Wireless Sensor Networks (WSNs). It is difficult to recharge or even replace batteries for a large number and sparsely distributed sensors. This condition is even worse in underwater due to the harsh aquatic medium [1, 15].

In [24], an energy efficiency derivations to ARQ and FEC in underwater environment has been done. Energy efficiency of both techniques depends on channel conditions, transmission power, distance, and packet size. ARQ is found to be more energy efficient in some cases and FEC is more efficient in others. In [25] a propagation model to calculate the signal to noise ratio for underwater acoustic channel was designed and implemented. In [26] modulation and encoding techniques for underwater communication system were studied and it was found that 8-PSK is the best modulation for underwater systems. Whereas convolution coding is found to achieves better coding gain compared to other coding techniques, so it is the modulation and encoding techniques used in this work. In [17] an optimization metric for energy efficiency was proposed, and it was used in [24, 27] for energy efficiency calculations. In [27] Tian et el. have proven that energy efficiency of ARQ techniques is independent of retransmission attempts, they compared ARQ and FEC techniques for terrestrials wireless sensor networks in terms of energy efficiency.

In this chapter, UWSNs applications are given in detail, underwater acoustic propagation features are declared and a comparison between underwater acoustic communications and terrestrial networks is presented. Error correction techniques are discussed in details, and at last ARQ, FEC and energy efficiency related works done in UAC are reviewed

2.2 Underwater Wireless Sensor Networks Applications [8, 28-31]

Underwater networks of sensors enable exploration, observation and prediction of the ocean. Using sensors which are networked in a wireless manner made a potential range of applications viable. Before this underwater sensors record data during monitoring mission and then recovered them, but this has many disadvantages as follows [4, 32]:

- No real time monitoring: data cannot be accessed until sensors are recovered, which may happened after several months, which is not suitable for most monitoring applications.
- No failure detection: if the system fails, or some configurations are missed, it will not be possible to detect it until the system is recovered, which will lead to the complete failure of the mission.

- No interaction: Interaction between the main control system and the monitoring system is not possible. So no adaptation for specific events or tuning is possible.
- Limited storage capacity: large capacity is needed to store the recorded data as the monitoring mission usually takes long time.

UWSNs applications can be detailed as follows:

2.2.1 Seismic Monitoring [29]

Seismic imaging for offshore oil field are carried out by a ship with a large arrays of hydrophones on the surface. Such technique is very costy, so seismic survey is carried out rarely. In contradiction to that, sensor networks are relatively cheap and can be deployed for long time. One of the most important application of underwater wireless sensor networks is seismic monitoring for oil extraction from underwater field which need frequent and continuous monitoring due to the variation in reservoir over time. Using sensors raises many challenges ranging from extracting data reliably and from distributed sensors, to the localization problems, energy management to increase sensors lifetime, and not ending with accurate data reporting.

2.2.2 Oceanographic Real-Time Data Collection [28, 30]

Sensors are used to monitor, record and capture many oceanographic variables such as ocean currents, winds, salinity, temperature, pressure, and detecting climate changes, and understanding the effects of human activities. The traditional way to do those activities is to store the data in a non-volatile memory, which needs to be retrieved periodically to download the data. Sensors retrieval is an expensive exercise due to the high costs of mobilizing the vessel and dive team. May take more than several weeks in which the sensor may be lost, damaged or become faulty, which leads to loss of valuable data which cannot be discovered until the sensors are retrieved.

For those reasons there is a pressing need in the industry for real-time data. However using a cable to transmit the data to surface is unreliable and exceedingly expensive to install and maintain.

2.2.3 AUV/UUV Communications [28, 33-34]

An Autonomous Underwater Vehicle (AUV) or Unmanned Undersea Vehicles (UUV) is a robot that driven through the water by a propulsion system, and controlled by onboard computer and it can function without tethers, cables, or remote control.

As underwater condition is not suitable for human exploration due to high water pressure, unpredictable underwater activities, and vast size of water area, AUVs/UUVs are used to carry out most underwater tasks, especially those that are too dangerous or impractical for manned or tethered underwater vehicles. They are used in gather data from underwater instruments, make maps of the seafloor before subsea infrastructure is built and for various maintenance tasks in oil and gas industry, they are also used in surveillance, intelligence gathering, and mine warfare. Using multiple vehicles in surveys increases productivity and insuring temporal and spatial data collected, but as AUVs do not have link with the deploying platform, a reliable wireless communications link is the solution. This communications link is used to monitor the AUV, as well as send commands and receive data and information.

2.2.4 Pipeline and Marine Cable Monitoring [28]

In subsea oil and gas production fields, pipelines and large tankers are an essential part of transporting the hydrocarbons and oils product to downstream processes. Problems arise in these pipelines and tankers because of corrosion, structural failure and sludge formation due to hydrocarbon chemical processes. Those problems have great effects on production and increase revenue loss, as well as maintenance costs. Furthermore hydrocarbon leaks into the ocean and oil spills have a great effect on environmental health to be avoided. The main contributor to oil pollution in the oceans (around 45 %) is operational discharge from tankers [2]. Minimizing these problems by forecasting and timely action is very important to the industry. Constant pipeline monitoring provides the data necessary to make the correct decisions.

2.2.5 Equipment Wireless Monitoring and Control [28-29]

Wireless monitoring and control is useful in a range of industries. In the oil and gas industry, valves and actuators need to be monitored and controlled at the surface. It will be so easy to remotely control and operate equipment if they are connected with acoustic wireless networks. Nowadays cables are used for this task. However using cables is associated with many problems ranging from high deployment cost, inflexibility in deployment, and many connectors and junctions are needed which are well known to be weak points in the signal chain. In contrast, underwater wireless links is supposed to be less costy and provide much more flexibility.

2.2.6 Submersible Retrieval Buoys [28, 35-36]

A submersible retrieval buoy is used as a submersible marine marker and retrieval system. It is attached at a predetermined location. When it needs to be recovered, the buoy's release can be triggered by remote control at the surface. The buoy then ascends, enabling the location to be visibly marked or the asset to be recovered.

The applications of the submersible retrieval buoy are as follows:

Replace conventional surface (non-submersible) buoys, which, are eyesores and particularly under low visibility conditions, become hazardous to marine navigation. In addition, with the submersible buoy, underwater assets can be hidden so that they are not vandalized or stolen.

Instead of deploying diving personnel, when needed, a submerged object can be retrieved via its connecting tether to the buoy.

2.2.7 River and Sea Seepage Monitoring [28]

Water management authorities use many sensors to measure various underwater parameters. Numerous cables are used to reticulate the sensor data to the surface. The cabled solution was found to be impractical and costly due to cable failure, and high maintenance costs. These issues can be overcome by using an underwater wireless communications system

2.2.8 Diver Location and Positioning [28, 37]

Diving which is a growing activity faced with the problem of determining divers position accurately. Most divers carry compasses which only approximate position. This positioning is even worse in case of adverse conditions like poor visibility and strong currents.

Nowadays there is no effective communications for diver if they are in dangerous or serious trouble. They only relay on hand signage and compasses which is a limited form of visual communication and usually fails in adverse conditions cases.

Diving positioning problem can be solved by using effective underwater communication system. By communicating with divers and monitor his position, it is easy to help him and alert others if he is in trouble or need assistance.

2.2.9 Underwater Asset Monitoring and Location Based Services [28]

Underwater assets are often costly items. For example, in oceanographic applications, several expensive instruments are deployed in a single package. Similarly in oil and gas applications, numerous instrumentation and other mobile devices such as Remotely Operated underwater Vehicles (ROVs) are used routinely.

Their cost of deployment and replacement in case of failure is also high. Replacement also takes time which has high impact on operation. Thus, the ability to monitor and locate these packages is important, so that the integrity of the package can be guaranteed and the location can be tracked for later retrieval if required.

2.3 Basics of Acoustic Propagation

There are many factors that characterized underwater acoustic propagation, ranging from path loss, noise, multipath, Doppler spread, and high and variable propagation delay. Those factors are the main reason for the variability in space and time of the acoustic channel, the limitation of bandwidth and variability of it with distance and frequency. Bandwidth varies from a few Kilo Hertz (KHz) in a long range system which operates over several tens of kilometers to more than hundred KHz in a short-range system that operates over several tens of meters. UAC system are classified according to their communication distances as very long, long, medium, short and very short systems as in Table 2-1below [8, 38]:

Table 2.1: Underwater Acoustic Communication System Ranges

	Range (Km)	Bandwidth (KHz)
Very long	1000	<1
Long	10-1000	2-5
Medium	1-10	=10
Short	0.1 -1	20-50
Very short	<0.1	>100

Below are the factors that characterize underwater acoustic propagation [1, 39-40]:

- Path loss: there are two main sources for path losses for underwater acoustic propagation which are:

  * Attenuation: it is mainly due to the conversion of acoustic energy into heat which known as absorption loss. In underwater absorption loss of acoustic signals are strongly increases with frequencies as in Figure 1.2. which shows the absorption losses at four frequencies that span the acoustic frequency band used in underwater communication systems.

It is also caused by scattering and reverberation (on rough ocean surface and bottom), refraction, and dispersion (due to the displacement of the reflection point caused by wind on the surface).

* Spreading: this is the loss due to the expansion of the amount of signal energy over a large area as the wave propagates forward. In short distance this area can be represented by a sphere, so the energy decays at a rate equal to the square of the distance. At long distance the propagation area will be like a cylinder due to the bounding by the surface and sea floor, so the decay will be proportional the distance. So the type of propagation is either spherical (Omni-directional point source), or cylindrical (horizontal radiation only).

At short ranges the spherical loss is much more than absorption loss. It is also clear from Figure 1.2 that absorption loss at 100 KHz exceeds that at 25 KHz by about 15 dBs, whereas at longer distance absorption loss dominates spreading losses.

- Noise: there are two kind of noise:

  * Man made noise: it is caused by man activities like man machinery noise (pumps, reduction gears, etc), shipping activities.

  * Ambient noise: and this is caused by the movement of water which includes tides, current, storms, wind, and rain. It is also caused by biological phenomena. Ambient noise depends mainly on frequency, so it must be considered when selecting frequency band in underwater communications systems [7].

- Multipath: In most environments ocean can be modeled as a wave guide for communication signals. This waveguide is characterized by a reflecting surface and ocean bottom and a variant sound speed. Reflection, refraction and diffraction will occur with those surfaces resulting in multiple propagation paths from the source to the receiver. This multipath with a varying impulse response leads to Inter Symbol Interference (ISI), this ISI cause severe degradation in the acoustic signal. It depends on the channel configuration;

horizontal channel is characterized by long multipath spreads compared with vertical one.

- High delay and delay variance: underwater acoustic signal speed is just 1500 m/s, which is lower than electromagnetic signal by more than 5 orders of magnitude, so the propagation delay is too large (about 0.67s/km). This propagation delay is varying due to variable channel conditions. This variable propagations delay makes it difficult to estimate the round trip time, and time synchronization; a key parameters in many common communication protocols.

- Doppler spread: it is significant in underwater acoustic channel, and cause degradation in the performance of digital communications. It generates simple frequency translation which can be easily compensated at the receiver, and a continuous spreading of frequencies that constitutes a non-shifted signal which is more difficult to be compensated. The Doppler spread can be ignored if the bandwidth of the Doppler spread (B) multiplied by the symbol duration of the signal (T) is less than unity, otherwise the channel is said to be overspread.

Most of the factors mentioned above are caused by the chemical-physical properties of the sea water such as temperature, salinity and density, which are varied with space and time.

2.4 Comparison between Underwater Acoustic Networks and Terrestrials Networks

There are big differences between UANs and terrestrials networks: this differences can classified into three fold:

1. Regarding Communication System Aspects [41-42]:
    a. In terrestrial networks, electromagnetic waves and optical signals are used. In underwater electromagnetic wave can only travel a short distances due attenuation and absorptions effects in underwater environment. At long distances radio waves propagate through conductive seawater at only low frequencies (30-300 Hz), which require large antenna and high

transmission power. It is found that the absorption of electromagnetic energy in sea water is about $45\sqrt{f}$ dB per kilometer (f in Hertz); whereas the absorption of acoustic signal is about three orders of magnitude lower [38, 41]. Optical signal suffers from scattering and absorption in underwater [38]. In addition to that optical signal also needs high precision in pointing the narrow laser beams. Thus it is appear that acoustic is the only type of signals that works in underwater.

Acoustic features which are different from radio waves make the protocols which are designed for terrestrial sensor networks unsuitable for UWSNs.

b. No internationally accepted standards for underwater communication yet.

2. Regarding Underwater Channel [41]:

Underwater acoustic channel is different from terrestrial radio channels in many aspects, including:

a. Very limited data rates: the available bandwidth of underwater acoustic channel is limited and strongly depends on transmission range and frequency. The longer the communication distances, the lower the available bandwidth of the underwater acoustic channel.

b. Transmission Distance and Bandwidth: for typical terrestrial radio environments, shorter transmission distances lead to either the ability to use lower power (due to less signal attenuation), or the ability to use higher bit rates (due to a higher signal-to-noise ratio), but the bandwidth available remains constant. For the underwater acoustic environment, however, not only do these two effects exist but the bandwidth available increases as the distance decreases, a fundamental difference between acoustic channels and radio channels. This is due to the fact that both signal propagation and noise in underwater environments show a significant dependence on frequency [38, 42-43].

c. Long propagation delay: Transmission speed of acoustic signal is 1500 m/s, which is five orders of magnitude less than that of electromagnetic signal (3×10^8 m/s).Additionally, the propagation speed is dependent on the depth of the nodes, temperature and salinity of water. So propagation delay is too long in an underwater acoustic signal, and this has profound implications on localization, time synchronization and many protocol issues.

d. High and variable error probability [41]: High fluctuation nature of sea channel causes high bit error rate. Underwater acoustic channel is also affected by path loss caused by spreading and absorption, noise which comes from many sources like water current, rain, wind, seismic and volcanic activities or biological phenomena [4]. Signal reflection and refraction from the surface and seabed, topographic sources like hills and hollows are some kinds of error sources.

In brief, underwater channels are characterized by large and variable propagation delay, high and variable bit error rate, limited bandwidth which is determined by both distance and frequency of acoustic signal.

3. Regarding Nodes:

The main differences between terrestrials and underwater nodes are:

a. Underwater systems are more expensive than terrestrial one [44]. There are several components to the cost of those systems, including fabrication, deployment and recovery. Regarding fabrication, the acoustic modem must be rugged with pressure housing. In addition to the sensor cost, a supporting hardware is also needed which drive the cost up. The high cost of underwater systems is not only due to the rugged construction required to survive underwater conditions, but also to the small quantities fabricated. Deployment is also costly due to the cost of ships used in deployment, whereas recovery is more expensive due to the harm underwater conditions and the sparsely deployed system.

b. Whereas terrestrial sensor networks are usually dense deployed, continuously connected coverage using inexpensive fixed or static node, underwater nodes are usually sparsely deployed due to the cost and deployment challenges and mobile due to water current and other underwater activities and sparsely deployed [45-46]. In general underwater nodes move at speed of 2-3 knots (3-6 kilometers per hour) [47], and this makes any protocol that does not take this mobility into account fails when deployed underwater.

c. Higher power is needed in underwater due to long distances and more complex signal processing. UWSNs are characterized by severely energy-limited nodes. They have small batteries which cannot afford much energy to complete tasks. It is also difficult to recharge or replace batteries once it is depleted of power [48]. Also transmission takes a large amount of energy compared to receiving, so minimum redundant bit or packets must be used in underwater communications [1].

d. Large capacity memory maybe needed in underwater to do some data cashing as the underwater channel maybe intermittent [30].

2.5 Error Correction Techniques

Data communication over the data networks comprising of various carriers like repeater, hub, gateways etc is prone to errors because of reasons such as traffic congestion, delay, network components getting down, packet drop, non receipt of acknowledgements and signaling factors. ARQ and FEC are strategies to combat error. ARQ which proposes retransmission [49], are widely used in data communications system for error control as they are simple and provide high reliability, however the throughput is not constant and decreases rapidly in high bit error rate cases[50]. In FEC, redundancy is added for error prevention. Redundant bits are encapsulated with data bits to form encoded information. However this increases the payload for transmission. Addition of redundant bit is known as channel coding. Error Correcting Codes (ECC) (block or convolutional) are used for this purpose. FEC codes have constant throughput which is equal to the code rate, however it has the drawback of using parity bit irrespective of the existing of errors or not. Reliability can be enhanced by combining FEC and ARQ as Hybrid-ARQ (HARQ).

2.5.1 Automatic Repeat Request

Automatic Repeat request (ARQ), is an error correction technique in data transmission to achieve reliable communications. It uses error detection codes, acknowledgement and/or negative acknowledgement messages, and time out to retransmit error packet. The basic idea is that the transmitter after sending the packet waits for specific time (time out) to receive an acknowledgement. If it receives positive Acknowledgement (ACK) that the packet has been received correctly, it sends the next packet; if it receives Negative Acknowledge (NAC) or timed out before receiving any acknowledgement then it retransmits the same packet until the packet received correctly or specific number of retransmission is reached. ARQ can be represented diagrammatically as in Figure 2.1 [50-52].

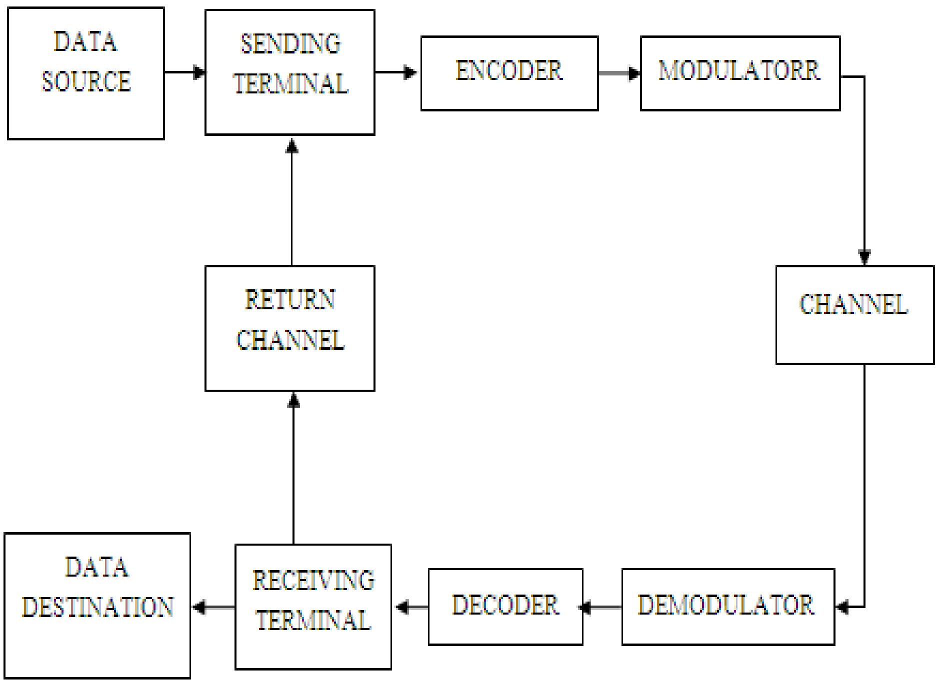


Figure 2.1: ARQ System

There are several types of ARQ protocols, the most famous are:

2.5.1.1 Stop and Wait (S&W) ARQ Protocol [49]

It is simplest type ARQ method; the sender sends one packet at a time and wait for an acknowledgement from the receiver as shown in Figure2.2 , if it receives positive acknowledgment then it transmits the next packet. If it receives negative acknowledgement or does not receive acknowledgement for specific time (time out), then it retransmits the same packet again. There is a maximum number of retransmission after which the packet will be dropped.

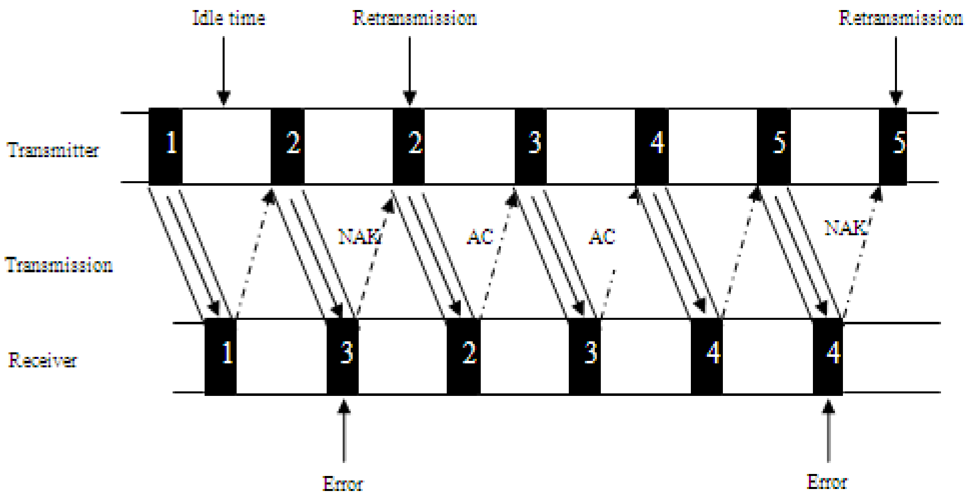


Figure 2.2: Stop-and-Wait ARQ

There are many problems associated with this protocol:

a. Redundancy check is needed to detect error occurrence.
b. If the acknowledgement message is lost, then the same packet will be sent again, and the receiver will confuse about this message, is it a new one or a duplicate of the previous message.
c. In underwater which is a high latency medium, the time may be out before the acknowledgment is received, then the same packet will be transmitted again, and in this case two packets will be received by the receiver and also two acknowledgements will be accepted by the sender which makes confusion to both sender and receiver.

To solve such problems a 1-bit sequence number is added to the packet, this sequence number alternate between 0 and 1 in a subsequent packets. If positive acknowledgement is received then the sequence number is changed, if negative or no acknowledgement received then the number will be the same to indicate that this is the same packet retransmitted again.

Stop and wait is time inefficient as the acknowledgment takes the same time as the packet transmitted. In underwater there is also the special problem of long propagation time of acoustic communication. So this type of error correction is not suitable for underwater. To solve such problem one can send more than one packet at a time with large sequence number as in the following two protocols.

2.5.1.2 Go-Back-N ARQ [49, 52]

It is special type of ARQ, in which the sender sends N packets continuously and receives one acknowledgment packet as in Figure 2.3. The receiver expect the packet with the next sequence number and ignore any other frame, whether it is a duplicate of a packet it has already received or a future packet past the packet it is waiting for. The receiver then sends an acknowledgement carrying the sequence number of the expecting packet and the sender will send another N packets starting from the packet with the last sequence number acknowledged. Go-back-N ARQ is more efficient in utilizing the connection than stop and wait protocol, but inefficient in energy consumption as packets maybe send multiple of times. If any packet or acknowledgement is lost or damaged, then that packet and all the following packets (even if received correctly) will be resent. And as a result of that all errors free but out of sequence packets of previous transmission has the chance to be in error in the following retransmission, and due to this a severe deterioration in throughput performance and waste of energy will happen especially in the case of high bit error rate as in underwater sensor networks.

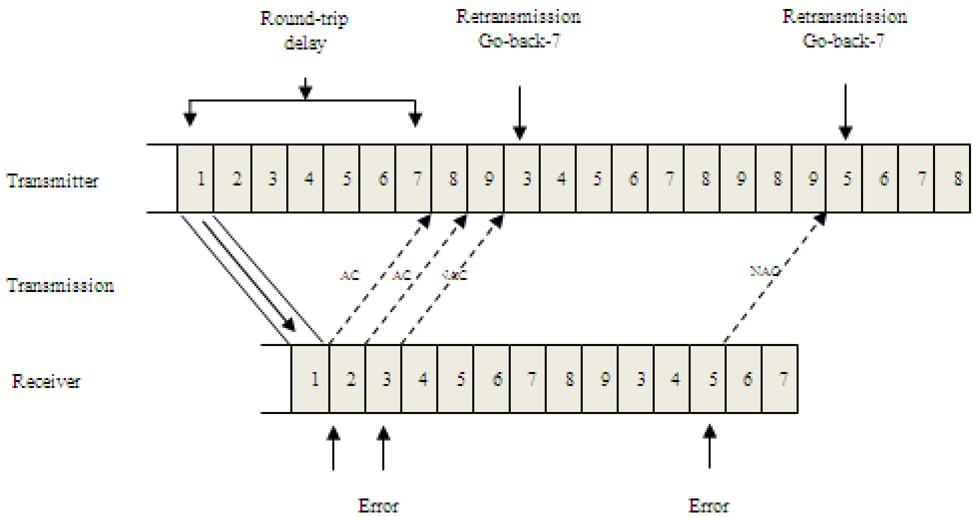


Figure 2.3: Go-Back-N ARQ

2.5.2 Selective Repeat/Reject ARQ [49, 52]

It is another specific type of ARQ used in delivering and acknowledging unit messages or sub messages. In case of delivering unit messages, it continues in sending packets until the window size is reached irrespective of loosing packets as in Figure 2.4. The receiver keeps the sequence number of the earliest loosen messages and send it with any acknowledge it sends back. The sender resend the loosen message after sending all the window packets. The size of the sending and receiving windows must be the same. In the case of subunit messages, the message is first divided in subunits in a process called segmentation. While in unit messages case the message is acknowledged or negatively acknowledged as a hole, in sub unit case the negative acknowledged message carry a flag indicating which sub unit received successfully, so only negatively acknowledged subunits are retransmitted. This sub unit selective repeat ARQ is useful in delivering long messages, as successfully delivered sub unit are retained after each transmission. This technique deals with the two main problems of underwater wireless sensors communications; the long propagation delay and the energy consumption issues, so it is the suitable one for retransmission in underwater communication, and it is the one we have used in this study.

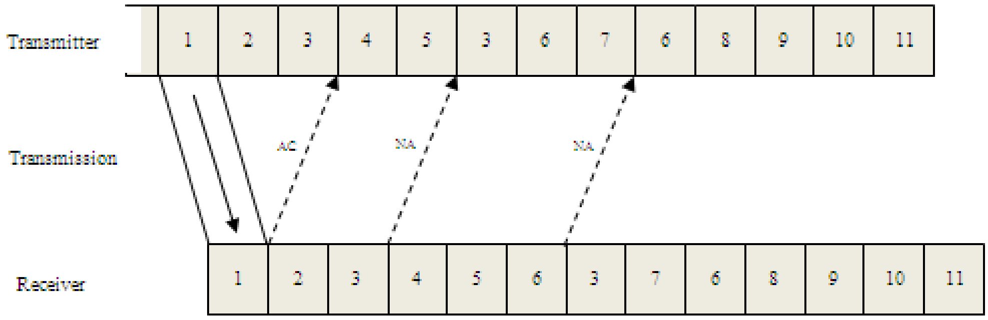


Figure 2.4: Selective Repeat ARQ

2.5.3 Forward Error Correction Technique

Forward Error Correction (FEC) or error control coding is a system for achieving reliable message transmission in a communication system by correcting errors in the receiver side (so the name Forward).

Recent and major activities on error control coding can be summarized as follows:

- Research on good structural properties, and high error correcting performance.
- Efficient encoding and decoding strategies.
- Applicability of coding in various transmission system and channels.

Forward error correction can be used in two levels, namely bit level and byte level. In bit level correction is achieved by adding redundant bits to the data in the sender using a predetermine algorithm to help in correcting error in the receiver. In packet level additional check packets are transmitted to recover the lost packets. In FEC no back channel is needed, but high bandwidth is required, so it is suitable in cases where retransmission is costly or impossible as in broadcasting. The maximum numbers of errors which can be corrected depend on code rate and type of coding used, so different FEC codes are suitable for different conditions.

There are two main types of FEC; the first one is the block codes which work on a fixed-size blocks (Packets of bits or symbols), the most famous block codes are Reed-Solemn, Golay, (Bose, Chandhuri and Hocquenghem) BCH code, Multidimensional parity and Hamming codes. The other type of FEC is convolutional codes, which work on bit or symbol streams of arbitrary length. It is often decoded using Viterbi algorithm, and it can be turned into block code if desired .Figure 2.5 below shows a tree classification for FEC codes.

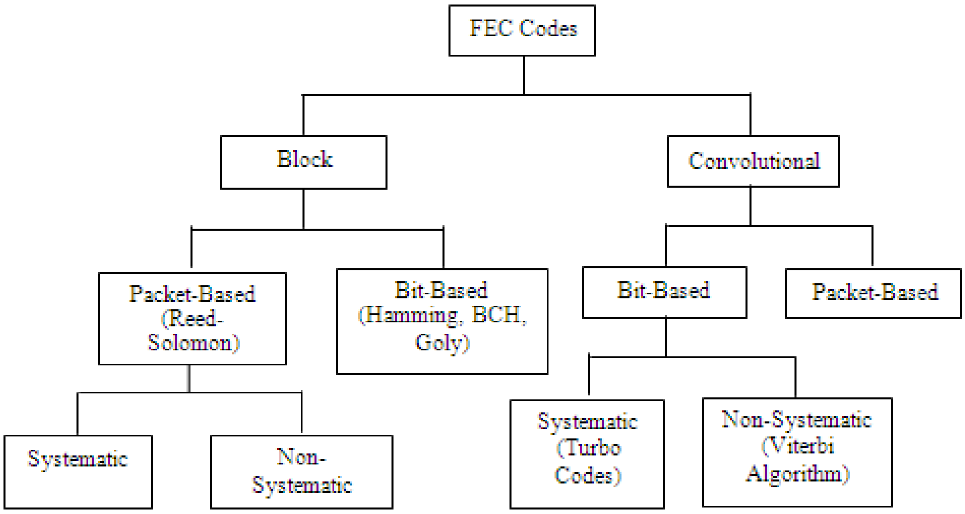


Figure 2.5: FEC Classifications

FEC process can be represented diagrammatically as in Figure 2.6 [53].

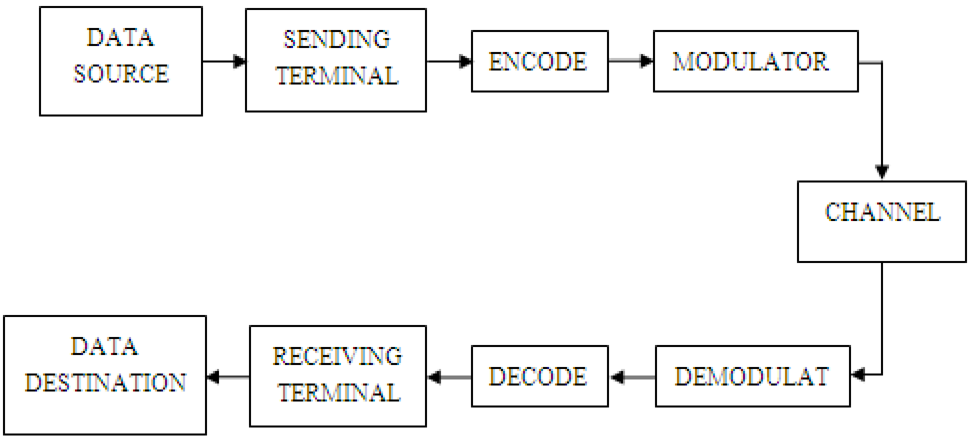


Figure 2.6: FEC (Encoding, Transmission and decoding)

2.5.3.1 Block Codes [54-55]

The encoder in the block codes divides the message into blocks of k bits. Then converts those blocks of length *k* into a codeword of length *n*, where *n* is always greater than *k* for the sake of redundancy in the transmitter. A block can be represented by a binary k-tuple $u = (u_1, u_2, \ldots\ldots, u_k)$ called a message. There are a total of 2^k different messages. The encoder transforms this message *u* into an n-tuple $v = (v_1, v_2, \ldots\ldots, v_k)$ of symbols called code word. The set of those 2^k codes of length *n* is called *(n,k)* block code, where $R = k/n$ is called the code rate. Block codes are memory-less systems as the output of the encoder *n* depends only on the encoder input *k*. In the receiver the decoder extracts the data from the received codeword. As an example for block codes consider Figure 2.7 which represents a code (3,1) where:

n =3 bits (block length)

k=1 message bit (I)

n – k= 2 parity bits (P)

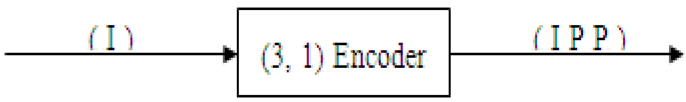


Figure 2.7: Block Encoding

2.5.3.2 Convolutional Codes [55]

2.5.3.2.1 Convolutional Encoding

In convolutional coding the encoder accept m-information bit and transformed into an n-bit encoded information. The information bit is processed along with the previous k bits which are stored in a linear shift registers using modulo-two addition to obtain the encoder output bit. How to use the memory in such away so as to achieve reliable communications is the main problem in convolutional encoding. The set of encoded sequence produced by *m* input, and *n* output encoder of memory *k* is called (*m, n, k*) convolutional code, and the ratio of the original information data (*m*) divided by the resulting encoded data (*n*) is called the code rate $R = {}^{m}/_{n}$, and the number of shift register plus one is called the constraint length . A convolutional encoding can be very complicated using various code rates and constraint length. A simple convolutional coding using transformation as a function of the memory registers and the generator polynomial can be shown in Figure 2.8 below:

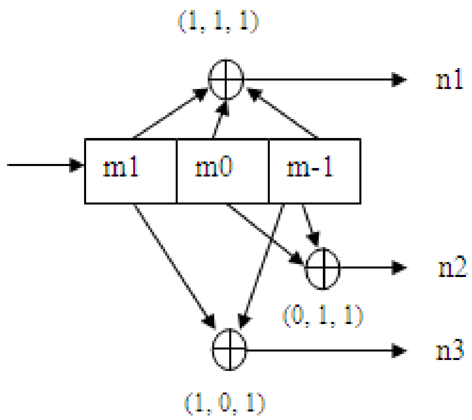


Figure 2.8: Non-Recursive Convolutional Encoder

In this Figure a rate 1/3 (m/n) encoder with constraint length (k) of 3, generator polynomials are G1=(1, 1, 1), G2= (0, 1, 1), and G3= (1, 0, 1); the output bits are calculated as follows:

- n1=m1+m0+m-1
- n2=m0+m-1
- n3=m1+m-1

There are two type of convolutional codes; recursive (systematic) and non-recursive (non- systematic). In the recursive one the input to the encoder is also included in the output of the encoder. Figure 2.8 above is an example of a non-recursive convolutional encoder, whereas Figure 2.9 is a recursive one.

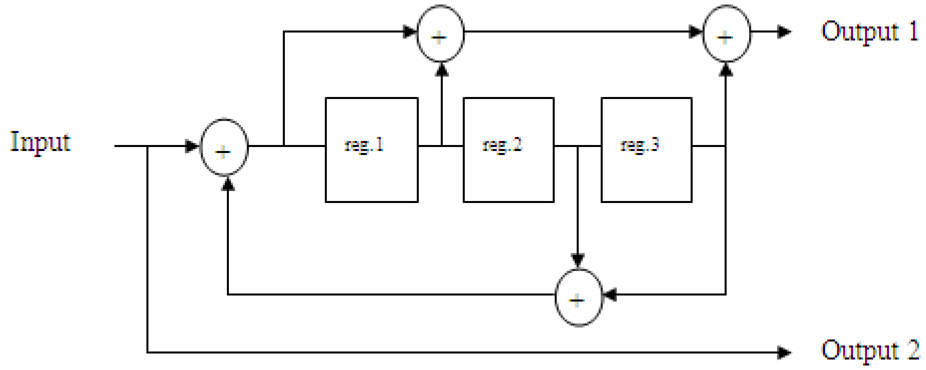


Figure 2.9: Rate ½ Recursive, Systematic Convolutional Encoder

A convolutional encoder is a discrete linear time invariant system, with the transfer function described in Z-transform as:

- $H_1(z) = 1 + z^{-1} + z^{-2}$
- $H_2(z) = z^{-1} + z^{-2}$
- $H_3(z) = 1 + z^{-2}$

for Figure 2.8and

- $H_1(z) = \frac{1 + z^{-1} + z^{-3}}{1 - z^{-2} - z^{-3}}$
- $H_2(z) = 1$

for Figure 2.9.

2.5.3.2.2 Viterbi Decoding Algorithm [55-57]

It is the most used technique in convolutional decoding, it uses maximum likehood decoding technique. Viterbi algorithm uses trellis diagram in estimating actual bit sequence. The decoding depends either on hard decision or soft decisions based on quantization type used. Hard decision uses one bit quantization while soft decision uses multi bit quantization by assigning not just one and zero to each received bit, but uses multi bit or infinite bit quantized. Generally soft decision decoding is better than hard decision decoding by more than 2 dB of coding gain.

2.5.3.2.3 Turbo Decoding Algorithm [55]

Turbo code encoder is consists of two identical Recursive Systematic Convolutional (RSC) codes with parallel concatenation. The encoders are separated by inter-leaver to change the input sequence with certain rules. Figure 2.10 shows a fundamental turbo code encoder:

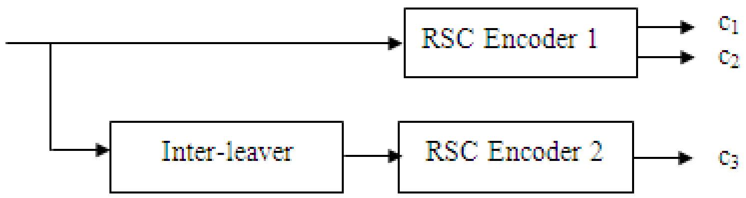


Figure 2.10: Fundamental Turbo Encoder

In the above diagram, only one of the systematic outputs of the two encoders is used as the other one will be just a permutation of it. The first RSC encoder outputs the systematic (c_1) and recursive convolutional (c_2) while the second RSC encoder discards its systematic sequence and only output the recursive convolutional (c_3) sequence.

2.5.3.2.4 Puncturing Technique

Puncturing is a technique by which high rate code is obtained by periodically deleting a part of the bit of a low rate convolutional code [58]. Puncturing codes are very attractive in implementing a rate-selectable convolutional encoder/viterbi decoder by employing various rate punctured codes derived from the same original codes. Constructing a high rate punctured code from a rate ½ code can be shown as in Figure 2.11 below:

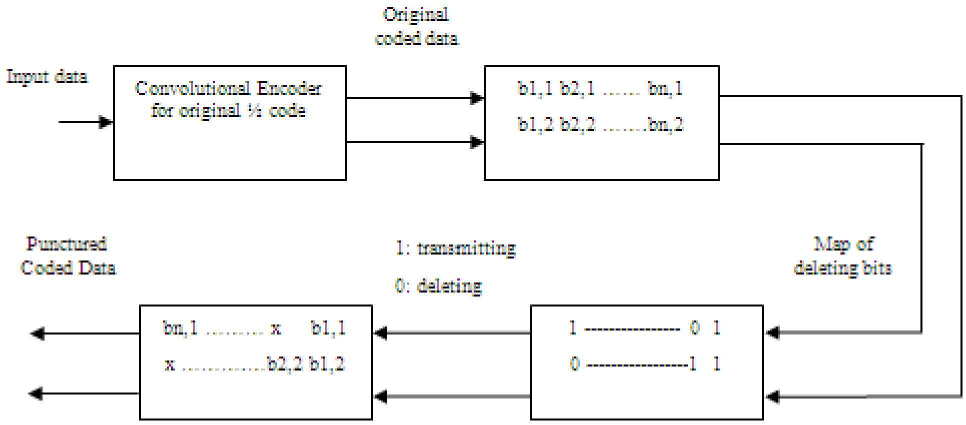


Figure 2.11: Basic Procedure of Punctured Coding from Rate ½ Convolutional Code

For any *n* bits data a *2n* bits coded data will be out from the original ½ convolutional encoder. Deleting (*n-1*) bits periodically from the original encoded data according to the puncturing map which indicates deleting bit position will yield a punctured code of rate *n/(n+1)*. Viterbi decoding is performed in the same way as for the original ½ code by inserting dummy bits in the position where coded bits were deleted. The position of the deleted bits has great effect on BER, so the map of deleting bits should be determined that the derived punctured code gives the best BER performance.

2.5.4 Hybrid ARQ-FEC

By combining ARQ and FEC, the advantages of both of them can be attained, and the drawbacks can be overcome. This combined system is referred to as Hybrid system [56, 59-60]. In hybrid system, an FEC system is induced to reduce the frequency of retransmission [50]. Using FEC increases system throughput performance by correcting the error pattern which occur most frequently; whereas ARQ increases system reliability by retransmitting the less frequent errors which is not corrected by the FEC system, so a proper combined hybrid system provides high reliability than a pure FEC system, and high throughput than a pure ARQ system.

Generally, there are two types of hybrid system [50, 56, 60-61]. The first is type-1 hybrid system. In this type when a received word is detected in error, the receiver try to correct it using FEC system if the number of errors is within the designed correcting capability of the code. If it is not within the correcting capability, the word is rejected and a retransmission is requested. This process is continues until either a word is received correctly or the error successfully corrected. As type-1 hybrid systems uses fixed parity code, it is not suitable for a communication system which has a variable noise level. It is suitable in a constant noise level where the suitable error correcting capability can be well designed. In a low error rate channels a pure ARQ system has a higher throughput than type-1 system due to the parity bit check used, whereas at high bit error rate the reverse is true because the error correcting capability reduces the number of retransmission.

For a channel with variable bit rate (type-ii), Incremental Redundancy (IR) hybrid system is designed. In a low bit error rate the system behaves like a pure ARQ using just Cyclic Redundancy Check (CRC) for error detection. Therefore it has the same throughput performance as the pure ARQ system. In a high bit error rate extra parity bits are needed to do correction. The procedure is as follows: the first message is sent with CRC only for error detection, and if an error is detected, the erroneous word is saved in a buffer, and at the same time retransmission is requested. The original code word is not retransmitted, instead of it the parity check bits which is formed based on the original message and an error correcting code is sent. This parity-check bits are used in the receiver to correct the errors in the word stored in the buffer. If it fails to correct it a second retransmission is requested. The second retransmission can be either a repetition of the original codeword or the parity-check bits depending on the strategy used.

The concept of parity retransmission for error correction appears first in [62] and it was used as a first type-ii hybrid ARQ by Miller [63]. This system nowadays extended and developed by many other scientist using different strategies like code combining [64], generalized [65] and selective combining [66].

2.6 ARQ Related Works in UWSN

In [67] an opportunistic (hybrid implicit/explicit) acknowledgement scheme suitable for stop and wait protocols in underwater is proposed. Due to them, simple stop and wait (S&W) protocol is the only choice in underwater acoustic communication due to the half-duplex property of acoustic modem. In a multi hop channel the acknowledgement can be achieved by explicitly transmitting an acknowledgement packet per successfully received packet, or implicitly making use of the broadcast nature of the medium when the node hears it is next-hop neighbor transmitting it forward. Implicit outperform explicit in terms of the number of bit transmitted, and waiting time for acknowledgement when channel condition is good, however it may not be so in bad channel conditions. So this ARQ scheme is suitable in a good channel conditions, and it is effectiveness is demonstrated only in the range of (5×10^{-5}<BER< 5×10^{-6}) and this only covers part of acoustic channel interval which is [10^{-6}, 10^{-2}] .

In [68], channel sharing property of underwater is utilized in proposing an efficient ARQ scheme. In this scheme packet size is controlled in such a way that transmission time becomes smaller than propagation delay. Collision free transmission between multiple nodes is achieved by scheduling packets sending properly. In a multiple hop the acknowledgement packet is replaced by overhearing packet transmitted from next hop. Using overhearing as an acknowledgement, not only saves energy but also minimizes overhead and transmission latency. The scheme is evaluated by comparing it with an existing stop and wait ARQ in term of the latency, and it shows a reduction in the latency. The latency and energy efficiency is still a problem in bad channel conditions cases.

In [69], they make use of the long propagation delay in underwater to transmit and receive in a juggling manner. This juggling enables a continuous ARQ to be implemented irrespective of the half-duplex property of the acoustic modem. This scheme decreases the propagation time by having more than one packet in the channel between transmitter and receiver. This leads to high throughput compared with the other variant ARQ schemes, but it is still unsuitable in bad channel conditions or in a longer distances.

In [70], a modular and lightweight of an opportunistic multi-hop ARQ [67] is implemented in real system. A flexible and extensible network stack suitable for challenged underwater acoustic networks is designed and implemented also. Evaluation demonstrated that the opportunistic ARQ can provide significant improvement in terms of data delivery ratio. The disadvantage of this technique is an increase in end-to-end delay due to queuing and retransmissions.

2.7 FEC Related Works in UWSN

Most telecommunication systems use fixed types of FEC code, which is designed for the expected worst case bit error rate. These codes will fail if the bit error rate gets ever worsen. However, some adaptive system is designed to adapt for a given channel error conditions; hybrid ARQ uses FEC to correct errors to specific limit, after that limit it switches to ARQ. Others use variable FEC codes by adding more bits in the high error rate case, and reduce them when the error rate is low.

Other types like concatenated FEC codes are a combination of block codes and convolutional codes. In this code a short constraint length veterbi- decoded convolutional code does most of the work and a block cod mops up any errors made by the convolutional decoder.

Turbo codes are soft decoding schemes consist of two or more convolutional codes and an inter-leaver to produce a block codes

In [71], error recovery through network coding is explored for underwater sensor networks. The computational power of underwater sensors along with the multiple routes provided by the broadcast nature of acoustic medium are the main reasons for applying network coding. In this technique the source and intermediate nodes encode packets and send them on multiple routes. The packet then recovered in the destination by combining packets from different routes.

In [15], Segmented Data reliable Transport protocol SDRT is proposed, it is a hybrid of FEC and ARQ. It sends data block by block and hop by hop. The sender encodes the packet using erasure codes, and sends it to an intermediate node. The intermediate node reconstructs the packet and encodes it and sends it to the next hop. The sender continues to send the data until it receive an acknowledgement from its next node, and this is the main problem with SDRT as it wastes energy. SDRT improve channel utilization and simplify protocol management.

In [72], ARRTP previously known as ADELIN [5] is proposed, it is a hybrid of two types of error correction techniques which encode message on bit and/or packet level. ARRTP is based on distance as adaptation factor. For each range of distance one or a hybrid of two techniques is used. The technique is also investigated on cooperation mode making use of the broadcast nature of acoustic signal. ARRTP is found to have better probability of success and energy efficient in single and multi-transmission. This technique is based on fixed channel conditions analysis, so it is unsuitable in variable channel conditions like underwater one.

2.8 Energy Efficiency Related Work in UWSN

2.8.1 Battery Technology

There are many types of batteries: Lithium ion, Nickel Cadmium, Nickel Metal Hydride and Silver/Zinc batteries. Among all those types Lithium iron has demonstrated a wide ranges of performance parameters, high energy and power density, long life cycle, high reliability, limited maintenance requirement, and low operation cost [73-74]. In the past underwater applications rely on silver/zinc batteries in providing their power requirement, however this silver/zinc batteries suffer from short life time and high maintenance cost, so Lithium iron are a good alternative in underwater applications.

Other researches have been done by Yardney Technical Products Inc. on various chemistries used in underwater environment. The results of those researches also state that Lithium Ion has the best performance compared to other technologies [75]. Some other results have also proven this superiority of lithium ion [76].

Lithium iron batteries were designed with different performance requirements ranging up to 650 W/kg power and 165 Wh/kg to suit different underwater applications, and this proves the flexibility of lithium iron technology.

2.8.2 Modem Technology

Until now underwater acoustic modem are too expensive, and this is the main reason for the limited spread of underwater sensor networks. The cost of one single modem is at least few thousand US dollar [73]. The lifetime of this modem is limited by the energy in its battery as it is difficult to recharge or even replace batteries in underwater environment, so increasing battery lifetime by optimizing energy consumption in all system components will increase modem lifetime. Energy optimization includes choosing the best Digital Signal Processing (DSP) scheme, the transducer used, interfaces and their corresponding electronics.

In [77], they developed Micro-modem based on Texas Instrument fixed-point DSP. This micro-modem operates in two modes; low-rate, low-power, non-coherent Frequency Shift Keying (FSK) mode and high-rate, high-power, coherent Phase Shift Keying (PSK) mode. It is compact modem and consumes low power.

Jack et al. developed an inexpensive low power modem for short distances communications [78], it uses a low power wake-up receiver to trigger the expensive data receiver. This wake-up receiver is the only wakeup component when no communication exists.

2.8.3 Energy Efficient MAC Protocols

Slotted FAMA (Floor Acquisition Multiple Access) is a Medium Access Control (MAC) protocol proposed by M. Molins and M. Stojanovic based on a channel access discipline [79]. It combines Carrier Sensing (CS) and a dialogue between the source and receiver prior to data transmission. Control packets are exchanged to avoid multiple transmissions at the same time. Energy is saved by using time slotting which eliminates the asynchronous nature of the protocol and the need for excessive large control packets. In this system guards time should be inserted in the slot duration to account for any clock drift. Another problem associated with this system is that the handshaking process affects the system throughput due to the high propagation delay of underwater acoustic channel. Also the carrier may sense the channel idle while it is transmitting [73].

In a distributed energy-efficient MAC protocol [80], the idea of sleep periods with low duty cycles saves energy. This protocol just tries to efficiently organize the sleep schedule; it does not consider bandwidth utilization or access delays.

In [81], D. Pompili et al. achieved low energy consumption by incorporating a closed-loop distributed algorithm to set the optimal transmit power and code length.

A. A. Sayed et al. in [82] proposed an energy efficient MAC protocol for short range acoustic sensor networks. They called it Tone Lohi. In TLohi energy is conserved using data reservation to avoid data collision. A wake-up tone hardware to resolve reservation contention with low power consumption is employed. They proposed three versions of TLohi; Synchronous TLohi (ST-Lohi), Aggressive Unsynchronous (UT-Lohi), and a Conservative Unsynchoronous TLohi (CUT-Lohi). Simulation results showed that ST-Lohi is the most energy efficient one of them, while a UT-Lohi achieves higher throughput and CUT-Lohi is the most robust packet delivery one.

2.8.4 Energy Efficient Routing Protocols

Generally there are three categories of routing protocols; proactive, reactive and geographical routing protocols. Proactive and reactive are energy inefficient as they apply a continuous overhead messages and uses flooding in route discovery; so they are not suitable for UWSNs. The third protocol faces the problem of accurately obtain localization in an efficient energy consumption manner [73].

In [83], E Sozer et al. proposed a routing protocol where a central manager gather information from all nodes by means of poll packet, establish route tree and decide the primary and secondary route to each destination. This technique is suitable only for static small scale UWSN.

In [84], P. Xie et al. proposed a Vector-Based forwarding (VBF) routing protocol for UWSN. In VBF localization and routing are performed at the same time. The packet carries the positions of the sender, destination and the forwarder. A routing vector is specified to connect source with destination. All the nodes receiving a packet compute their distance from the forwarder and their angle of arrival of the signal. If the node is within specific distance from the forwarder, it will add its position in the packet and forward it, otherwise it discards the packet. In this protocol there are many paths, so it is robust against packet loss and node failure.

Chenn – Jung Huang et al. proposed and developed a clustering protocol that combines the ideas of energy efficient clustering protocol and data aggregation [85]. In this protocol sensor nodes are organized into cluster. The cluster head receives information from all other members and transmit and receive to and from other cluster heads. This protocol was compared with LEACH (Low- Energy Adaptive Clustering Hierarchy) [86], and VBF. It was found that it achieves better node lifetime.

A distributed Underwater Clustering Scheme (DUCS) is proposed by M. C. Doming and R. Prior [87]. It is also clustering technique as the one in [85], the difference is that the cluster head performs signal processing functions on the data and send only non- redundant data to the sink. Nodes close to each other process frequent correlated data as they usually monitor nearby areas. In each cluster the cluster head coordinates the data transmission in the cluster using TDMA schedule and transmit this schedule to the other members using CDMA. This TDMA/CDMA with DUCS results in a reduction of the interference and improves communication quality. DUCS was compared with LEACH and it achieves higher delivery ratio, reduces overhead and increases throughput.

CHAPTER 3

ENERGY EFFICIENCYMATHEMATICAL DERIVATIONS

3.1 Introduction

Underwater acoustic channel are characterized by variable channel conditions, whereas underwater sensor networks are characterized by variable distances between nodes due to water currents. This variability in channel conditions and distances between nodes leads to unreliable and inefficient communications. For such situations reliable and efficient communication data transport is needed.

Reliability is usually achieved by using error correction techniques. From the literature Forward Error Correction (FEC) and Automatic Repeat reQuest (ARQ) are the two main error correction techniques that guarantee the reliability of data transmission in underwater acoustic links [31-32, 69]. Whereas for efficiency; energy is the most important efficiency issue in a Wireless Sensor Networks (WSN) as it is difficult to recharge or even replace batteries for a large number and sparsely distributed sensors. This condition is even worse in underwater due to the harsh aquatic medium [1, 15].

In this chapter underwater propagation model will be presented in section 2, then a mathematical derivation for energy efficiency in FEC and ARQ techniques in underwater environment will be done based on communication distance and packet size in section 3. The effects of wind speed, and shipping factor will be studied. In section 4 a simulation using MATLAB is done to validate the mathematical derivation results. A comparison results between ARQ and FEC energy efficiencies for different packet size, different distances, and different channel conditions (wind speed and shipping factors) is presented in section 5. In section 6 the chapter is concluded.

3.2 Underwater Propagation Model

The propagation model is responsible for calculating the SNR at the receiver after attenuation and noise are taken into account. To calculate the SNR at the receiver, both the attenuation of the acoustic signal in water and the ambient noise need to be calculated. The total attenuation is calculated based on the spreading losses and Thorp approximation for the absorption loss [25, 43, 48, 72].

3.2.1 Attenuation

Attenuation consists of two parts, the first one is the absorption loss and the second part is the spreading loss. To calculate the absorption loss at a given frequency, Thorp's approximation function divides the frequencies into two groups; one group under 400 Hz and the other one over 400 Hz as follows:

$$10 \log a(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4200+f} + 2.75 \times 10^{-4} f^2 + 0.003 \qquad f>0.4$$

$$= 0.002 + 0.11 \times (\frac{f}{1+f}) + 0.011 f \qquad f< 0.4 \qquad (3.1)$$

where *a(f)* is given in dB/km and *f* in KHz for underwater communications. Combining absorption effects and spreading loss, the total attenuation is as follows:

$$10 \log A(l, f) = k \log l + l \times 10 \log a(f) \qquad (3.2)$$

where the first term is the spreading loss and the second term is the absorption loss. The spreading coefficient *k* defines the geometry of the propagation (i.e., *k* = 1 for cylindrical propagation (shallow water), *k* = 2 for spherical propagation (deep water), and *k* = 1.5 for practical spreading) [43].

3.2.2 Noise

The background noise in ocean has many sources which vary with frequency and location [88]. Ocean turbulence is the main source of noise at frequencies from 0.1 Hz to 10 Hz [89], turbulence noise level decreases from 140 dB at 1 Hz to just 30 dB for frequencies around 10 Hz. Distant ship noise is dominant at frequencies around 100 Hz. Wind noise is the main source between 1 KHz and 30 KHz, and thermal noise is dominant at frequencies above 100 KHz. At this frequency thermal noise level is around 25 dB, and it increases by 20 dB per decade. The following formulas give the power spectral density of the four noise components [25, 48, 72]:

$$10\log N_t(f) = 17 - 30\log(f) \tag{3.3}$$

$$10\log N_s(f) = 40 + 20(s - 0.5) + 26\log(f) - 60\log(f + 0.03) \tag{3.4}$$

$$10\log N_w(f) = 50 + 7.5 \times w^{0.5} + 20\log(f) - 40\log(f + 0.4) \tag{3.5}$$

$$10\log N_{th}(f) = -15 + 20\log(f) \tag{3.6}$$

Where N_t is the noise due to turbulence, N_s is the noise due to shipping (the shipping variable s take the values between 0 and 1), N_w is the noise due to wind (the wind variables w represent wind speed in m/s), and N_{th} represents thermal noise. The overall noise power spectral density for a given frequency f (KHz) is then:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \tag{3.7}$$

3.2.3 Signal to Noise Ratio

It is well known that SNR of an emitted underwater signal at the receiver is given by [25, 48, 90]

$$SNR = SL - A(l, f) - N(f) - DI \tag{3.8}$$

where *N(f), A(l,f)*are in dBs given from equations (3.2) and (3.7). Assuming Omni-directional directivity, directivity index (DI) = 0. The source level $SL = {20\log I}/{1\mu Pa}$, where I is the intensity at 1 m from the source in watt/m^2, given by:

$$I = \frac{P_t}{2\pi H} \tag{3.9}$$

Where P_t is the transmission power, and H is the water depth in m.

SNR in underwater can be found using the algorithm in Figure 3.1 below:

Algorithm 3-1 SNR in Underwater Channel
SNR (f (frequency in KHz),*l* (distance in m), *s* (Shipping factor), *w* (wind speed in m/s), *k* (spread coefficient), P_t (Transmit power in watts),*H* (depth in m)).
$absorption \leftarrow 10\log a(f) = 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4200+f} + 2.75\times10^{-4} f^2 + 0.003$
$atten \leftarrow 10\log A(l,f) = k\log l + l\times 10\log a(f)$
$turbulence \leftarrow 17 - 30\log(f)$
$turb \leftarrow pow(10,(turbulence\times 0.1))$
$shipping \leftarrow 40 + 20(s-0.5) + 26\log(f) - 60\log(f+0.03)$
$ship \leftarrow pow(10,(shipping\times 0.1))$
$wind \leftarrow 50 + 7.5\times w^{0.5} + 20\log(f) - 40\log(f+0.4)$
$win \leftarrow pow(10, wind\times 0.1))$
$thermal \leftarrow -15 + 20\log(f)$
$therm \leftarrow pow(10,(thermal\times 0.1))$
$noise \leftarrow turb + ship + win + therm$
$I = {P_t}/{2\pi H}$
$SL \leftarrow 20\log({I}/{1\mu Pa})$
$DI \leftarrow 0$
$SNR \leftarrow SL - atten - noise - DI$
Return *SNR*

Figure 3.1: Algorithm 3.1 SNR in Underwater Channel

3.3 Energy Efficiency Mathematical Derivation

The data packet in ARQ case can be presented as in Figure 3.2 (a). It consists of a header field α bits long, payload of size n bits and a Frame Check Sequence (FCS) τ bits long. The acknowledgement packet length is *ack*.

In FEC case it can be presented as in Figure 3.2 (b). It consists of a payload of size (*n*-*k*) bits long, a parity check of *k* bits and a header field α bits long.

Header	FCS	Payload
α	τ	*n*

Figure 3.2 (a): ARQ Packet Format

Header	Parity check	Payload
α	k	n-k

Figure 3.2 (b): FEC Packet Format

3.3.1 Optimization Metric

Energy efficiency is the suitable metric which captures both energy and reliability constraints, and it is defined as [17, 27]:

$$\eta = \eta_e (1 - PER)$$

$$= \frac{E_{eff}}{E_{tot}} (1 - PER) \qquad (3.10)$$

Where η is the energy efficiency, η_e is the energy throughput, $r = (1\text{-}PER)$ is the Packet Acceptance Rate (PAR), which accounts for data reliability, and $\frac{E_{eff}}{E_{tot}}$ denotes the energy throughput. Therefore, the energy efficiency η represents the useful fraction of the total energy expenditure in a communication link between sensors.

3.3.2 Bit Error Rate Calculation

Using 8-Phase Shift Keying (PSK) scheme as the suitable modulation techniques for underwater acoustic communication [26], the symbol error probability P_s for ARQ is given by [26, 91]:

$$P_s \approx 2Q(\sqrt{2\gamma_s} \sin\frac{\pi}{M} \tag{3.11}$$

where M=8 for 8-PSK, and the bit error probability P_b is given by:

$$P_b = {P_s}/{3} \tag{3.12}$$

Whereas for FEC convolution code [92]:

$$P_b = \frac{1}{k} \sum_{d=d_{free}}^{\infty} w(d) Q(\sqrt{2dR_c\gamma_b} \tag{3.13}$$

where $w(d)$ is the weight distribution function, d_{free} is the minimum hamming distance, and γ_b is the received SNR, $R_c = {k}/{k+1}$ is the code rate.

3.3.3 ARQ Energy Efficiency Mathematical Derivation

Energy consumption of sensor node for communication in one hop is given by:

$$E_{ARQ} = E_{ARQ}^{tr} + E_{ARQ}^{re} \tag{3.14}$$

Where E_{ARQ}^{tr} is the energy consumed by the sender in transmitting the data and receiving the acknowledgement, and E_{ARQ}^{re} is the energy consumed by the receiver in receiving the data and transmitting the acknowledgement as presented in the following equations:

$$\begin{aligned} E_{ARQ}^{tr} &= E_{data}^{tr} + E_{ack}^{re} \\ &= P_{tr} l_{data} T_{tr} + P_{re} l_{ack} T_{tr} \end{aligned} \tag{3.15}$$

$$\begin{aligned} E_{ARQ}^{re} &= E_{data}^{re} + E_{ack}^{tr} \\ &= P_{re} l_{data} T_{tr} + P_{tr} l_{ack} T_{tr} \end{aligned} \tag{3.16}$$

Where $P_{tr/re}$ is the power consumed in transmitting/ receiving, and $T_{tr} = {1}/{R}$ is the time of transmitting 1 bit. From Figure 3.2 (a), using the bit error rate probability P_b in

(3.12), and assuming independent bit errors, the Packer Error Rate (PER) for ARQ can be derived as follows:

$$PER_{ARQ} = 1-(1-P_b)^{n+\alpha+\tau} \tag{3.17}$$

This expression closely approximate PER under bursty error conditions.

From equation (3.9) energy efficiency of ARQ without retransmission strategy can hence be written as:

$$Eff_{ARQ} = \frac{E_{ARQ}^{eff}}{E_{ARQ}^{tot}}(1-PER_{ARQ})$$

$$= \frac{(P_{tr}+P_{re})nT_{tr}}{(P_{tr}+P_{re})(n+\alpha+\tau+ack)T_{tr}}(1-PER_{ARQ})$$

$$= \frac{n}{(n+\alpha+\tau+ack)}(1-PER_{ARQ}) \tag{3.18}$$

where E_{ARQ}^{eff} is the energy consumed by the payload only, E_{ARQ}^{tot} is the total energy consumed. This equation can be explained with the diagram in Figure 3.3 below:

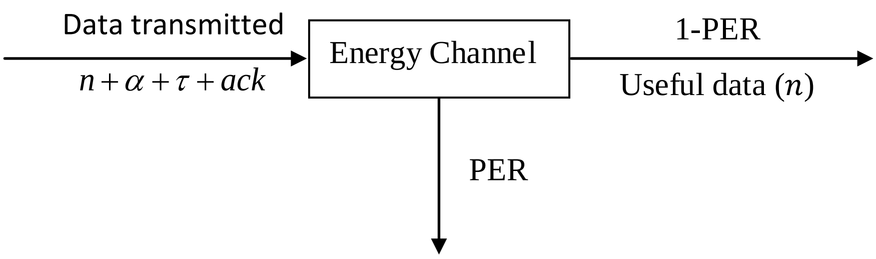


Figure 3.3: Energy Efficiency Concept

With the use of ARQ retransmission, retransmission is continues until the data is received correctly or the maximum number of allowable retransmission is attained. If we assume that the maximum number of transmission is n, energy consumption can be given by [27]**:**

$$E_{ARQ}^{tot-n} = E_{ARQ}^{tot}(1+PER_{ARQ}+PER_{ARQ}^{2}+......+PER_{ARQ}^{n-1}) \tag{3.19}$$

At this time, the PAR at maximum number of retransmission n, can be calculated as:

$$PAR_n = (1-PER_{ARQ}) + PER_{ARQ}(1-PER_{ARQ}) + ...+ PER_{ARQ}^{n-1}(1-PER_{ARQ})$$

(3.20)

So the energy efficiency can be calculated in the case of retransmission as:

$$Eff_{ARQ}^{n} = \frac{E_{ARQ}^{eff}}{E_{ARQ}^{tot-n}} PAR_n$$

$$= \frac{E_{ARQ}^{eff}((1-PER_{ARQ}) + PER_{ARQ}(1-PER_{ARQ}) + ...+ PER_{ARQ}^{n-1}(1-PER_{ARQ}))}{E_{ARQ}^{tot}(1+PER_{ARQ} + PER_{ARQ}^{2} + ...+ PER_{ARQ}^{n-1})}$$

$$= \frac{E_{ARQ}^{eff}(1-PER_{ARQ})}{E_{ARQ}^{tot}} \tag{3.21}$$

which is the same as equation (3.18), so for ARQ; energy efficiency is independent of retransmission attempts and is unchangeable with the number of retransmission [27]. ARQ energy efficiency can be calculated using the algorithm in Figure 3.4 below:

Algorithm 3.2: ARQ Energy Efficiency Calculation
Eff $\boldsymbol{Eff_{ARQ}}$ (SNR, n(payload), α (Header), τ (FCS), *ack* (Acknowledgement length))
1 $P_b \leftarrow 0.67Q(\sqrt{2SNR}\sin\frac{\pi}{M})$
2 $PER_{ARQ} \leftarrow 1-(1-P_b)^{n+\alpha+\tau}$
3 $Eff_{ARQ} \leftarrow \frac{n}{n+\alpha+\tau+ack}(1-PER_{ARQ})$
Return Eff_{ARQ}

Figure 3.4: Algorithm 3.2 ARQ Energy Efficiency Calculation

3.3.4 FEC Energy Efficiency Mathematical Derivation

The energy consumption of FEC is given by:

$$E_{FEC} = E_{FEC}^{tr} + E_{FEC}^{re} + E_{dec} + E_{enc} \tag{3.22}$$

Using convolution turbo code as forward error correction techniques, encoding (E_{enc}) and decoding energy (E_{dec}) are considered to be negligibly small [17, 27], and from Figure 3.2 (b), the expression for the energy efficiency is defined as:

$$Eff_{FEC} = \frac{E_{FEC}^{eff}}{E_{FEC}^{tot}}(1 - PER_{FEC})$$

$$= \frac{(P_{tr} + P_{re})(n-k)T_{tr}}{(P_{tr} + P_{re})(n+\alpha)T_{tr}}(1 - PER_{FEC})$$

$$= \frac{(n-k)}{(n+\alpha)}(1 - PER_{FEC}) \tag{3.23}$$

Where PER_{FEC} is calculated using equation (3.13).

FEC energy efficiency can be calculated using the algorithm in Figure 3.5 below:

Algorithm 3.3: FEC Energy Efficiency Calculation
Eff_{FEC} (SNR, (n-k)(payload), α (Header), parity check (k),R_c(code rate), w(d) *(weight distribution, d_{free}(minimum free distance)*
1 $P_b \leftarrow \frac{1}{k}\sum_{d=d_{free}}^{\infty} w(d)Q(\sqrt{2dR_c\gamma_b})$
2 $PER_{FEC} \leftarrow 1-(1-P_b)^{n+\alpha}$
3 $Eff_{FEC} \leftarrow \frac{(n-k)}{(n+\alpha)}(1-PER_{FEC})$
Return Eff_{FEC};

Figure 3.5: Algorithm 3.3 - FEC Energy Efficiency Calculation

3.4 Simulation

Simulation offers a powerful tool to validate mathematical analysis. The simulation is carried out for a two system using different error correction techniques using MATLAB. Two types of parameters are considered for design parameters and configuration parameters. Energy efficiency and packet probability of success (PAR) are taken as the main performance factors to compare the two systems.

3.4.1 Design Parameters

The design parameters are the parameters that can be varied in order to study their effect on the system energy efficiency. In the first system ARQ technique is used as the error correction technique, where 8-PSK is used as the modulation technique as it is the best modulation technique in underwater channel as stated in the literature [26]. In the second convolutional coding is used as the FEC error correction technique [26].

The design parameters used are the distance, shipping factor and wind speed. Shipping factor and wind speed are taken as a representative for variable channel conditions; any other channel condition factor will have the same effect.

Modulation and encoding technique types and design parameters can be written as in Table 3.1 below:

Table 3.1 Modulation, Encoding Types and Design Parameters

Parameter	Description	Type or Value
Modulation	Modulation technique used in ARQ case	8-PSK
Encoding	Encoding technique used for error correction	Convolution coding
Distance	Communication distance	From 800 to 3000 m
Shipping factor	Factor describe the effect of shipping	From 0 to 1
Wind speed	Factor describe the effect of wind	Any value in m/s

3.4.2 Configuration parameters

A simple schematic diagram for the simulation of energy efficiency in ARQ system is illustrated as in Figure 3.6 below:

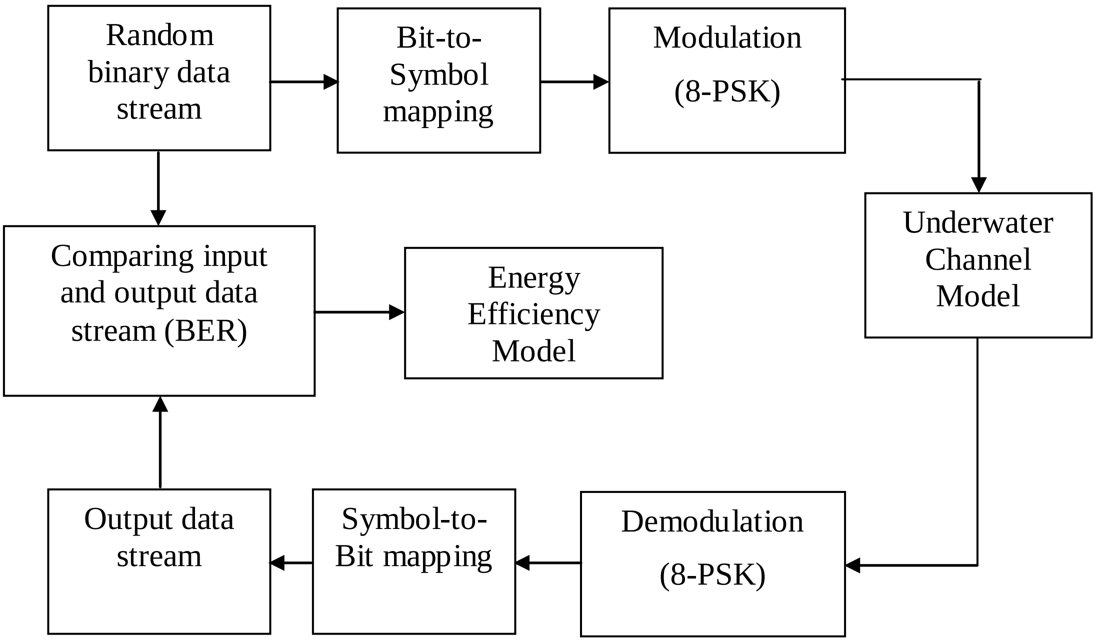


Figure 3.6: ARQ Energy Efficiency Simulation Diagram.

The simulation is carried out using MATLAB [93]

In the transmitter a random bit generator is used with the parameters as follows:

- *Size of signal constellation M = 8;*
- *number of bit per symbol k = 3,*
- *and number of bit processed n = 3e^{4}.*
- *Binary data stream are created as a column vector using the function: x = randint (n, 1);*

A Bit-to-Symbol mapping which convert the bits in x into k-bit symbols is done using the function*:*

- *xsym = bi2de (reshape (x, k, length (x) /k) .',' left-msb');*

Then an 8-PSK modulator is used to modulate the signal with the function:

- *y = modulate (modem.pskmod (M), xsys);*

The model for SNR in underwater channel is written as in algorithm 3-1, and an AWGN function is used as:

- *ynoisy = awgn (y, snr, "measured');*

In the receiver side 8-PSK demodulator is used to demodulate the signal using the function:

- *zsym = demodulate (modem.pskdemod (M), noisy);*

the Symbol-to-Bit mapping is done using the function:

- *z = de2bi (zsym,'left-msb');*

then BER is obtained by comparing the input x with the output z using the function:

- *[number_of_errors,bit_error_rate] = biterr (x, z);*

The energy efficiency model is calculated from the BER as in algorithm 3-2

In the second system the 8-PSK is replaced by a convolutional encoder as in the Figure 3.7 below

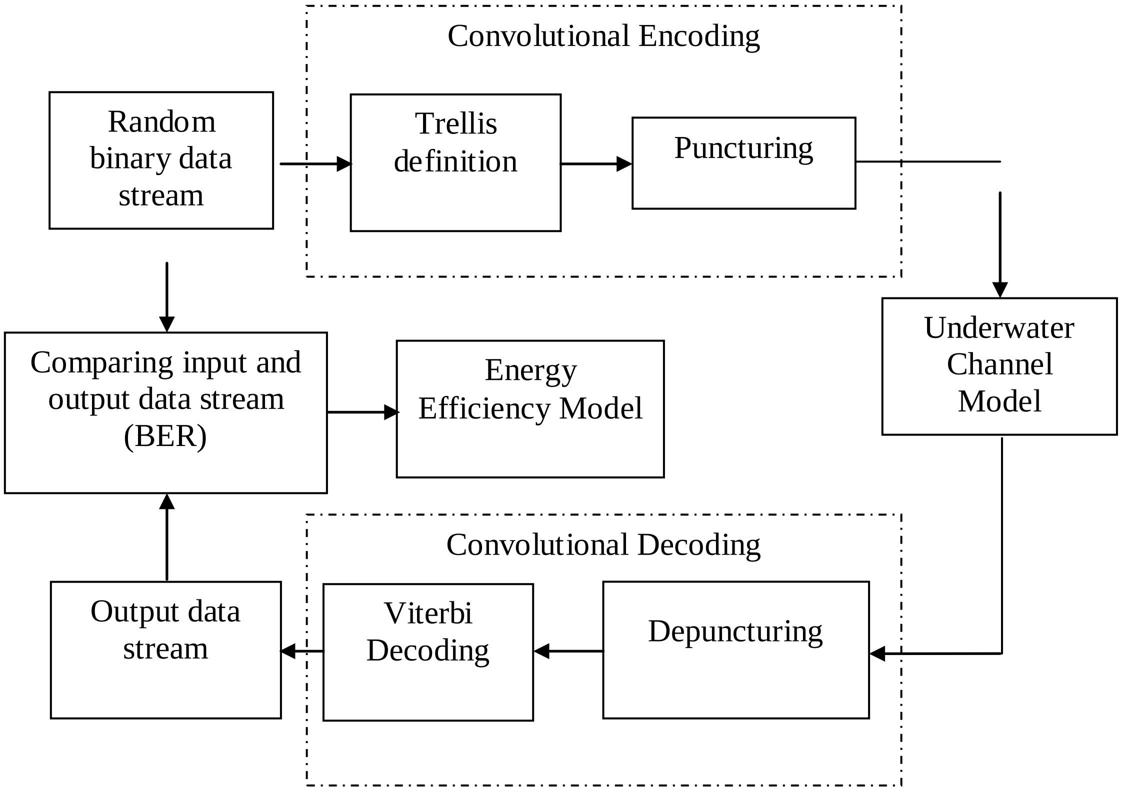


Figure 3.7: FEC Energy Efficiency Simulation Diagram.

Trellis is defined using the following function:

- *t = poly2trellis (3, [5 7]);*

Then puncturing is attained by the following function:

- *punctcode = convenc (x, t, [1 1 0 1 1 0 1 0 1 0]);*

This puncturing is for 5/6 code rate.

Then 0 bit is mapped to 1 and 1 bit to -1 using the function:

- *tcode = 1 – 2*punctcode;*

The model for SNR in underwater channel is written as in algorithm 3.1, and an AWGN function is used as:

- *ncode = awgn(tcode, snr, 'measured');*

In the receiver side, the punctured code is decoded by viterbi using the function:

- *decoded = vitdec(ncode, t, 96, 'trunc', ...'unquant', [1 1 0 1 1 0 1 0 1 0]); % Decode.*

then BER is obtained by comparing the input *x* with the output *decoded* using the function:

- *[numErrPE, berPE] = biterr(decoded, x);*

The energy efficiency model is calculated from the BER as in algorithm 3-3

3.5 Results and Analysis

The results are obtained using a MATLAB, with LinkQuest UWM2000 acoustic modem [94], and the parameters given in Table 3.2:

Table 3.2: Simulation Parameters

Symbol	Parameters	
	Definition	Quantity
P_t	Transmitting Power	2 W
P_{re}	Receiving Power	0.75
R	Bit Data Rate	10 kbps
l_{ack}	Acknowledge packet length	7 Byte
$\alpha + \tau$	Header + FCS length	11 Byte

First, a suitable frequency range based on AN Factor as in Figure 3.8 was calculated; this frequency range corresponds to the minimum AN factor. A suitable range is found from 10 KHz up to 25 KHz, below and above this range the AN Factor increases sharply.

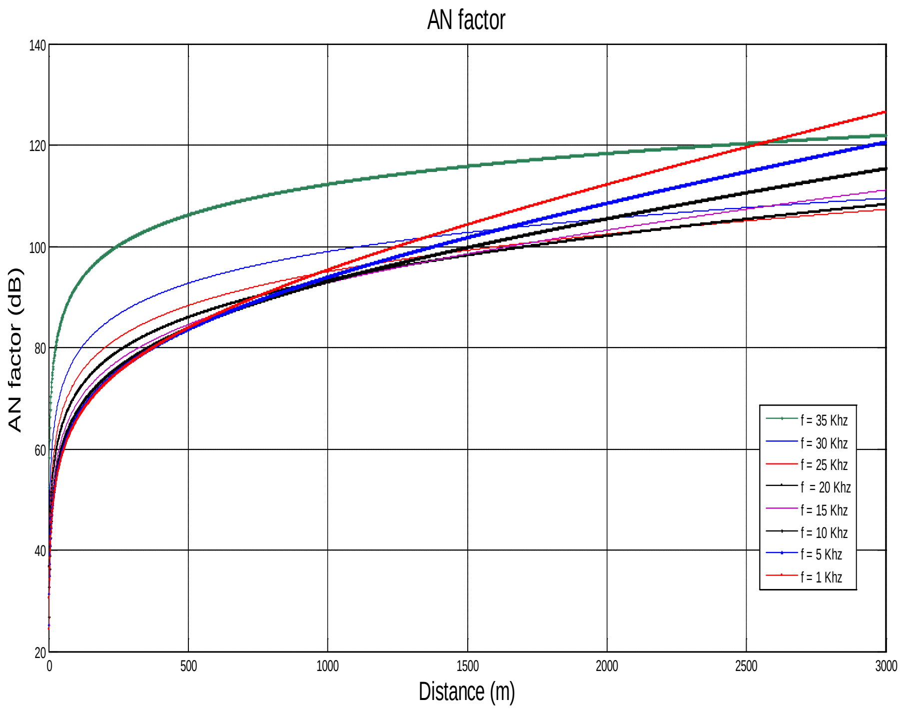


Figure 3.8: AN Factor

From Figures 3.9 (a) and 3.9 (b), it is clear that the energy efficiency of both techniques increases with increasing packet size in short distances, whereas decreases in long distances for both techniques. It is also clear that there is only a slight differences between mathematical and simulation results which validate the results. This differences between mathematical and simulation results decreases as the number of bits transmitted in the simulation increases

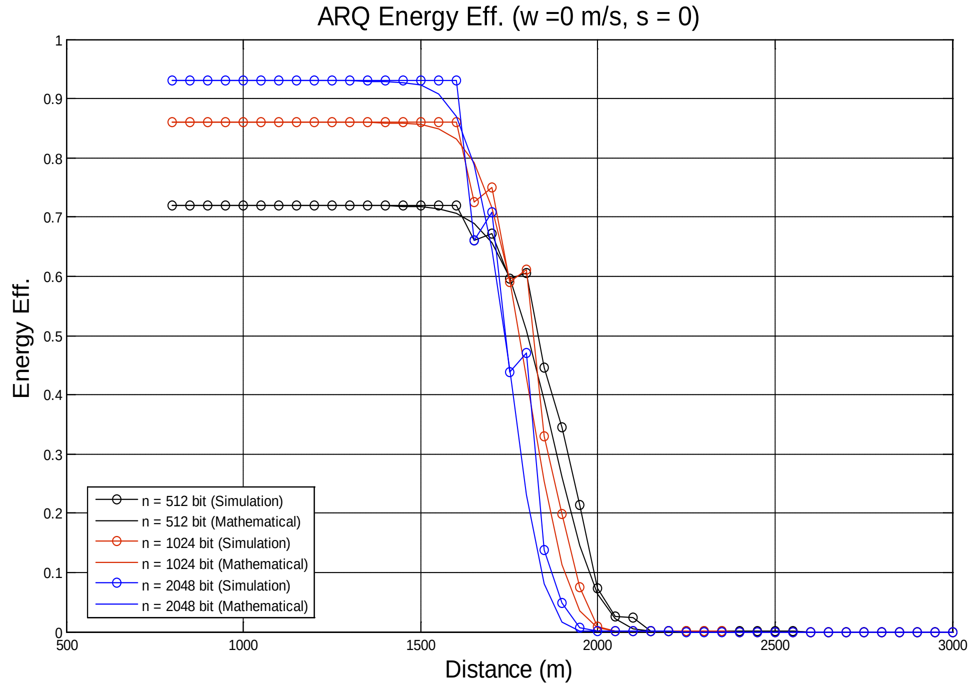


Figure3.9 (a): ARQ Energy Efficiency (Mathematical and Simulation Results)

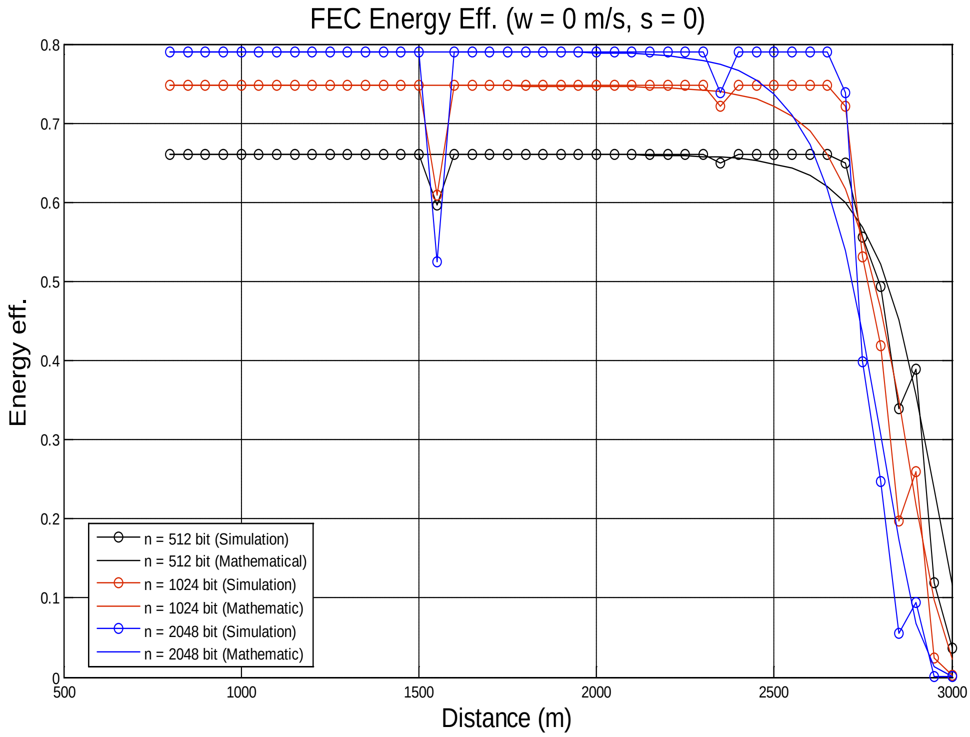


Figure 3.9 (b): FEC Energy Efficiency (Mathematical and Simulation Results)

In Figure 3.10 (a) energy efficiency of ARQ and FEC for a packet length of 512 bit is shown. It is apparent that ARQ is more energy efficient than FEC below a specific distance (cut-off distance), and FEC is more energy efficient after this distance. The effect of shipping is unseen and can be neglected. In Figure 3.10 (b) the effect of wind is very clear, and the cut-off distance decreases from 1700 m when no wind exists to 1250 m when the wind speed is 1 m/s. ARQ efficiency starts to decrease at 1600 m when no wind exists, and at 1100 m when the wind speed is 1 m/s, whereas for FEC it starts to decrease at 2500 m when no wind exist and at 1800 m when the wind speed is 1 m/s.

Regarding PAR, both techniques have 100 % PAR when the distance is less than 1500 m when there is no wind as in Figure 3.10 (c). After 1500 m ARQ PAR starts to decrease until it becomes 90 % at distance of 1700 m where FEC PAR continues with PAR of 100 % until 2400 m and more than 90 % until 2700 m.

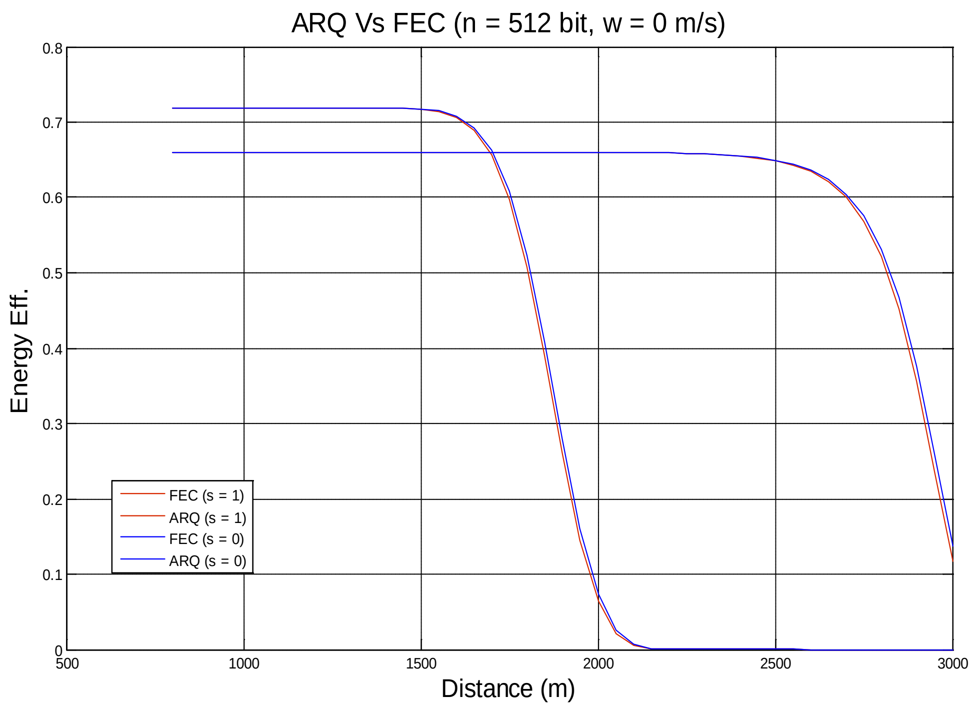


Figure 3.10 (a): ARQ Vs FEC Energy Efficiency (n = 512 bit, Variable Shipping Factor)

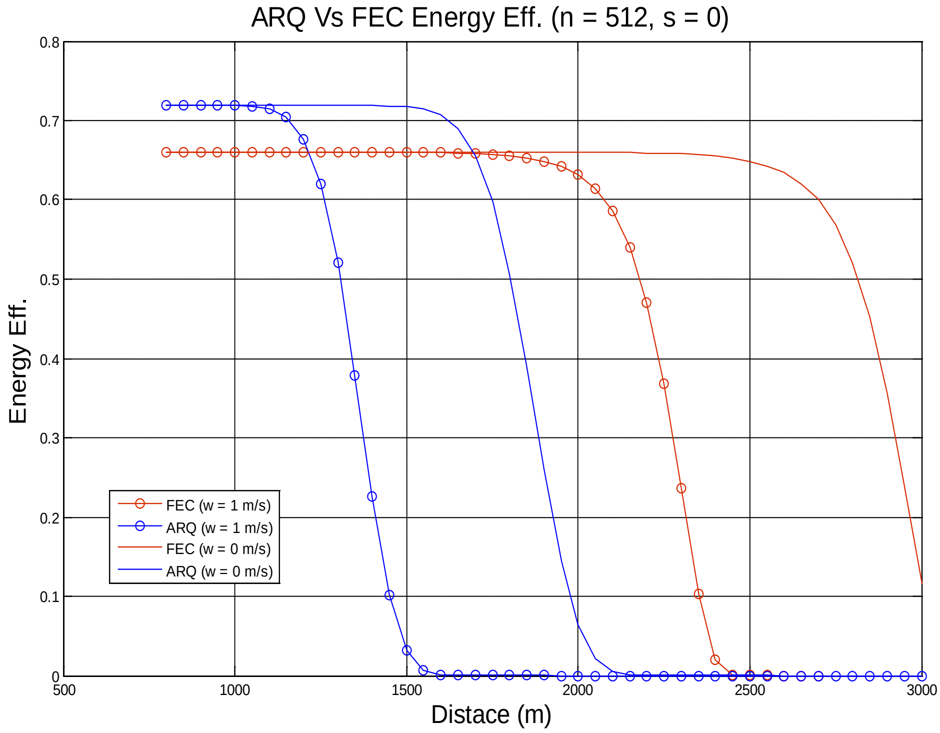


Figure 3.10(b): ARQ Vs FEC Energy Efficiency (n = 512 bit, Variable Wind Speed)

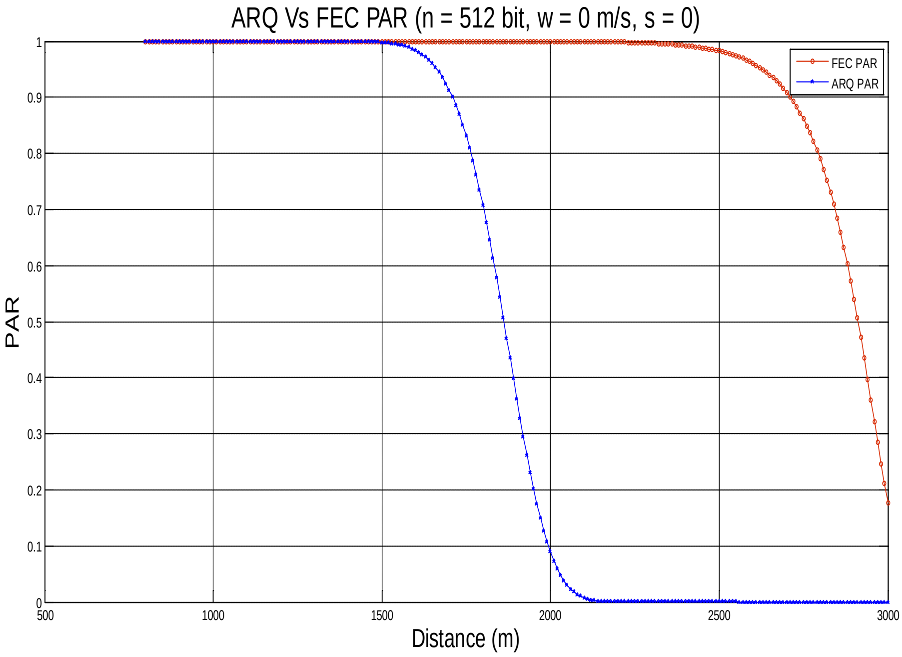


Figure 3.10(c): ARQ Vs FEC PAR (n = 512 bit, w = 0 m/s, s = 0)

In Figures 3.11 (a) and3.11 (b); energy efficiency for a packet size of 1024 bit is studied. It is clear that shipping factor has no noticeable effects on energy efficiency, where as for wind speed, it is shown that ARQ is more efficient than FEC below the cut-off distance and less efficient after that, this cut-off distance decrease from 1650 m when no wind exists to 1200 m when wind speed of 1 m/s exists. It is also clear that ARQ efficiency starts to decrease at 1450 m when no wind exists, and at 1100 m when the wind speed is 1 m/s, where-as for FEC it starts to decrease at 2200 m when no wind exists, and at 1650 m when there is 1 m/s wind speed.

Regarding PAR, both techniques have 100 % PAR when the distance is less than 1450 m when there is no wind as in Figure 3-11 (c). After 1450 m ARQ PAR starts to decrease until it becomes 90 % at distance of 1650 m where FEC PAR continues with PAR of 100 % until 2350 m and more than 90 % until 2650 m.

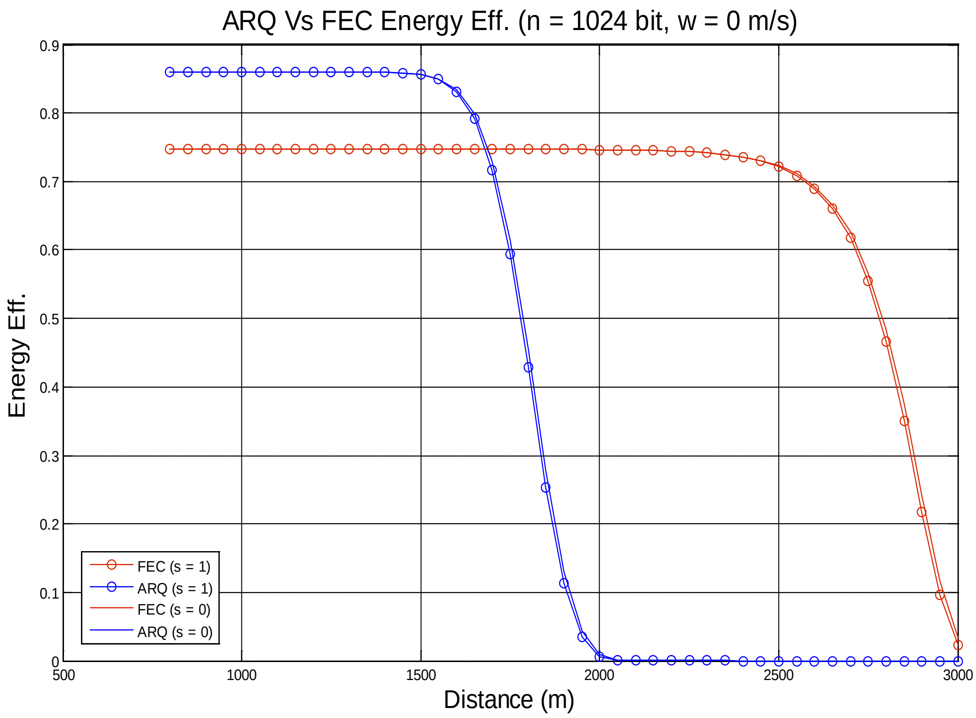


Figure 3.11 (a): ARQ Vs FEC Energy Efficiency (n = 1024 bit, Variable Shipping Factor)

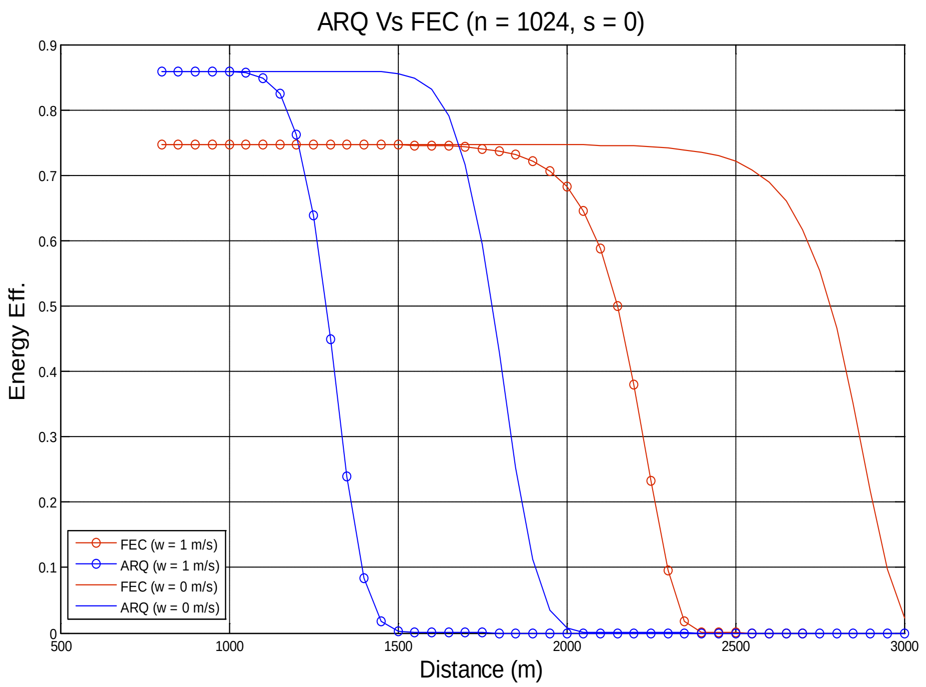


Figure 3.11 (b): ARQ Vs FEC Energy Efficiency (n = 1024 bit, Variable Wind Speed)

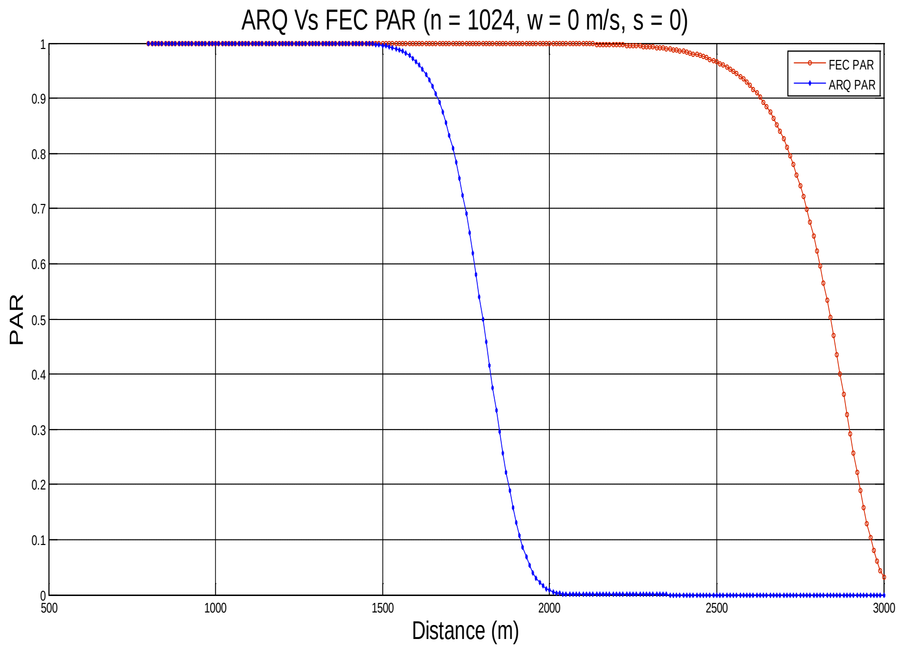


Figure 3.11(c): ARQ Vs FEC PAR (n = 1024 bit, w = 0 m/s, s = 0)

In Figures 3.12 (a) and3.12 (b) for a packet size of 2048 bit the effect of shipping is negligible, whereas the effect of wind speed is clearly visible, and the cut-off distance decreases from 1600 m when no wind exists to 1100 m when wind speed of 1 m/s exists. It is also clear that ARQ efficiency starts to decrease at 1400 m when no wind exists, and when the wind speed is 1 m/s it starts to decrease at 1000 m,; whereas for

FEC it starts to decrease at 2000 m in case of no wind, and at 1600 when there is 1 m/s wind speed.

Regarding PAR, both techniques have 100 % PAR when the distance is less than 1400 m when there is no wind as in Figure 3.11 (c). After 1400 m ARQ PAR starts to decrease until it becomes 90 % at distance of 1620 m where FEC PAR continues with PAR of 100 % until 2220 m and more than 90 % until 2550 m.

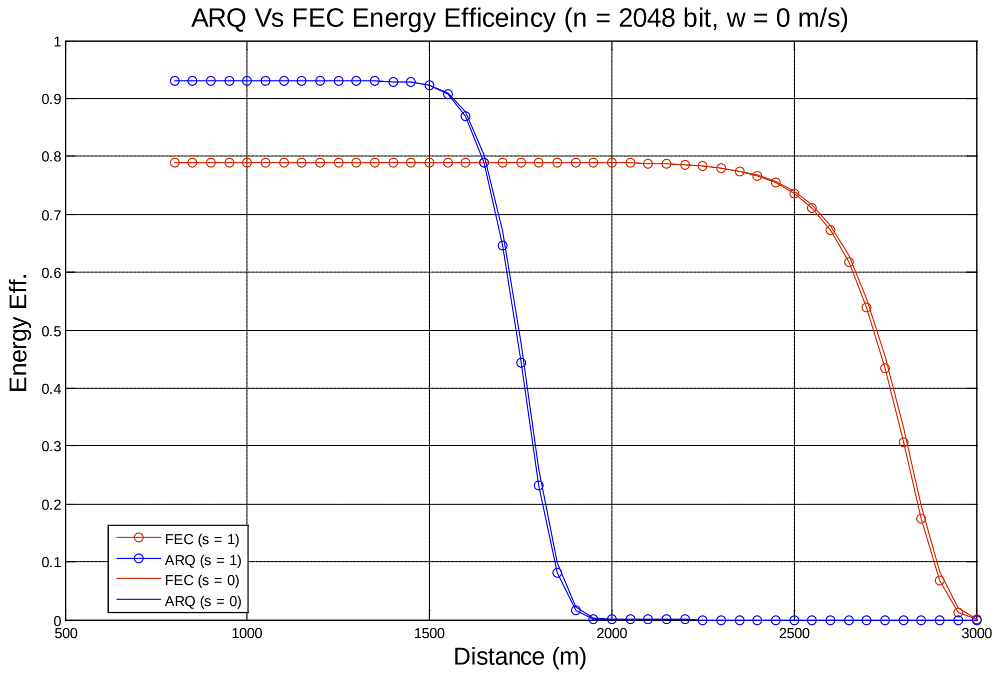


Figure 3.12 (a): ARQ Vs FEC Energy Efficiency (n = 2048 bit, Variable Shipping Factor)

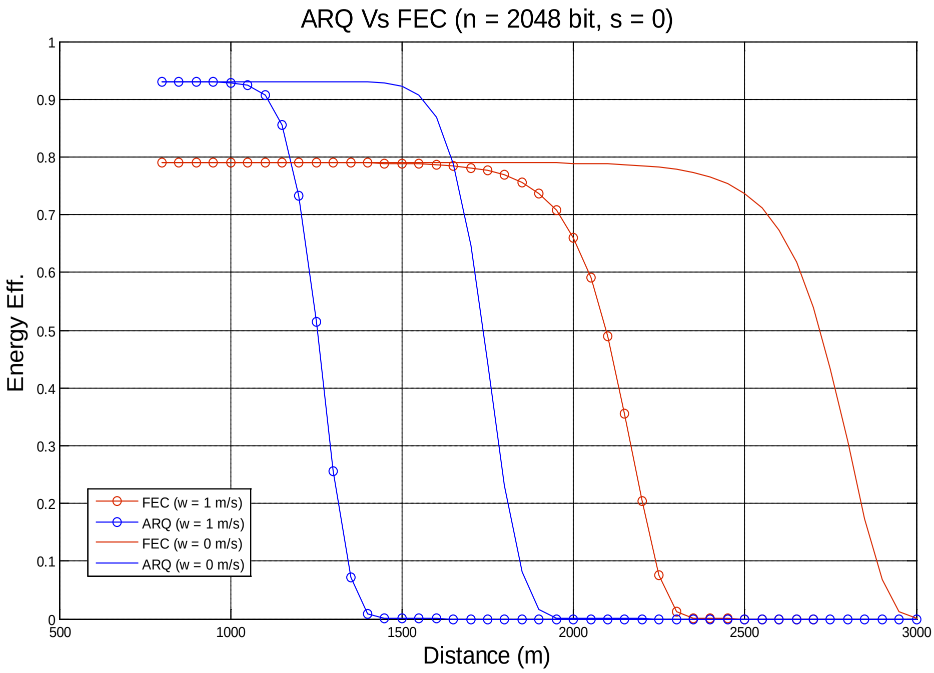


Figure 3.12 (b): ARQ Vs FEC Energy Efficiency (n = 2048 bit, Variable Wind Speed)

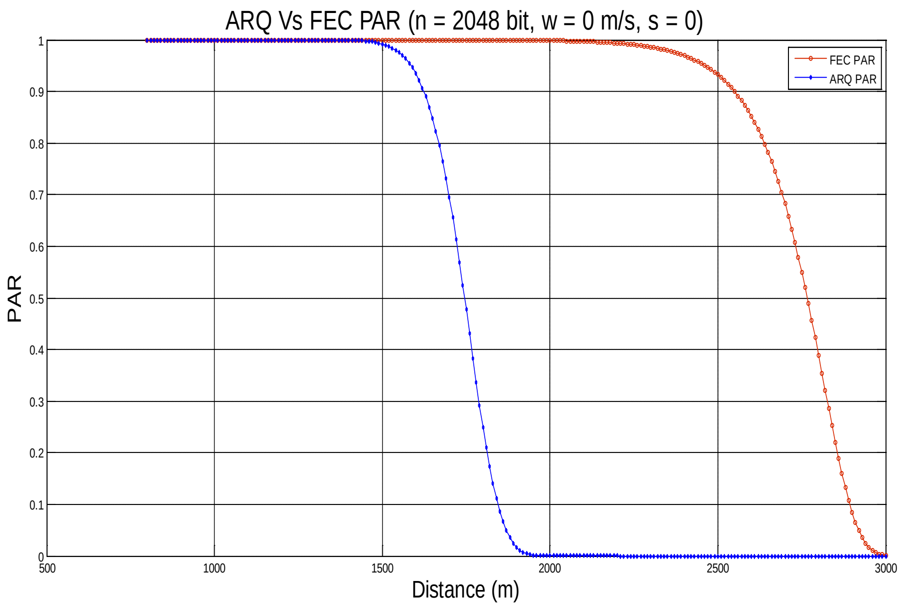


Figure 3.12(c): ARQ Vs FEC PAR (n = 2048 bit, w = 0 m/s, s = 0)

3.6 Conclusion

In this chapter a mathematical derivation for energy efficiencies of ARQ and FEC has been done, and a comparison between the two techniques in terms of energy efficiency and PAR in underwater environment is presented. Simulation is done which validates the mathematical derivation results. It is found that energy efficiency in underwater increases with increasing packet size in short distances and decreases with packet size in longer distances. It is also found that ARQ is more energy efficient below a specific distance (cut-off distance), whereas FEC is more efficient after that distance. This cut-off distance is affected by the packet length and wind speed. Shipping factor has been found to have no effect on this frequency values.

From those results we can say that variable distances and variable channel conditions which characterize underwater channel make it energy inefficient to use one or fixed type of error correction techniques.

The results obtained from this chapter will be the basis for designing and implementing a new adaptive hybrid energy efficient error correction protocol for underwater wireless sensor networks in the next chapter.

CHAPTER 4

ADAPTIVE HYBRID ENERGY EFFICIENT ERROR CORRECTION TECHNIQUE FOR UWSN

4.1 Introduction

As it is energy inefficient to use one or fixed type of error correction in a variable underwater channel conditions and variable distances between sensor nodes due to water current; it is important to propose hybrid error correction technique. This hybrid error correction technique must adapt to the variation in channel conditions and to the variation in distances between sensor nodes.

In this chapter we will propose an Adaptive Hybrid energy efficient Error Correction (AHEC) technique for Underwater Wireless Sensor Networks (UWSN). The proposed technique will depends on an adaptation algorithm which determines what is the most energy efficient error correction technique for the current channel conditions and distance. The adaptation algorithm is based on the current Bit Error Rate (BER), current error correction technique, and a pre-calculated Packet Acceptance Rate (PAR) ranges look-up table which is pre-calculated using the energy efficiency derivation has been done on chapter three. Based on this adaptation algorithm a periodically 3-bit feedback is added to the acknowledgement packet to tell the sender which error correction technique is most suitable for current channel conditions and distance. The error correction is chosen from a pure ARQ in a good channel conditions and short distances to a hybrid of ARQ and FEC with variable encoding rates on bad channel condition and long distances.

In this chapter adaptive hybrid error correction technique main concept will be presented in section 2, and then the AHEC technique algorithm will be presented in section 3. In section 4 we will present how to calculate the pre-calculated PAR ranges look-up table. In section 5 we will present the case where power supply variability is used as adaptation factor. In section 6 we will make energy efficiency analysis for Adaptive Redundancy Reliable Transport Protocol (ARRTP)[72], previously known as Adaptive rELIable traNsport protocol (ADELIN) [5] so as to make a comparison between it and our AHEC technique. In section 7 we will compare our AHEC technique with the techniques that use only ARQ or only FEC as error correction technique in variable channel conditions and variable distance cases, and then we will compare it with the case when variable power supply is used in adaptation. AHEC technique will also be compared with ARRTP in a variable distances case. In the last section we will conclude the chapter.

4.2 Adaptive Hybrid Error Correction Technique

The results of the derivations in chapter three state that energy efficiency of error correction techniques varies with the variation in transmission distances and channel conditions. In some cases, one technique is better than the other, and vice versa. With this in mind we propose AHEC technique which achieves high energy efficiency in a varying distance, variable channel condition cases by adaptively changes the error correction technique used.

The technique works like this: for variable distances and variable channel conditions, AHEC technique always search for the technique with the highest energy efficiency, and since reliability is one part in energy efficiency calculation as stated in equation (3.10), it will also be a reliable technique. The technique depends on an adaptation algorithm which based on the current PAR, current encoding technique used, and a pre-calculated PAR ranges look-up table to determine which error correction technique is most suitable for the current distance and current channel conditions. AHEC technique can designed as in the diagram Figure 4.1, and flowchart Figure 4.3.

In AHEC technique, only modulation technique (i.e. ARQ) is used in good channel conditions and short distances, which means low BER. Selective-Repeat-reQuest ARQ will be the most suitable type of ARQ for two reasons:

- As the bit error rate is very low, no acknowledgement is needed for every packet, so either Go-Back-N or selective repeat is most suitable.
- In Go-back-N, the error packet and all the subsequent packets will be retransmitted, which results in a waste of energy; whereas in selective repeat only the error packet will be retransmitted.

In bad channel conditions and long distances a hybrid of ARQ and variable code rates convolutional encoding are used. Convolutional encoding is used for two reasons also:

- It is the best encoding technique for underwater communications as stated by [26].
- With convolutional coding, we can easily use puncturing technique to obtain variable code rates, which is needed in our AHEC technique.

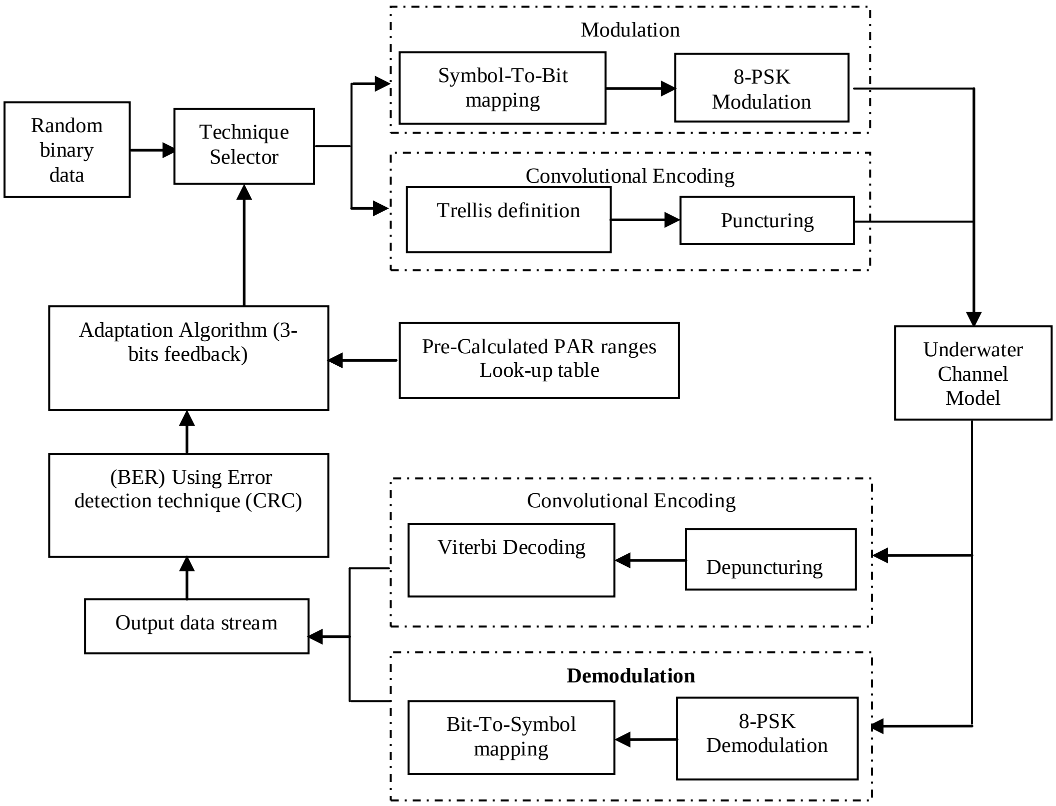


Figure 4.1: AHEC Technique Design

Variable code rates are obtained using puncturing technique by deleting a part of the bits of low-rate convolution code [95], as in Table 4.1, and it is represented in MATLAB using systematic puncturing convolution codes with the parameters obtained from [95] as shown in Table 4.2.

Table 4.1: Puncturing Matrix

Code rate	Puncturing Matrix
2/3	[1 1 0 1]
3/4	[1 1 0 1 1 0]
4/5	[1 1 0 1 1 0 1 0]
5/6	[1 1 0 1 1 0 1 0 1 0]
6/7	[1 1 0 1 1 0 1 0 1 0 1 0]

Table 4.2: Minimum Hamming Distances (d_{free}) and Weight Distribution (w_{dfree}) for Variable Rate Convolutional Codes.

Rc	2/3	3/4	4/5	5/6	6/7
d_{free}	3	3	2	2	2
w_{dfree}	1	15	1	2	5
$w_{dfree+1}$	10	104	36	111	186
$w_{dfree+2}$	54	540	309	974	1942
$w_{dfree+3}$	226	2520	2058	6815	16428
$W_{dfree+4}$	853	11048	12031	43598	124469
$W_{dfree+5}$	3038	46516	65754	263671	887512
$W_{dfree+6}$	10432	190448	344656	1536563	6088910
$W_{dfree+7}$	34836	763944	1755310	8724988	40664781
$W_{dfree+8}$	114197	3016844	8754128	46801477	266250132

4.3 AHEC Technique Adaptation Algorithm

The adaptation algorithm is as follows:

Using error detection technique in the receiver, BER is periodically calculated, and from the BER, PAR is calculated using the packet length n as:

$$PAR = (1 - BER)^n \tag{4.1}$$

Then the suitable error correction technique is calculated from the function:

$$J = f(PAR, I, PARMAX(I, J), PARMIN(I, J)) \tag{4.2}$$

where J is the suitable error correction technique required, PAR is the current packet acceptance rate, I is the current error correction technique used, and *PARMAX(I,J), PARMIN(I,J)* are the pre-calculated PAR ranges look-up.

We can mathematically model this function as in the following formula:

$$J = \sum_{n=1}^{6} n \times I_{A_i^n}(PAR) \tag{4.3}$$

where A_i^n is a look-up table taken from the energy efficiency derivation of six error correction techniques (One ARQ and five varying code rates FEC), and

$$I_B(x) = \begin{cases} 1....if.x \in B \\ 0.....otherwise \end{cases} \tag{4.4}$$

From the value of J obtained, a 3-bit feedback is added to the acknowledgement to state which error correction technique to use as in Table 4.3 below:

Table 4.3: Error Correction Techniques Details

Correction Technique	Consists of	FEC Code Rate	Feedback
1	Pure ARQ		000
2	Hybrid ARQ& FEC	6/7	001
3	Hybrid ARQ& FEC	5/6	010
4	Hybrid ARQ& FEC	4/5	011
5	Hybrid ARQ& FEC	3/4	100
6	Hybrid ARQ& FEC	2/3	101

The adaptation algorithm can be written in algorithm 4.1 Figure 4.2 below:

Algorithm 4.1 Adaptation Algorithm

Feedback *($BER_{current}$(current BER) , n (packet length), PARMAX(I,J), PARMIN(I,J), I (current error correction technique))*

1 let J=1

2 $PAR_{current} = (1 - BER_{current})^n$

3 If PARMIN(I,J) < $PAR_{current}$ *<PARMAX(I,J)*

4 Suitable Error Correction Technique = J

5 Go to 8

6 else J=J+1

7 Go back 3

8 If J = 1, then Feedback = 000

9 Else If j = 2, then Feedback = 001

10 Else If J = 3, then Feedback = 010

11 Else If J = 4, then Feedback = 100

12 Else If J =5, then Feedback = 101

13 Else Feedback = 110

14 end

Return(Feedback)

Figure 4.2: Algorithm 4.1 Adaptation Algorithm

This algorithm can be explained by flowchart 4.1 in Figure 4.3.

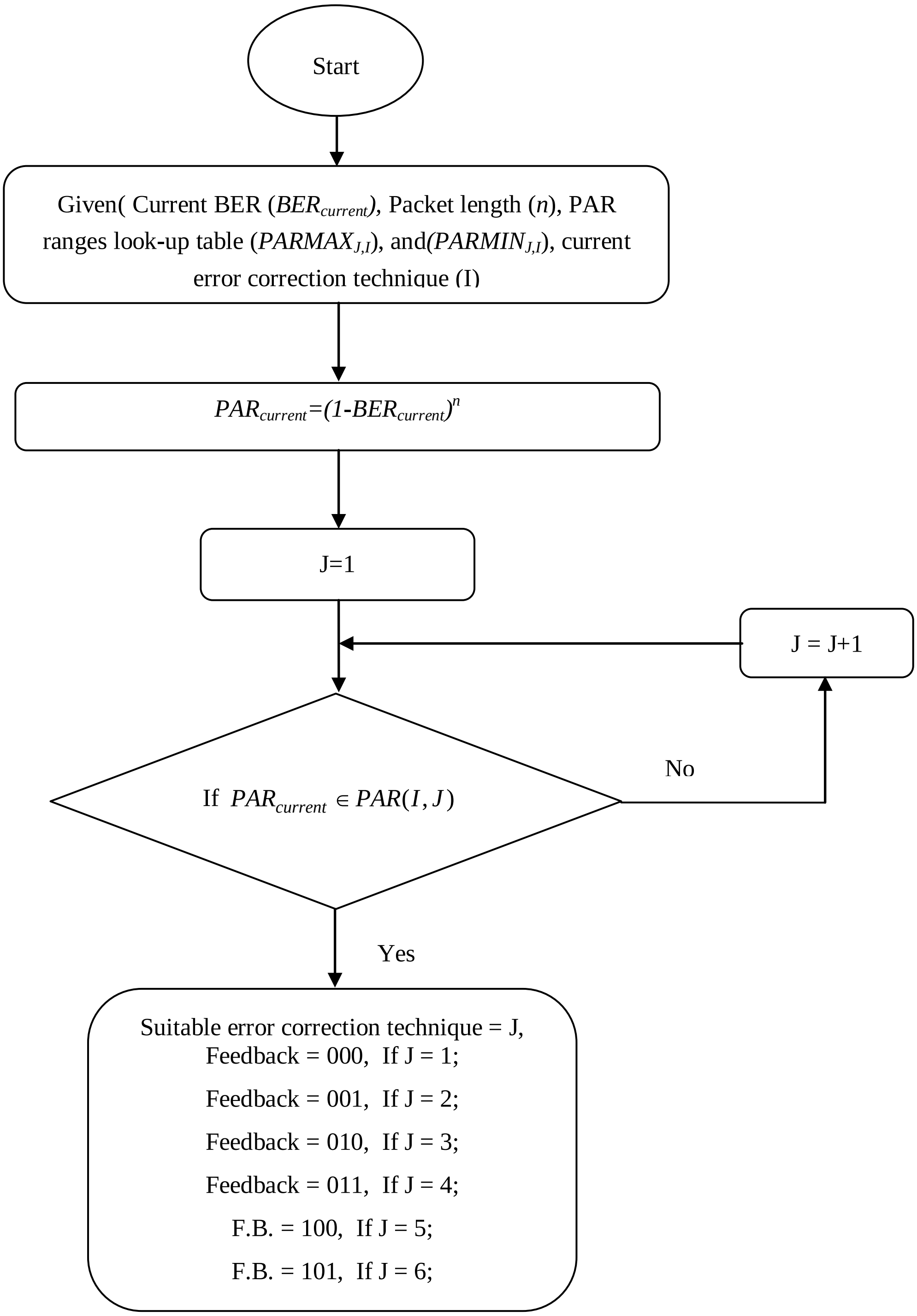


Figure 4.3: Adaptation Algorithm Flowchart

4.4 Pre-Calculated PAR Ranges Look-Up Table Calculations

The pre-calculated PAR ranges look-up table is calculated as follows:

1. Energy efficiencies and PARs of the six error correction techniques (One ARQ plus five variable code rates FECs) for variable values of SNR are found as in algorithms 3.2 and 3.3, and is given as in Table 4.5. (SNR is taken as a measure for distance and channel conditions variations).

2. Starting with the SNR values which gives PAR values equal to 1 for all the techniques; at this SNR ARQ will have the maximum energy efficiency compared to the others, so the PAR for all those technique at this point is the maximum values in the ranges which makes the suitable technique is technique 1 (pure ARQ).
This means $PARMAX_{J,1} = 1$, i.e. if the current technique is J and the current PAR is in the range that has 1 as the maximum value, then technique one is the most energy efficient technique.

3. Then decreasing SNR value until the energy efficiency of the first technique is less than the energy efficiency of the second technique; at this SNR the PAR for all technique will be the minimum values in the ranges which makes the suitable technique is technique 1 (pure ARQ). This means the PAR of any technique J at this point = $PARMIN_{J,1}$,i.e. if the PAR of the current technique J is in between $PARMIN_{J,1}$ and $PARMAX_{J,1}$then technique one is the most energy efficient technique.

As the minimum values in the first ranges equal the maximum values in the second range, then:

$$PARMAX_{J,2} = PARMIN_{J,1}$$

4. Then decreasing SNR value until the energy efficiency of the second technique is less than the energy efficiency of the third technique; at this SNR the PAR for all technique will be the minimum values in the ranges which makes the suitable technique is technique number two.

This means the PAR of any technique J at this point = $PARMIN_{J,2}$i.e. if the PAR of the current technique J is in between $PARMIN_{J,2}$ and $PARMAX_{J,2}$, then technique number 2 is the most energy efficient technique.

As the minimum values in the second ranges equal the maximum values in the third range, then:

$$PARMAX_{J,3} = PARMIN_{J,2}$$

5. Then decreasing SNR value until the energy efficiency of the third technique is less than the energy efficiency of the fourth technique; at this SNR the PAR for all technique will be the minimum values in the ranges which makes the suitable technique is technique number 3.

This means the PAR of any technique J at this point = $PARMIN_{J,3}$ i.e. if the PAR of the current technique J is in between $PARMIN_{J,3}$ and $PARMAX_{J,3}$, then technique number 3 is the most energy efficient technique.

As the minimum values in the third ranges equal the maximum values in the fourth range, then:

$$PARMAX_{J,4} = PARMIN_{J,3}$$

6. Then decreasing SNR value until the energy efficiency of the fourth technique is less than the energy efficiency of the fifth technique; at this SNR the PAR for all technique will be the minimum values in the ranges which makes the suitable technique is technique number 4.

This means the PAR of any technique J at this point = $PARMIN_{J,4}$ i.e. if the PAR of the current technique J is in between $PARMIN_{J,4}$ and $PARMAX_{J,4}$, then technique number 4 is the most energy efficient technique.

As the minimum values in the fourth ranges equal the maximum values in the fifth range, then:

$$PARMAX_{J,5} = PARMIN_{J,4}$$

7. Then decreasing SNR value until the energy efficiency of the fifth technique is less than the energy efficiency of the six technique; at this SNR the PAR for all technique will be the minimum values in the ranges which makes the suitable technique is technique 5.

This means the PAR of any technique J at this point = $PARMIN_{J,5}$ i.e. if the PAR of the current technique J is in between $PARMIN_{J,5}$ and $PARMAX_{J,5}$, then technique number 5 is the most energy efficient technique.

As the minimum values in the fifth ranges equal the maximum values in the sixth range, then:

$$PARMAX_{J,6} = PARMIN_{J,5}$$

8. At last zero will be the minimum values for the ranges that makes technique six is the most energy efficient technique ($PARMIN_{J,6} = 0$, for all techniques).

The pre-calculated PAR ranges look-up table can be calculated from algorithm 4.2 in Figure 4.4

Algorithm 4.2: PAR Ranges Look-Up Table Calculation

PARMAX(I,J), PARMIN(I,J)(*Energy Eff (J, SNR) from algorithm 3.2 (ARQ Energy Efficiency calculation), and algorithm 3.3 (FEC Energy Efficiency calculations))*
1 for J = 1:6;
*2*$PARMAX_{J,1} = 1; PARMIN_{J,6} = 0;$
3 SNR = SNRMAX;//SNRMAX is the any value of SNR which gives PAR equal 1 for all techniques//
4 For I= 1:5;
5 If Energy Eff. (I, SNR)<Energy Eff. (I+1, SNR);
6 then $PARMIN_{J,I}$ *= PAR (J, SNR);*
7 $PARMAX_{J+1,I}$ *= PAR (J, SNR);*
8 SNR = SNR -1;
9 else go to 5;
10 end;
11 end;
Return ($PARMIN_{J,I}$***,*** $PARMAX_{J,I}$ ***)****//The maximum and minimum values in the lookup table from error correction techniques 1 to error correction techniques 6//*

Figure 4.4: Algorithm 4.2 Pre-Calculated PAR Ranges Look-Up Table Calculation

4.5 Adaptive Variable Power Supply (AVPS)

Adaptivity for the variation in distances and channel conditions can also be achieved using variable power supply; for different channel conditions and different distances variable transmit power values can be used to achieve the highest energy efficiency using the same idea of adaptation algorithm. When using variable power supply as adaptation, ARQ with six different power supply values as in Table 4.4 is used instead of the six error correction techniques used in AHEC technique to calculate the pre-calculated PAR ranges look-up table. The energy efficiency in case of variable power supply can be calculated using the following formula:

$$
\begin{aligned}
Eff_{vps-ARQ} &= \frac{E_{ARQ}^{eff}}{E_{ARQ}^{tot}}(1 - PER_{ARQ}) \times \frac{P_{ref}}{P_t} \\
&= \frac{n}{n + \alpha + \tau + ack}(1 - PER_{ARQ}) \times (\frac{P_{ref}}{P_t}) \qquad (4.4)
\end{aligned}
$$

Where $Eff_{vps-ARQ}$ is the energy efficiency for ARQ when using variable power supply, P_{ref} is a reference transmit power, or the designed power, and P_t is the variable transmit power.

From the pre-calculated PAR ranges look-up table, current PAR, and current power supply value used, the suitable power supply values which will gives the most energy efficient transmission can be calculated.

Table 4.4: AVPS Error Correction Technique Details

Correction technique	Transmit power (Watt)	Feedback
1	2.0	000
2	2.5	001
3	3.0	010
4	3.5	011
5	4.0	100
6	4.5	101

4.6 Internodes Distance-Based Adaptive Redundancy Reliable Transport Protocol (ARRTP) Energy Efficiency Derivation

Energy Efficiencies for different ARRTP schemes [72], Figure 4.5, previously known as ADELIN [5] is found as follows:

For non-cooperative scheme-1,

$$PAR_{scheme-1} = \sum_{i=0}^{t} \binom{n}{i} (1-P_b)^{n-i} (P_b)^i \tag{4.5}$$

where $PAR_{scheme-1}$ is the packet acceptance rate, t is the correctability factor, n is the packet length.

$$Eff_{scheme-1} = \frac{E^{eff}_{scheme-1}}{E^{tot}_{scheme-1}} (PAR_{scheme-1})$$

$$= \frac{n-\alpha-\Phi}{n} (PAR_{scheme-1}) \tag{4.6}$$

For non-cooperative scheme-2 and scheme-3, since reconstructing k original data packets needs receiving any k packets out of $k+s$ packets, the probability of successfully transmission of k packets is given by:

$$PAR_{scheme-2,3} = \sum_{i=k}^{k+s} \binom{k+s}{i} \times P_s^i (1-P_s)^{k+s-i} \tag{4.7}$$

where P_s is the probability of successfully transmitting one packet over one hob without encoding for scheme-2 and with BCH coding for scheme-3 which is the same as equation (4.5).

For scheme-2 energy efficiency can be given by:

$$Eff_{scheme-2} = \frac{E^{eff}_{scheme-2}}{E^{tot}_{scheme-2}} (PAR_{scheme-2})$$

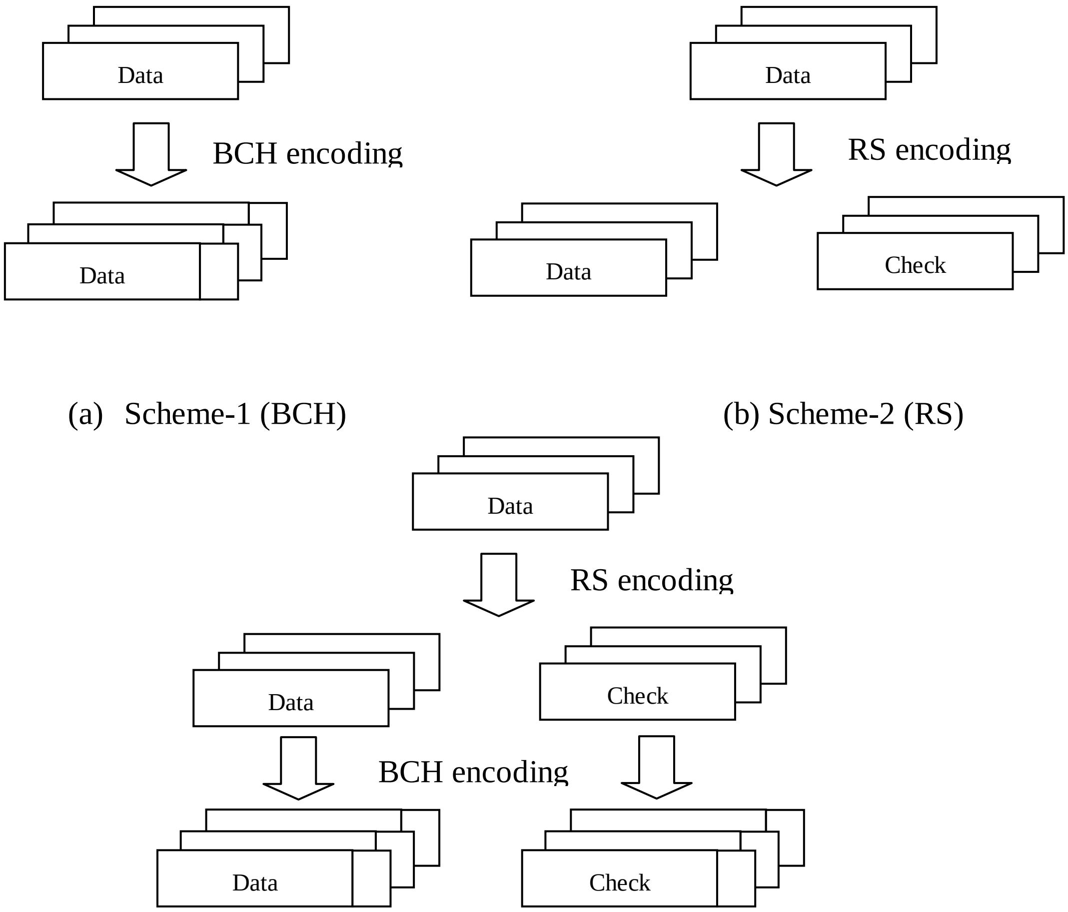
$$= \frac{k(n-\alpha)}{(k+s)n}(PAR_{scheme-2}) \tag{4.8}$$

And scheme-3, energy efficiency can be given by:

$$Eff_{scheme-3} = \frac{E^{eff}_{scheme-3}}{E^{tot}_{scheme-3}}(PAR_{scheme-3})$$

$$= \frac{k(n-\alpha)}{(k+s)(n+\Phi)}(PAR_{scheme-3}) \tag{4.9}$$

where Φ is overhead in the data packet due to BCH coding and the overhead in the check packet due to BCH coding.



(c) Scheme-3 (BCH-RS)

Figure 4.5: Different ARRTP Schemes

4.7 Results and Discus sion

In this section we first present how to calculate the pre-calculated PAR ranges look-up table, which is an essential part in our adaptation algorithm, then we will compare our AHEC technique with the previous works in the literature that depend on only ARQ or only FEC for error correction [15, 67-69, 71, 96] in variable channel conditions and variable distances. In part three of this section we will compare AHEC technique with AVPS which uses variable power supply in adaptation. In the last part we will compare it with ARRTP [72], previously ADELIN [5] for variable transmission distances.

4.7.1 AHEC Technique Energy Efficiency Calculations

To calculate the pre-calculated PAR ranges look-up table, energy efficiencies versus PARs for the six techniques are calculated using algorithms 3.2 for ARQ and algorithm 3.3 for the five variable code rate FEC, which can be displayed in Table 4.5 below:

Table 4.5: Energy Efficiency Vs PAR for the Six Error Correction Techniques

SNR\ECT	ECT6 Eff	ECT6	ECT5 Eff	ECT5	ECT4 Eff	ECT4	ECT3 Eff	ECT3	ECT2 Eff	ECT2	ECT1 Eff	ECT1
18	0.494	1.0	0.578	1.0	0.627	1.0	0.660	1.0	0.684	1.0	0.714	0.994
*	*	*	*	*	*	*	*	*	*	*	*	*
17	0.494	1.0	0.578	1.0	0.627	1.0	0.660	1.0	0.684	1.0	0.688	9.5E-01
16.9	0.494	1.0	0.578	1.0	0.627	1.0	0.660	1.0	0.684	1.0	0.682	9.4E-01
16.8	0.494	1.0	0.578	1.0	0.627	1.0	0.660	1.0	0.684	1.0	0.675	9.4E-01
*	*	*	*	*	*	*	*	*	*	*	*	*

6.8	6.9	7	*	7.4	7.5	7.6	*	8.2	8.3	8.4	8.5	8.6	8.7
0.466	0.470	0.473	*	0.482	0.483	0.485	*	0.490	0.490	0.491	0.491	0.491	0.492
9.43E-01	9.5E-01	9.57E-01	*	9.75E-01	9.78E-01	9.81E-01	*	9.9E-01	0.992	0.993	0.994	0.995	0.995
4.54E-01	4.7E-01	4.82E-01	*	5.21E-01	5.28E-01	5.34E-01	*	5.6E-01	5.6E-01	0.562	0.564	0.566	0.567
7.85E-01	8.1E-01	8.33E-01	*	9.00E-01	9.13E-01	9.23E-01	*	9.7E-01	9.7E-01	0.973	0.976	0.979	0.981
3.98E-01	4.2E-01	4.44E-01	*	5.12E-01	5.24E-01	5.36E-01	*	5.8E-01	5.9E-01	0.590	0.594	0.598	0.601
6.35E-01	6.7E-01	7.09E-01	*	8.16E-01	8.36E-01	8.54E-01	*	9.3E-01	9.4E-01	0.942	0.948	0.953	0.958
2.64E-01	2.9E-01	3.32E-01	*	4.45E-01	4.68E-01	4.88E-01	*	5.7E-01	5.8E-01	0.592	0.599	0.606	0.612
4.00E-01	4.5E-01	5.03E-01	*	6.74E-01	7.08E-01	7.39E-01	*	8.7E-01	8.8E-01	0.897	0.908	0.918	0.927
1.88E-01	2.3E-01	2.61E-01	*	3.94E-01	4.22E-01	4.48E-01	*	5.6E-01	5.7E-01	0.586	0.596	0.605	0.614
2.76E-01	3.3E-01	3.82E-01	*	5.76E-01	6.17E-01	6.55E-01	*	8.2E-01	8.4E-01	0.857	0.872	0.885	0.898
2.97E-39	2.7E-38	2.32E-37	*	1.11E-33	8.68E-33	6.66E-32	*	8.1E-27	5.2E-26	3.24E-25	1.9E-24	1.2E-23	6.6E-23
4.13E-39	3.7E-38	3.23E-37	*	1.54E-33	1.21E-32	9.27E-32	*	1.1E-26	7.2E-26	4.50E-25	2.7E-24	1.6E-23	9.3E-23

From the above table, the pre-calculated PAR ranges look-up table can be calculated using algorithm 4.2, and it can be displayed as in Table 4.6 below:

Table 4.6: Pre-Calculated Look-Up PAR Ranges Table

i\j	1	2	3	4	5	6
1	0.95 -1.0	0.95 – 0.0				
2	1.0	0.89 – 1.0	0.84 -0.89	0.62-0.84	0.32-0.62	0. 00-0.32
3	1.0	0.92 -1.0	0.89 -0.92	0.72 -0.89	0.45-0.72	0.00-0.45
4	1.0	0.96 -1.0	0.94 -0.96	0.85 – 0.94	0.68 -.85	0.00 – 0.68
5	1.0	0.98 – 1.0	0.97 – 0.98	0.92– 0.97	0.81–0.92	0.00 -0.81
6	1.0	0.995 – 1.0	0.992 -0.995	0.992 -0.98	0.95 – 0.98	0.00 – 0.95

From the Pre-calculated PAR ranges look-up table above, and from the current PAR, current encoding technique, AHECT energy efficiency can be calculated as in algorithm 4.1.

4.7.2 AHEC Technique versus the ARQ and FEC Probability of Success and Energy Efficiency

From Figure 4.6 below; it is clear that AHEC technique has higher probability of success (PAR) compared with both ARQ and FEC, except for a short distance from 2200 m to 2400 m; where FEC has a higher probability of success than AHEC technique. This differences which is around 2-3 % has no noticeable effect on the system since both techniques have more than 90 % probability of success.

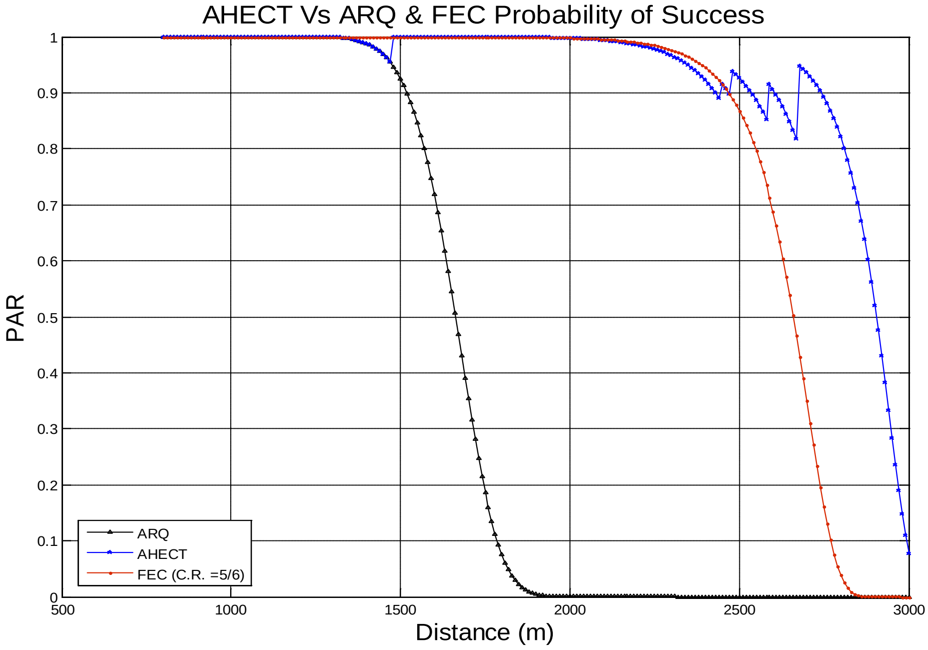


Figure 4.6: AHEC Technique Vs ARQ & FEC Probability of Success

Figure 4.7 below gives a comparison between the energy efficiency of AHEC technique and the pure ARQ and pure FEC for varying distances. From this figure it is clear that AHEC technique is more energy efficient than both ARQ and FEC in variable distances situation.

Compared with the pure ARQ, AHEC technique achieves 10 % increase in saving energy when the distance is around 1500 m and more than 60 % when the distance increases above 1700 m. When compared with FEC, it achieves around 10 % increase in energy saving when the distance is below 1500 m, and around 7 % saving when the distance goes above 1500 m.

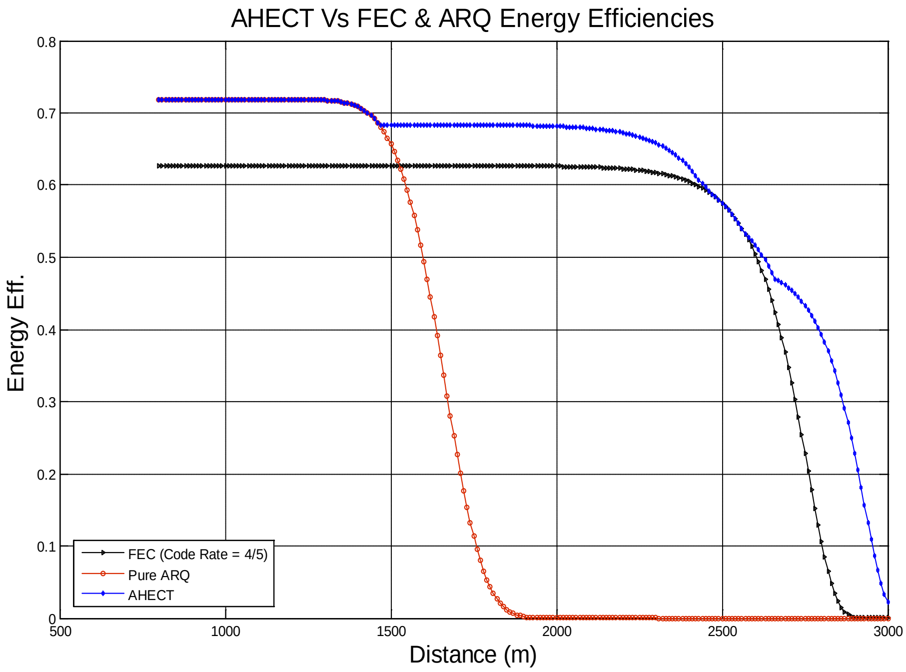


Figure 4.7: AHEC Technique Vs ARQ & FEC Energy Efficiency (Variable Distances Case)

In Figure4.8 variable wind speed is taken as a measure for the variation in channel conditions. From this Figure it is clear that AHEC technique is more energy efficient than both ARQ and FEC for variable wind speed (i.e. variable channel conditions). Compared with the pure ARQ, and when the transmission distance is 1500 m, AHEC technique achieves 6 % increase in energy saving when wind speed is 0.5 m/s, more than 50 % energy saving when wind speed increases to 1 m/s, and more than 60 % when wind speed is greater than 1.5 m/s. When compared with FEC, AHEC technique achieves around 8 % increase in energy saving when wind speed is below 0.5 m/s and around 6 % when wind speed is more than 0.5 m/s.

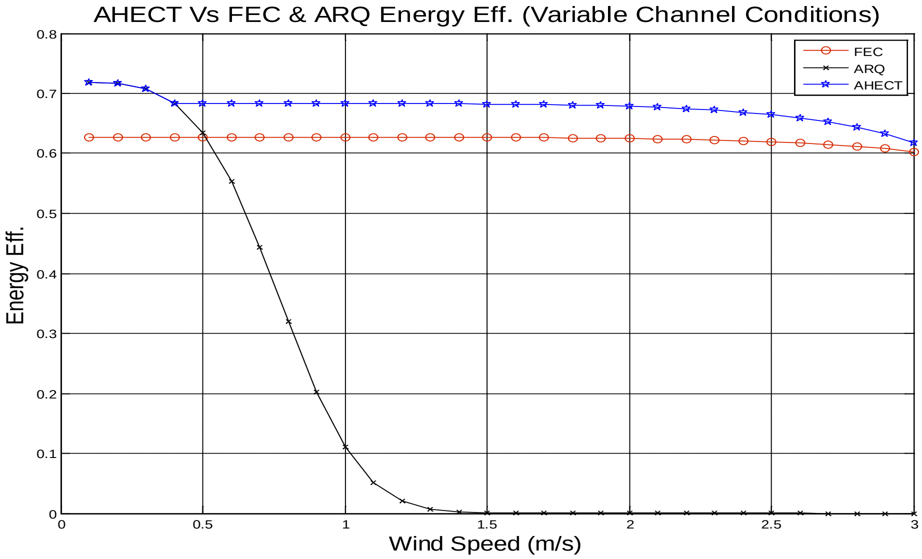


Figure 4.8: AHEC Technique Vs ARQ & FEC Energy Efficiency (Variable Channel Conditions)

4.7.3 AHEC Technique versus AVPS Probability of Success and Energy Efficiency

From Figure 4.9 below, it is clear that AHEC technique has higher probability of success than AVPS. This differences range from 10 % in short distances (around 1000 m) to more than 80 % in long distances (around 2400 m).

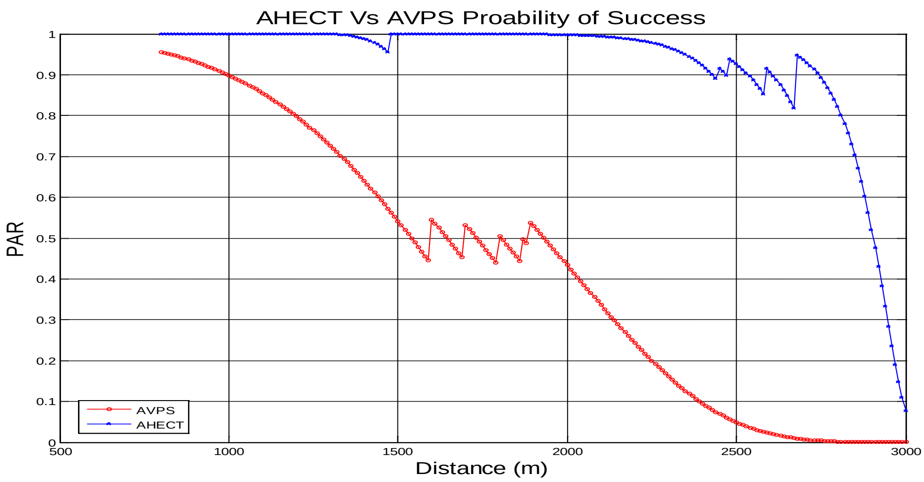


Figure 4.9: AHEC Technique Vs AVPS Probability of Success

Figure 4.10 below gives a comparison between the energy efficiency of AHEC technique and the AVPS for varying distances. From this Figure it is clear that AHEC technique is more energy efficient than AVPS in variable distances situation.

Compared with AVPS, AHEC technique achieves 20 % increase in saving energy when the distance is around 1700 m, and more than 60 % when the distance increase above 2200 m.

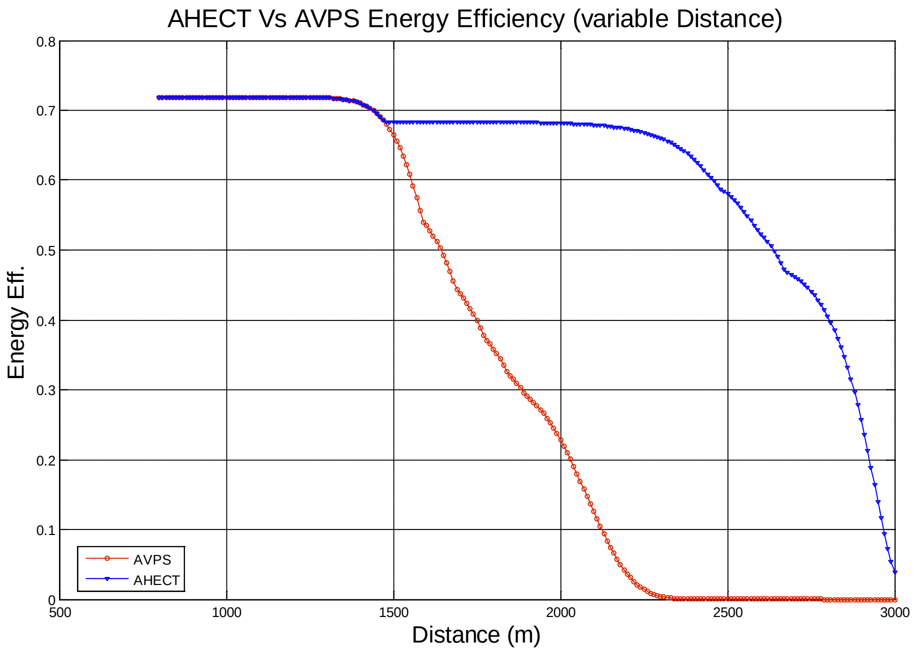


Figure 4.10: AHEC Technique Vs AVPS Energy Efficiency (Variable Distance Case)

In Figure 4.11, variable wind speed is taken as a measure for the variation in channel conditions. From this figure it is clear that AHEC technique is more energy efficient than AVPS for variable wind speed (i.e. variable channel conditions). Compared with AVPS when the transmission distance is 1500 m, AHEC technique achieves 5 % increase in saving energy when there is wind of speed 0.5 m/s, more than 30 % when wind speed increases to 1 m/s, and more than 60 % when wind speed is greater than 2 m/s.

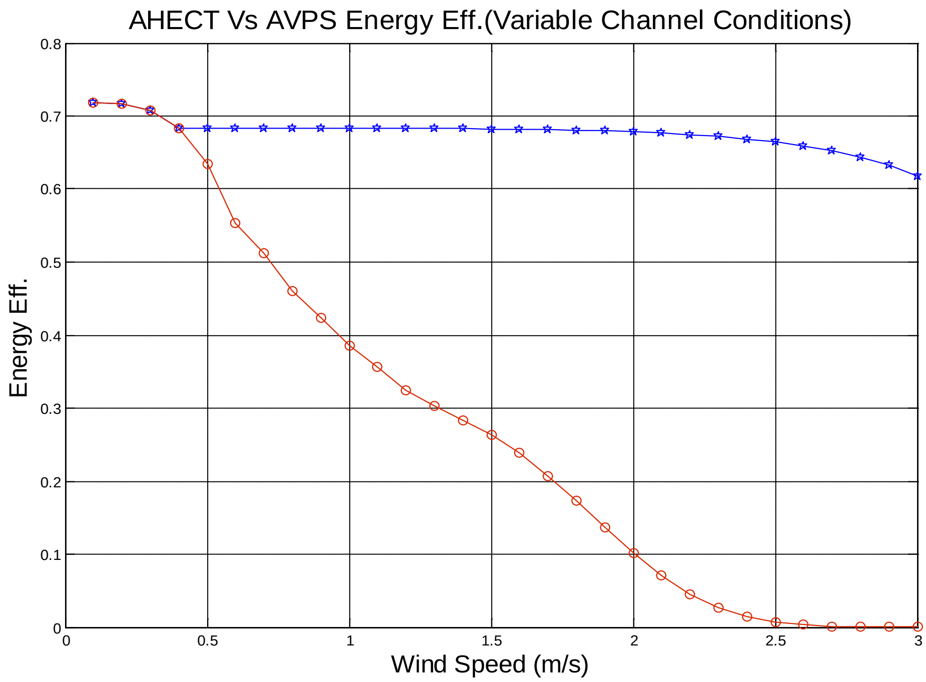


Figure 4.11: AHEC Technique Vs AVPS Energy Efficiency (Variable Channel Conditions)

4.7.4 AHEC Technique versus ARRTP Probability of Success and Energy Efficiency

From the Figure 4.12 below; it is clear that AHEC technique has higher probability of success than ARRTP; this differences range from around 20 % when the transmission distance is around 2000 m to more than 90 % when the transmission reach 2500 m. It is also clear that ARRTP with both BCH and CS has higher probability of success than when having only BCH coding.

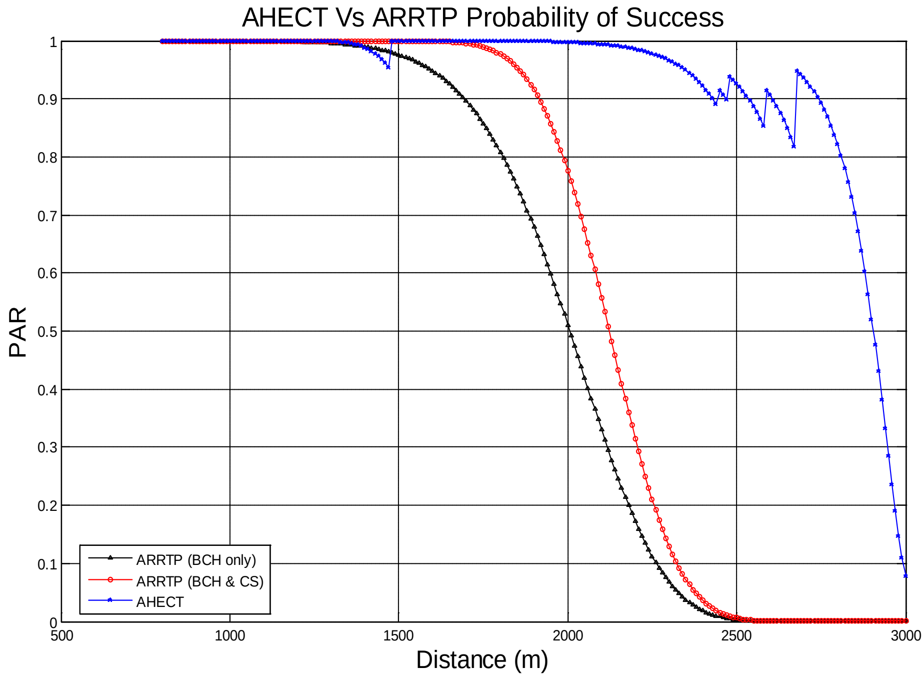


Figure 4.12: AHEC technique Vs ARRTP Probability of Success

Figure 4.13 below gives a comparison between the energy efficiency of AHEC technique and ARRTP for varying distances. From this Figure it is clear that AHEC technique is more energy efficient than both types of ARRTP in variable distances situation.

Compared with ARRTP (Only BCH), AHEC technique achieves 5 % increase in energy saving when the distance is below 1500 m, and more than 50 % when the distance increase above 2200 m. when compared with ARRTP (BCH and CS), AHEC technique achieves around 25 % saving in energy when the distance is less than 1700 m and more than 50 % when the distance is more than 2200 m.

Regarding variable channel conditions, ARRTP don’t adapt to the variations in channel conditions, as it uses approximate formula for calculating noises, which ignore the effect of wind speed and shipping factors.

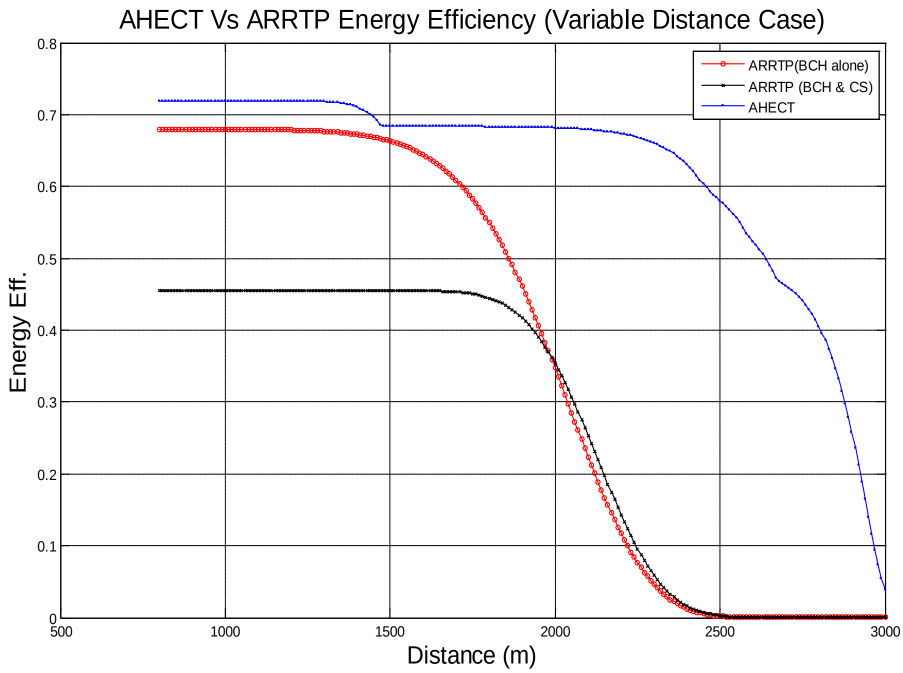


Figure 4.13: AHEC Technique Vs ARRTP Energy Efficiency (Variable Distances Case).

4.8 Conclusions

In this chapter, we have presented our AHEC technique idea, and how the adaptation occurs. The adaptation algorithm is based on:

- A pre-calculated PAR ranges look-up table which depends on the energy efficiency analysis we have done on chapter three.
- Current BER, which can be easily determined using any error detection techniques, packet length, and current error correction techniques.

Based on the results of the adaptation algorithm the receiver sends 3-bit feedback with the acknowledgement telling the sender which error correction technique is most suitable for the current distance and current channel conditions.

The results show that our AHEC technique has more probability of success and more energy efficient than all the other error correction techniques.

CHAPTER 5

VARIABLE ERROR CORRECTION TECHNIQUES APPLICATIONS

5.1. Introduction

Underwater networks are characterized by variable channel conditions[8]. This variability in channel conditions has great effects on the packet probability of success and energy efficiency of communication systems. Many protocols which were proposed for communications in underwater wireless sensors networks don’t take this variability into consideration. Adaptive Redundancy Reliable Transport Protocol (ARRTP) [72], previously known as ADaptive rELIable traNsport protocol (ADELIN) [5] is one of the transport protocols which depends only on inter-node distance in adaptivity to choose between three types of error correction techniques. Another technique which depends only on distance is bounded distance routing protocol [97]. The design of the bounded distance routing protocol is based on the assumption that there is an optimum per hop distance (i.e. optimum number of relays between sender and receiver) that achieves minimum total energy consumptions. In this technique they assumed fixed channel conditions on choosing this optimum per hop distance.

In the first part of this chapter, we will apply our adaptation algorithm which accounts for both distance and channel conditions variations to choose between the three types of error correction technique used in ARRTP. The adaptation algorithm depends on the current error correction technique used, current Bit Error Rate (BER), packet length, and a pre-calculated Packet Acceptance Rate (PAR) ranges look-up table to determine which error correction technique is most suitable for the current channel conditions and distance. We will call this technique Packet Acceptance

Rate-based ARRTP. To do so, we will first describe ARRTP and show how the adaptation occurs. Then we will present the effects of variable channel conditions on the packet probability of success for the three encoding technique used in ARRTP. After that we will describe our adaptation algorithm for ARRTP and present how to calculate the pre-calculated PAR ranges look-up table. The results of applying this adaptation algorithm will be presented in the last section of this part.

In the third part we will apply our AHEC technique to reduce the effects of variable channel conditions on choosing the optimum number of relays in the design of bounded distance routing protocol. To do so, we will first briefly describe bounded distance routing protocol, then we will study the effects of variable channel conditions on choosing the optimum number of relays between sender and receiver in bounded distance routing protocol. After that we will present the result of applying AHEC technique in bounded distance routing protocol.

In the last part we will conclude this chapter

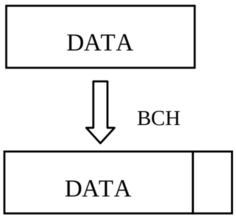
5.2. PAR-Based ARRTP

5.2.1 ARRTP [72]

As an example for redundancy based, three different implementations were investigated as in Figure 5.1 and Figure 5.2 below: the first implementation encodes data packet with bit-level FEC (BCH), whereas the second and third implementations integrate both bit-level and packet-level coding with different encoding rates.

For BCH, consider the following properties: For all positive integers' m and t, there exists a binary BCH code that has a code segment length of $n = 2^m - 1$, of which at most $\varphi = mt$ are overhead bits that can reliably correct up to t errors.

For the RS implementation, the following properties were considered: For RS codes, k original data packets can be reconstructed by receiving any k packets out of k + s ones, with s check packets.



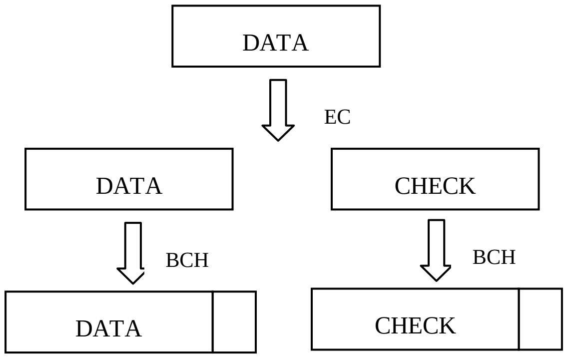


Figure 5.1: BCH Encoding Only   Figure 5.2: BCH-RS Hybrid Encoding

In [5, 72], they studied the performance of three schemes, one BCH only and two different BCH-RS combination in non-cooperative and cooperative mode using two different metrics; probability of success for transmitting a block of packets and the expected energy efficiency. From the results, which can be shown in Figure 5.3 and Figure 5.4, they concluded that to obtain 99 % probability of success they have to use different schemes for different inter-node distances.

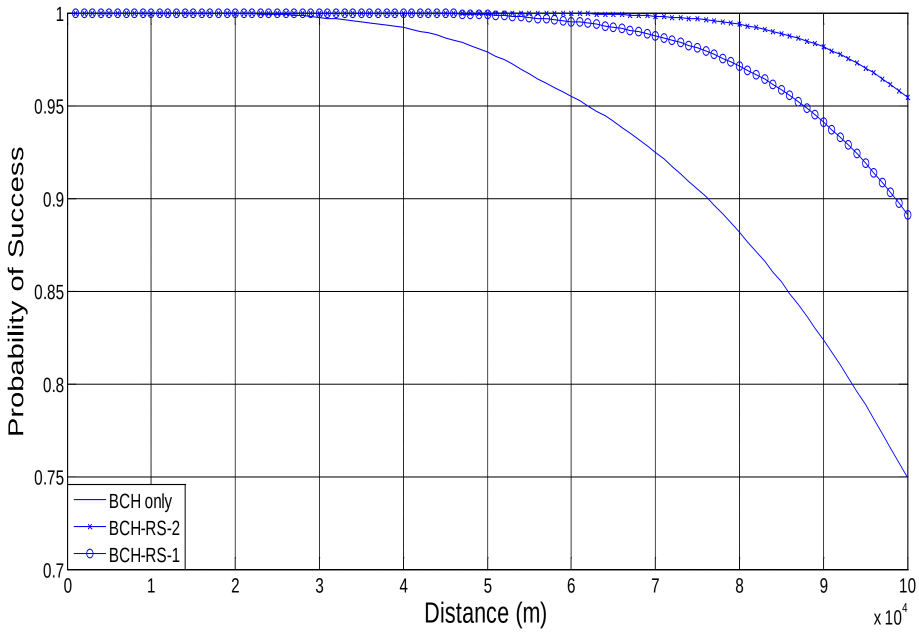


Figure 5.3: Encoding Techniques Probability of Success (Fixed Channel Conditions Case)

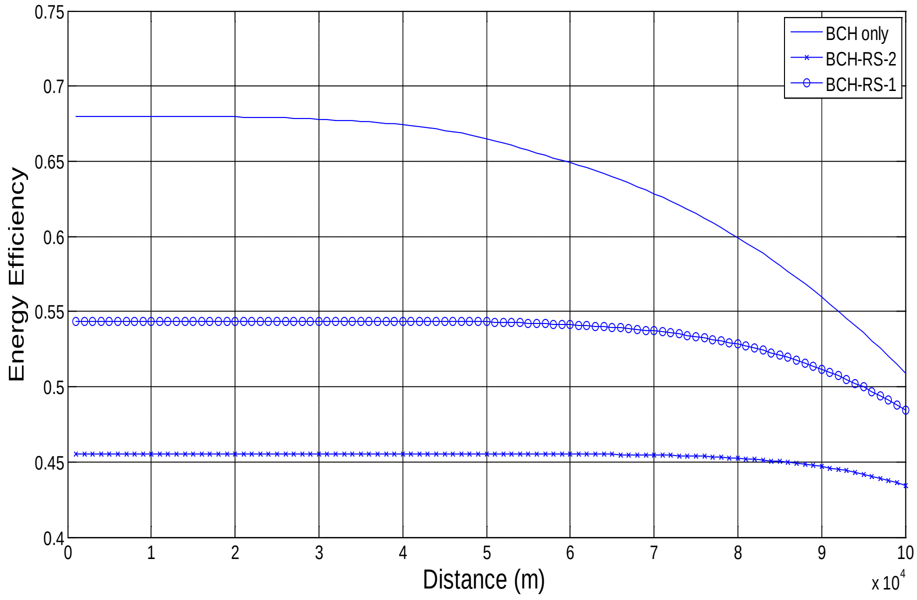


Figure 5.4: Encoding Techniques Energy Efficiency (Fixed Channel Conditions Case)

For ARRTP they use only BCH coding for the range [0 – 40 km] where the probability of success is more than 99 % and the energy efficiency is the maximum compared with the other two techniques. In the range [40 – 65 km], ARRTP uses BCH with RS-1 coding (4 data packets and 1 check packet) where the probability of success is more than 99 % which is better than BCH only, and the energy efficiency is better than BCH with RS-2 coding (4 data packets and 2 check packets). For the rest of the distance ARRTP uses the third technique.

5.2.2. Variable Channel Conditions Effects on ARRTP Packet Probability of Success

In ARRTP [72], an approximate value for noise which is found in [98] is used as:

$$N(f) = 50 - 18\log(f) \qquad (5.1)$$

In this formula for noise calculation they assumed fixed channel conditions. Noise depends only on frequency; it doesn't take the effect of wind speed and shipping factor into account.

The empirical formulas for noise calculation which is found in section 3.2.2 constitute the four major components of noise: turbulence, shipping, wind and thermal noise. Those formulas take the effect of wind speed and shipping factor into account in addition to the frequency.

When we apply those formulas for noise calculation instead of the approximate formula (5.1), the effect of the variation in channel conditions due to wind speed variation can be explained as in Figure 5.5 below:

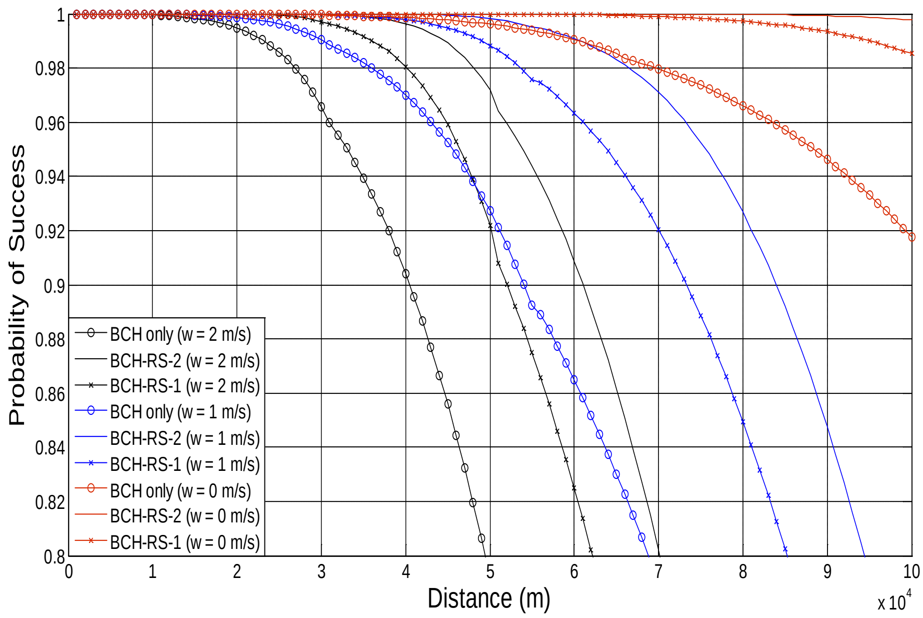


Figure 5.5: Effect of Wind Speed on Packet Probability of Success

From Figure 5.5 above it is clear that the range for obtaining more than 99 % probability of success for BCH only changes from [0 – 23 km] when there is a wind of speed 2 m/s to [0 – 30 km] when there is a wind of speed 1 m/s, and to [0 – 60 km] when there is no wind. For BCH-RS-1; this range change from [0 – 35 km] when there is a wind of speed 2 m/s to [0 – 50 km] when wind speed is 1 m/s, and to [0 – 90 km] when there is no wind. For the third technique; the range for obtaining more than 99 % probability of success changes from [0 – 45 km] when wind speed is 2 m/s to [0 – 65 km] when wind speed is 1 m/s, and to [0 – more than 100 km] when there is no speed. From the above analysis, it is clear that the range for obtaining more than 99 % probability of success changes with the changes in wind speed (channel conditions), so building adaptation protocol based only on a fixed inter-node distances without taking the effect of channel conditions variation into account is not accurate.

5.2.3 Adaptation Algorithm

From the Figure 5.3 and Figure 5.5 above it is clear that taking inter-node distance as the base on which ARRTP depends on choosing which encoding technique is suitable, is not accurate on variable channel conditions medium like underwater channel, so choosing another factor which accommodate both inter-node distance and channel conditions variation is a must.

The proposed adaptation algorithm here is the same adaptation algorithm found in section 4.3, with a three different error correction techniques instead of the six error correction techniques used in section 4.3 the encoding technique can be presented in the Table 5.1 below:

Table 5.1: ARRTP Error Correction Techniques Details

J	Error Correction Technique	Encoding details
1	BCH only	
2	BCH-RS-1	4 data packet + 1 Check packet
3	BCH-RS-2	4 data packet + 2 check packet

5.2.4 Pre-Calculated PAR Ranges Look-Up Table

The pre-calculated PAR ranges look-up table is calculated as follows:

1. Probability of success for the three encoding techniques for variable values of SNR are found as in section 4.6, (SNR are taken as a measure for distance and channel conditions variations).

2. Starting with the SNR values which gives probability of success (PAR) values equal to 1 for all the techniques; at this SNR BCH will have the maximum energy efficiency compared to the others, so the PAR for all those technique at this point is the maximum values in the ranges which makes the suitable encoding technique is BCH.

This means $PARMAX_{J,1}$= 1, i.e. if the current technique is J and the current PAR is in the range that has 1 as the maximum value, then BCH is the most suitable encoding technique.

3. Then decreasing SNR value until the PAR of BCH is less than 0.99, at this SNR the PAR for all technique will be the minimum values in the ranges which makes the suitable encoding technique is BCH.

This means the PAR of any technique J at this point = $PARMIN_{J,1}$ i.e. if the PAR of the current technique J is in between $PARMIN_{J,1}$ and $PARMAX_{J,1}$, then BCH is the most suitable encoding technique.

As the minimum values in the first ranges equal the maximum values in the second range, then:

$$PARMAX_{J,2}=PARMIN_{J,1}$$

4. Then decreasing SNR value until the PAR of BCH-RS-1 is less than 0.99, at this SNR the PAR for all technique will be the minimum values in the ranges which makes the suitable encoding technique is BCH-RS-1.

This means the PAR of any technique J at this point = $PARMIN_{J,2}$i.e. if the PAR of the current technique J is in between $PARMIN_{J,2}$ and $PARMAX_{J,2}$, then BCH-Rs-1 is the most suitable encoding technique.

As the minimum values in the second ranges equal the maximum values in the third range, then:

$$PARMAX_{J,3}=PARMIN_{J,2}$$

5. At last $PARMIN_{J,3}$ = 0 for all techniques.

This calculation can be done using the algorithm Figure5.6 below:

Algorithm 5.1 PAR Ranges Look-Up Table Calculation

(PARMAX(I,J), PARMIN(I,J))*(PAR (J, SNR))*

1 for J = 1:3;

2 $PARMAX_{J,1}$=1; $PARMIN_{J,3}$= 0;

3 SNR = SNRMAX;

4 For I= 1:2;

5 If PAR (I, SNR)<=0.99;

6 then $PARMIN_{J,I}$ = PAR (J, SNR);

7 $PARMAX_{J,I+1}$ = PAR (J, SNR);

8 SNR = SNR -1;

9 else go to 5;

10 end;

11 end;

***Return** ($PARMIN_{J,I}$,$PARMAX_{J,I}$)//The maximum and minimum values in the lookup table from encoding techniques 1 to 3//*

Figure 5.6: PAR Ranges Look-Up Table Calculation Algorithm

5.2.5 Results and Discussion

The pre-calculated PAR ranges look-up table is obtained using the algorithm in Figure 5-6 above, and can be written as in Table 5-2 below, where I is the current encoding technique and J is the suitable encoding technique:

Table 5.2: PAR-Based ARRTP PAR Ranges Look-Up Table

I/J	BCH only	BCH-RS-1	BCH-RS-2
BCH only	1.00 – 0.99	0.99 – 0.94	0.94 – 0.00
BCH-RS-1	1.00 – 0.9997	0.9997 – 0.9920	0.992 – 0.00
BCH-RS-2	1.00 – 0.9999	0.9999 – 0.9990	0.999 – 0.00

Keeping this table in the receiver, and from the current PAR and current encoding technique number, the suitable encoding technique can be determined. The receiver periodically informs the sender about the suitable encoding technique.

Applying this PAR-based ARRTP always obtains more than 0.99 or the best probability of success which is required in the design irrespective of the variation of channel conditions as in Figure 5.7 below:

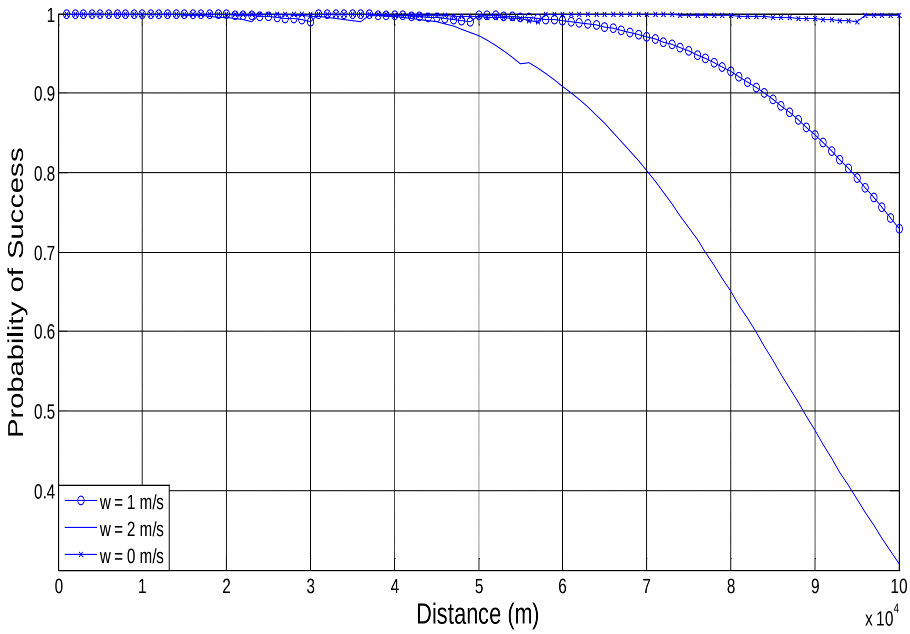


Figure 5.7: PAR-Based ARRTP Probability of Success

5.3 AHEC Technique-Based Bounded Distance Routing Protocol

5.3.1 Bounded Distances Routing Protocol [97]

The main concept of designing bounded distance routing protocol is based on the idea that given specific characteristics of a modem, there is an optimum distance between relays that minimizes total energy consumptions, which implies a specific number of relays per unit distance, area or volume that can be used in network deployment. The exact value of this per relay distance depends on the desired SNR for a successful transmission and the specific transmit and receive power of the acoustic modem. For specific parameters they found that this per hop distance is around 150 m, they used this per hop distance on designing bounded distance routing protocol and found that it achieves large energy saving compared with other routing protocols.

In Figure 5.8 below; it is clear that the total path energy consumptions depend on the number of relays. The path energy is highest for direct transmission (no relay), but decreases rapidly as the number of relays increases until six relays, after that the total path energy consumptions starts to increase again. It is also clear that having less number of relays than optimum has great effect on energy consumptions than having more relays. So routing algorithm should approach the number of relays from above the optimum.

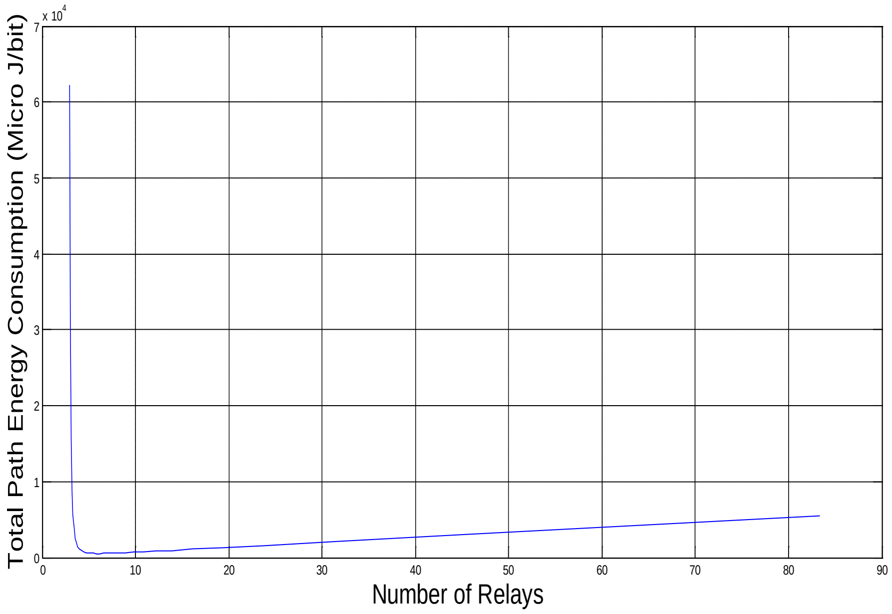


Figure 5.8: Total Path Energy Consumption Vs Number of Relays (Fixed Channel Conditions Case)

5.3.2 Variable Channel Conditions Effects on Bounded Distance Routing Protocols

Variable channel conditions have great effects on the attenuation-noise (AN) factor. This effect is clearly seen when taking wind speed as one factor for channel conditions variations.

From Figure 5.9 below which graphs wind speed versus AN factor, it is clear that change of wind speed from 1 m/s to 3 m/s will make a change of around 6 dBs in AN factor. This change in AN factor has great effect on the optimal per hop distance, which makes the optimum number of relays varies with the variation in wind speed as in Figure 5.10. So designing bounded distance routing protocol based on optimum number of relays which do not take the effect of variable channel conditions into consideration is not accurate in variable channel conditions channel like underwater one. This effect can be reduced by using variable error correction techniques for variable channel conditions as in the following section.

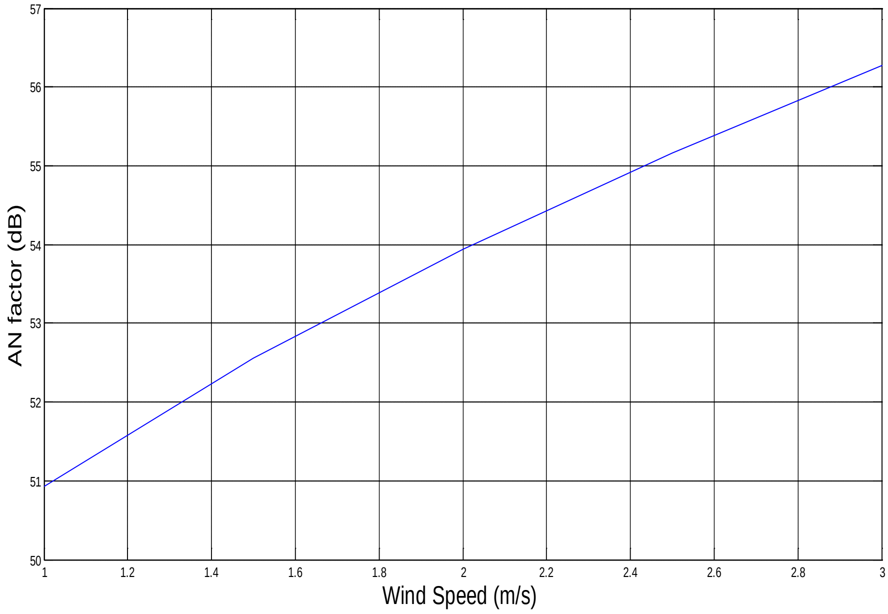


Figure 5.9: Effect of Wind Speed on AN Factor

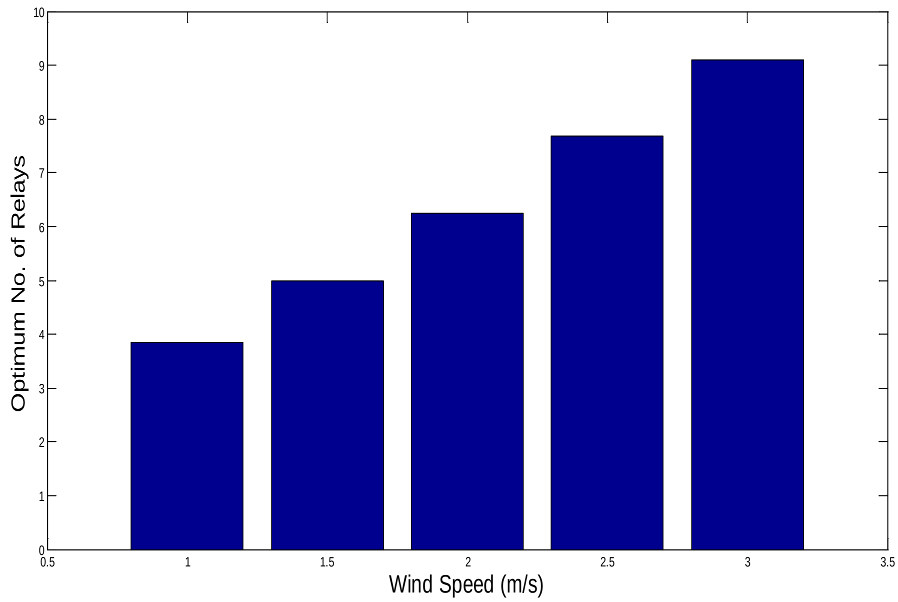


Figure 5.10: Effect of Wind Speed on Optimum no. of Relays (Using Fixed Error Correction Technique)

5.3.3 Applying AHEC Technique to the Bounded Distance Routing Protocol

To reduce the effect of variable channel conditions on the design of bounded distance routing protocol, we can use our AHEC technique in chapter four, which adaptively changes the error correction technique to the technique with the highest energy efficiency. From Figure 5.10 and Figure 5.11 it is clear that when applying variable error correction technique, the effect of variable channel conditions on choosing the range of optimum number of relays between sender and receiver is minimized from six relays when applying fixed error correction technique (three relays as a minimum number of relays when wind speed is 1 m/s to nine relays as a maximum number of relays when wind speed is 3 m/s), to just two when applying variable error correction technique (three relays as a minimum number of relays when wind speed is 1 m/s to five relays as a maximum number of relays when wind speed is 2.5 m/s).

So designing a bounded distance routing protocol based on the assumption of fixed channel conditions is not accurate, and the value of optimum number of relays is greatly affected by channel conditions as seen in Figure 5.10. The effects of this variation in channel conditions can be minimized by using variable error correction technique as seen in Figure 5.11 below.

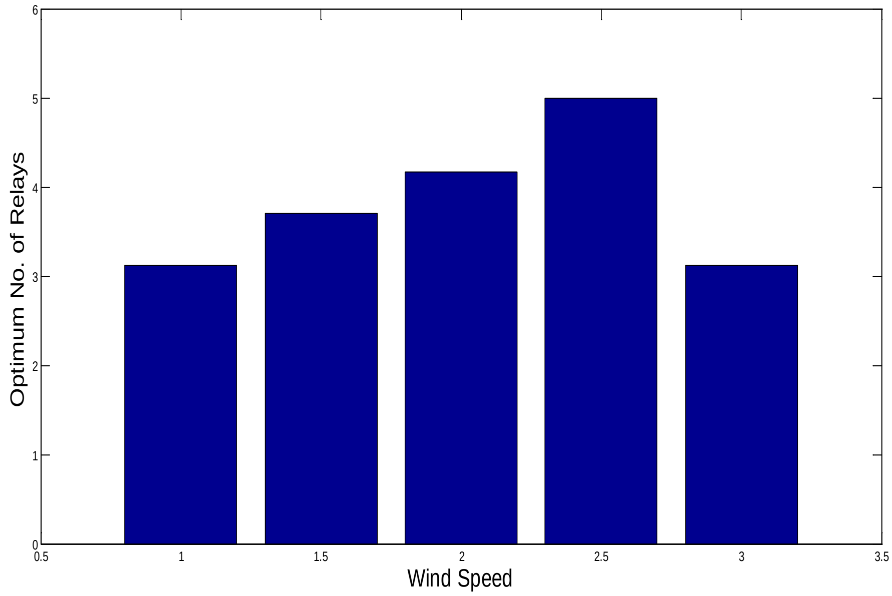


Figure 5.11: Effect of Wind Speed on Optimum no. of Relays (Using AHEC Technique)

5.4 Conclusions

From the investigation we have done in this chapter, it is clear that variable channel conditions have great effects on energy efficiency and packet probability of success for communication in a variable conditions channel like underwater one.

Regarding ARRTP which is based in inter-node distance to obtain more than 0.99 probability of success, it is clear that channel conditions have great effect on packet probability of success, so designing any protocol without taking this factor into consideration will not be accurate. PAR-based ARRTP takes both channel conditions variations and distances in the adaptation which will reduce the effects of channel conditions variations.

Regarding bounded distance routing protocol; it depends mainly in choosing an optimum number of relays between sender and receiver in minimizing energy consumptions. This optimum number of relays varies greatly with the variation of channel conditions, so it is inaccurate to choose this optimum number of relays based on fixed channel conditions analysis. This inaccuracy can be minimized by using variable error correction technique like AHEC technique. The results show a decrease in the variation of the optimum number of relays from six when fixed error correction technique is used to only two when variable error correction technique is used for a variation of 2 m/s in wind speed.

CHAPTER 6

CONCLUSIONS

An overview of this thesis along with highlights of the contributions, discussion and the future work are the main issues discussed in this chapter.

6.1 Overview

Underwater wireless sensor networks find many applications in today's life, ranging from environmental monitoring, oil exploration, equipment monitoring and many other applications. For such sensors, energy utilization is the most important and most cited topics as it is difficult to recharge or even replace batteries in most aquatic medium. Underwater is characterized by variable channel conditions whereas underwater sensors are usually mobile due to water currents which leads to variable distance between sensors. This variability of channel conditions and distances leads to inefficient energy error correction techniques and data communications in general.

In this research, we have mathematically derived, proposed and applied new ideas in order to maximize energy efficiency of error correction techniques in variable channel conditions and variable distances between sensor nodes cases.

In chapter 2; underwater wireless sensor networks applications are given in detail, underwater acoustic propagation features are declared and a comparison between underwater acoustic communications and terrestrial networks is presented. Error correction techniques are discussed in details, and ARQ, FEC and energy efficiency related works are reviewed.

In chapter 3; underwater propagation model is presented, then a mathematical energy efficiency derivation for FEC and ARQ techniques in underwater environment is done based on communication distance and packet size. The effects of wind speed, and shipping factor is studied. A simulation using MATLAB is done which validated the mathematical derivation results and a comparison between ARQ and FEC energy efficiencies for different packet size, different distances, and different channel conditions (wind speed and shipping factors) is presented. Then we have concluded the chapter.

In chapter 4; we have proposed Adaptive Hybrid Error Correction (AHEC) technique. AHEC technique main concept is presented along with its algorithm. Then we have presented how to calculate the pre-calculated PAR ranges look-up table for AHEC technique. After that we presented the case where power supply variability is used as adaptation factor. Then we have mathematically derived energy efficiency for ARRTP, which is previously known as ADELIN so as to make a comparison between it and our AHEC technique. After that we have compared our AHEC technique with the techniques that use only ARQ or only FEC as error correction technique in variable channel conditions and variable distance cases, and then we have compared it with the case when variable power supply is used in adaptation. AHEC technique is also compared with ARRTP in a variable distances case. At last we have concluded the chapter.

In chapter 5; we have applied our adaptation algorithm which accounts for both distance and channel conditions variations to choose between the three types of error correction technique used in ARRTP. The adaptation algorithm depends on the current error correction technique used, current Bit Error Rate (BER), packet length, and a pre-calculated Packet Acceptance Rate (PAR) ranges look-up table to determine which error correction technique is most suitable for the current channel conditions and distance. We have called this technique PAR-based ARRTP. To do so, we first described ARRTP and show how the adaptation occurs. Then we have presented the effects of variable channel conditions on the packet probability of success for the three encoding technique used in ARRTP. After that we have described our adaptation algorithm for ARRTP and present how to calculate the pre-calculated PAR ranges look-up table. The results of applying this adaptation algorithm have been presented in the last section of this part. In the third part of this chapter we have applied our AHEC technique to reduce the effects of variable channel conditions on choosing the optimum number of relays in the design of bounded distance routing protocol. To do so, we first briefly describe bounded distance routing protocol, then we have studied the effects of variable channel conditions on choosing the optimum number of relays between sender and receiver in bounded distance routing protocol. After that we have presented the result of applying AHEC technique in bounded distance routing protocol. Then we have concluded the chapter.

6.2 Contributions

In this thesis, we have mathematically derived energy efficiency for the two main error correction techniques in underwater environment. A simulation is done to validate the mathematical derivation results. ARQ is found to be more energy efficient than FEC below specific distance, and FEC is better after that. We call this specific distance cutoff distance. We found that this cutoff distance is not fixed and varies with the variation in channel conditions and packet size.

The main contributions of this thesis are as follows:

Based on the above mathematical derivations, and as a first contribution we have proposed an energy efficient Adaptive Hybrid Error Correction (AHEC) technique. The proposed technique adaptively changes the error correction technique to the technique with the highest energy efficiency compared to the others. An adaptation algorithm which based on the current PAR, current encoding technique, and a pre-calculated PAR ranges look-up table have been proposed. From the output of this adaptation algorithm a periodically 3-bit feedback is send to the sender indicating which error correction technique is most suitable for the current distance and channel conditions. Retransmission is used after improving PAR by the encoding technique to obtain 100 % reliability. The proposed technique has been compared with the techniques which use only ARQ or FEC. It has also been compared with the case when variable power supply is used in adaptation. It has been compared also with ARRTP (previously known as ADELIN). The results show that our proposed technique is more energy efficient than all the mentioned techniques in both variable distances and variable channel conditions cases.

As a second contribution, we have applied our adaptation idea to solve variable channel conditions problem which is ignored on ARRTP design. The new technique depends on PAR which accommodates for both the variation in channel conditions and variable distance. We have called this technique PAR-based ARRTP. We have also incorporated our AHEC technique with the bounded distance routing protocol to minimize the effects of variable channel conditions in choosing the optimum number of relays between sender and receiver (optimum per hob distance) which minimize total energy consumptions.

6.3 Discussion

UWSN is a promising field which will solve many problems in today's life. But until now it faces many challenges; the most important one is the severe energy constraint of the batteries, which can't be recharged or replaced in aquatic medium. Another issue which characterize UWSN is the variability of channel conditions and distance between underwater sensors. This variability in channel conditions has great effect in energy efficiency of communication system, and it has been ignored in most of the communication system for UWSN.

The variable channel conditions make it energy inefficient to use one or fixed error correction technique, and make the design of most communication protocols in underwater very challenging. To overcome this problem, or reduce it's effects an adaptive technique must be considered. BER which can be easily determined using any error detection technique can be used as a measure for the distance and channel conditions variations. With this BER and the pre-calculated PAR ranges look-up table which is built on the energy efficiency analysis done in chapter three, and knowing the current encoding technique used, the receiver can calculate and determine the suitable and the most energy efficient technique for the current channel conditions and distance. The receiver sends back a 3- bit telling the sender what is the suitable technique to use. The proposed technique is found to be more energy efficient than the pure ARQ, pure FEC, and some other communications techniques. It was also applied to solve the variable channel conditions problem in one transport technique and on routing technique, and it is successfully minimize its effects.

6. 4 Future works

1. In this thesis, we have considered the analysis regarding error correction techniques energy efficiency. However, there are many other techniques can be used to improve energy efficiency as energy efficient routing and power control mechanisms. Cross-layer design is also a promising method to achieve high energy efficiency. All these methods may be considered together.

2. Energy efficiency is the most important factor to UWSN, but it is not limited to it. There are other issues in UWSNs that need to be considered, such as high throughput and low transmission delay in network with large number of nodes. The UWSNs could be considered as a whole view, and not only one aspect.

REFERENCES

[1] Y.Colin, Chan, and Mehul Motani, "An integrated energy efficient data retrieval protocol for underwater delay tolerant networks," in *Proceeding of IEEE ocean'07*, Aberdeen, Scotland, 2007.

[2] A. Khan and L. Jenkins, "Undersea wireless sensor network for ocean pollution prevention," in *WISARD 2008 - 1st International ICST Workshop on Wireless Systems: Advanced Research and Development*, 2008.

[3] F. Salvi-Garau and M. Stojanovic, "Multi-Cluster protocol for Ad Hoc Mobile Underwater Acoustic Networks," in *Proc. of MTS/IEEE Conference and Exhibition for Ocean Engineering*, San Francisco, CA, 2003.

[4] D. Pompili, "Efficient communication protocols for underwater acoustic sensor networks," PhD, School of Electrical and Computer Engineering, Georgia Institute of Technology, 2007.

[5] L. Bin, Floren Garcin, Fengyuan Ren, and Chaung Lin "A study of forward error correction schemes for reliable transport in underwater sensor networks," in *Proceedings of the 5th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON '08),* 2008, pp. 197–205.

[6] M. Chitre, L. Freitag, E. Sozer, S. Shahabodeen, M. Stojanovic, J. Potter "An Architecture for underwater networks " in *Proc. of OCEANS'06 IEEE ASIA PACIFIC*, 2006.

[7] J. Preisig, "Acoustic Propagation considerations for underwater Acoustic communications network Development " *SIGMOBILE Mob. Computer Commun. Rev.*, vol. 11, pp. 2-10, 2007.

[8] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: research challenge " *Ad Hoc Networks (Elsevier),* vol. 3, pp. 257-279, 2005.

[9] M.Stojanovic, "Underwater Acoustic Communications," in *Encyclopedia of Electrical and Electronics Engineering* vol. 22, ed: John G. Webster, Ed., John Wiley & Sons, 1999, pp. 688-698.

[10] J. Catipovic, "Performance limitations in Underwater Acoustic Telemetry " *IEEE Journal Oceanic Eng.*, vol. 15, pp. 205-216, 1990.

[11] E. An, P. Beuajean, B. Baud, T. Carlson, A. Folleco, T Tarn, "Multiple Communicating Autonomous Underwater Vehicles," in *Proc. of the 2004 IEEE International Conference on Robotics and Automation, ICRA '04*, 2004.

[12] P. Xie, "Underwater acoustic sensor networks: Medium access control, routing and reliable transfer," PhD, University of Connecticut, 2008.

[13] S. Shahabudeen and M. Chitre, "Design of networking protocols for shallow water peer-to-peer acoustic networks," in *IEEE Oceans'05 Europe*, Brest, France, 2005.

[14] M. Chitre, S. Shahabudeen, M. Stojanovic, "Underwater Acoustic Communications & Networking: Recent Advances and Future Challenges," *Marine Technology Society Journal*, vol. Spring 2008, pp. 103-116, 2008.

[15] P. Xie and J.-H. Cui, "An FEC- based reliable data transport protocol for Underwater sensor networks " in *Proc. of 16th International Conference on Computer Communications and Networks*, 2007, pp. 747-753.

[16] G. Xie and G. Gibson. (2000, A networking protocol for underwater Acoustic networks

[17] Y. Sankarasubramaniam, I. Akyidiliz, S. Mclaughlin, "Energy efficiency based packet size optimization in wireless sensor networks " in *1st IEEE International Workshop on Sensor Network Protocols and Applications SNPA'03 (held in conjunction with IEEE ICC'03)*, Anchorage, Alaska, USA, 2003.

[18] D. Bingiham, T. Drake, A. Hill, R. Lott, "The application of autonomous underwater vehicle (AUV) technology in oil industry-vision and experience," presented at the XXII International Congress, Washington DC, 2002.

[19] Y. Guan, A. Song, J. Yakoshi,C. Chen, M. Badiey, "Simulation of Underwater Acoustic Networks with Field Measurements," 2009.

[20] N. Nasri, *A. Kashouri*, L. Andrieux, M. Samet, "Design considerations for wireless underwater communication Transceiver " in *2nd International Conference on Signals, Circuits and Systems, SCS 2008.* , 2008, pp. 1-5.

[21] M. C. Vuran and I. F. Akyildiz, "Cross Layer analysis of error control in wireless sensor networks " in *3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks, SECON '06.*, 2006, pp. 585-594.

[22] C. Wan, T.Andrew , Campbell, L. Krisnamurthy, "PSFQ: a reliable transport protocol for wireless sensor networks," in *WSNA '02 Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications,* 2002.

[23] F. Stann and J. Heidemann, "RMST: Reliable data transport in sensor networks," in *Proc. 1st IEEE Intl. Workshop on Sensor Network Protocols and Applications (SNPA)*, Anchorage, Alaska, 2003.

[24] A. Babiker and N. Zakaria, "Energy Efficiency Analysis of Error Correction Techniques for Underwater Wireless Sensors Networks," *Journal of Engineering Science and Technology*, vol. 6, pp. 17 - 28, 2011.

[25] A. Harris and M. Zorzi, "Modelling the underwater acoustic channel in ns2," in *In proceedings of the 2nd international conference on Performance evaluation methodologies and tools*, 2007.

[26] Y. Labrador, M. Karimi, D. Pan, J. Miller, "Modulation and error correction in the underwater acoustic communication channel," *International Journal of Computer Science and Network Security,* vol. 9, pp. 123-130, 2009.

[27] Z. Tian, D. Yan, and Q. Liang, "Energy efficiency analysis of error control schemes in wireless sensor networks," in *In proceeding of International Wireless Communications and Mobile Computing Conference, IWCMC '08,* 2008, pp. 401-405.

[28] *DSPCOMM*. Available: http://www.dspcomm.com/applications_oceanographic.html

[29] J. Heidemann, W. Ye, J. Wills, A. Syed, and Y. Li, "Research Challenges and Applications for Underwater Sensor Networking," in *Proceedings of the IEEE Wireless Communications and Networking Conference.*, Las Vegas, Nevada, USA, April 2006, pp. 228-235.

[30] Codiga, Daniel L, Rice, A. Joseph, Baxley, A. Paul, Hebert, David, "Networked Acoustic Modems for Real-Time Data Telemetry from Distributed Subsurface Instruments in the Coastal Ocean: Application to Array of Bottom-Mounted ADCPs.," *J. Atmos. Oceanic Technol.*, vol. 22, pp. 704–720, 2005.

[31] I. F. Akyildiz, D. Pompili, and T. Melodia, "State-of-the-Art in Protocol Research for Underwater Acoustic Sensor Networks," in *Proc. of ACM International Workshop on Under-Water Networks (WUWNet)*, Los Angeles, CA, 2006.

[32] J. Proakis,J. Rice, M. Stojanovic, "Shallow water acoustic networks," *IEEE in Communications Magazine* vol. 39, pp. 114 - 119, 2001.

[33] D. Blidberg, "The Development of Autonomous Underwater Vehicles (AUV); A Brief Summary," Autonomous Undersea Systems Institute, Lee New Hampshire- USA.

[34] C. Alt, "Autonomous Underwater Vehicles," presented at the the Autonomous Underwater Lagrangian Platforms and Sensors Workshop, 2003.

[35] *submersible buoy product* Available: http://www.fiomarine.com/

[36] *submersible buoy product in australia*. Available: http://www.defence.gov.au/teamaustralia/marker_buoy_and_retrieval_system_%28Fiobuoy_submersible%29.htm

[37] D. Bowlus, "Development and Testing of an Acoustic Based Underwater Positioning System," M.Sc, Florida Institute of Technology, 2008.

[38] I. Akyildiz, D. Pompili, and T. Melodia, "Challenges for Efficient Communication in Underwater Acoustic Sensor Networks," *ACM Sigbed Review,* vol. 1, 2004.

[39] M. Stojanovic and J. Preisig. (2009) Underwater Acoustic Communication Channels: Propagation Models and Statistical Characterization *IEEE Communications* 84-89.

[40] S. Joshy and A. Babu, "Capacity of Underwater Wireless Communication Channel with Different Acoustic Propoagation Loss Models," *International Journal of Computer Networks & Communications (IJCNC),* vol. 2, 2010.

[41] Z. Jiang, "Underwater Acoustic Networks – Issues and Solutions," *International Journal of Intelligent Control and Systems,* vol. 13, pp. 152-161, 2008.

[42] M. Zorzi, P. Casari, N. Baldo, and A. Harris, ", "Energy-Efficient Routing Schemes for Underwater Acoustic Networks," *IEEE Journal on Selected Areas in Communications,* , vol. 26, pp. 1754-1766, 2008.

[43] R. J. Urick, *Principles of Underwater Sound*: New York: McGraw-Hill, 1983.

[44] J. Partan, J. Kurose, and B. Levine, "A Survey of Practical Issues in Underwater Networks," *ACM SIGMOBILE Mobile Computing and Communications Review,* vol. 11, 2007.

[45] H. Luo, and Z. Guo, “, "Energy Balanced Strategies for Maximizing the Lifetime of Sparsely Deployed Underwater Acoustic Sensor Networks," *Sensors*, vol. 9, pp. 6626-6651, 2009.

[46] K. Treeprapin, and A. Kanzaki, "A Node Deployment Strategy for Efficient Sensing with Mobile Sensors in Sparse Sensor Networks " *Journal of Information Processing,* vol. 19, pp. 103-117, 2011.

[47] P. Xie, "Underwater acoustic sensor networks: Medium access control, routing and reliable transfer ", 2007.

[48] H. Yang and B. Liu, "Optimization of Energy Efficient Transmission in Underwater Sensor Networks" in *Proceedings of CoRR*, 2009.

[49] K. Kunal, R. Tripathi and V. Singh, "An HARQ based Optimized Error Correction Technique," *International Journal of Computer Applications,* vol. 9, 2010.

[50] S. Lin,D. Costello, M. Miller, (1984) Automatic-Repeat-Request Error-Control Schemes. *IEEE Communications Magazine*. 5-17.

[51] H. Burton and D. Sullivan, "Errors and error control," in *Proceedings of the IEEE*, 1972, pp. 1293–1301.

[52] Y. Shih, "A Multiple-copy Scheme for Multi-Channel Stop-and-Wait HARQ," Master Project, SJSU, 2007.

[53] S. era, A. Shah, "An efficient selective repeat automatic repeat request scheme for half-duplex infrared links under high bit error rate conditions," in *IEEE CCNC proceedings,* 2006.

[54] O. Micolau, D. Rodriguez, N. Fornos, J. Vidal, "Hamming Block Codes," 2000.

[55] A. Kalhan, C. Ceken, and I. Erturk, "Comparative Performance Analysis of Forward Error Correction Techniques Used in Wireless Communications," in *the Third International Conference on Wireless and Mobile Communications (ICWMC'07)*, 2007.

[56] S. Lin and J. Costello(1983). *Error Control Coding: Fundamental and Applications*.

[57] J. Hagenauer and P. Hoeher, "A Viterbi algorithm with soft-decision outputs and its applications," in *Proc. IEEE Global Telecommunications Conference 1989*, Dallas, Texas, 1989, pp. 1680–1686.

[58] Y. Yasuda, K. Kashiki, and Y. Hirata, "High-Rate Punctured Convolutional Codes for Soft Decision Viterbi Decoding," *IEEE Transaction on Communications*, vol. 32, pp. 316-319, 1984.

[59] M. Elbehri,H. Boujernaa and M. Siala, "Performance Comparison of Type I, II and III Hybrid ARQ Schemes over. AWGN Channels," in *IEEE international conference on industrial technology (ICIT)*, 2004.

[60] A. Agustin, J. Vidal, and O. Munoz, "Hybrid Turbo FEC/ARQ Systems and Distributed Space-Time Coding for Cooperative Transmission," *International Journal of Wireless Information Networks* vol. 12, pp. 263-280, 2005.

[61] Robert H. Deng and M. L. Lin, "A Type I Hybrid ARQ System With Adaptive Code Rates," *IEEE TRANSACTIONS ON COMMUNICATIONS*, vol. 43, 1995

[62] S. Lin and P. S. Yu, "SPEC-An Effective Hybrid-ARQ Scheme," 1979.

[63] Miller and S. Lin, "The Analysis of Some Selective-Repeat ARQ Schemes with Finite Receiver Buffer," *IEEE Trans. Commun.*, vol. COM-29, pp. 1307-1315, 1981.

[64] S. Kallel, "Analysis of type II hybrid ARQ schemes with code combining," *IEEE Trans. Comm.*, vol. 38, pp. 1133-1137, 1990.

[65] S. Kaller and D. Haccoun, "Generalized type II hybrid ARQ schemes using puncuring convolutional coding," vol. 37, 1989.

[66] Q. Zhang and S. A. Kassam, "Hybrid ARQ with selective combining for fading channel," *IEEE Journal on Selected Areas in Communications,* vol. 17, pp. 867-880, 1999.

[67] H. Tan, W. Seah. and L. Doyle., "A multi-hop ARQ protocol for underwater acoustic networks," in *Proceedings of OCEANS 2007 18-21 June 2007, IEEE,* Europe, 2007 pp. 1 - 6.

[68] J. Lee, , J. Kim, J. Lee, Y. Jang, K. Dho, "An improved ARQ scheme in underwater acoustic sensor networks," in *Proc. MTS/IEEE Oceans*, Kobe, Japan, 2008, pp. 1-5.

[69] M. Gao, W. Soh and M. Tao, "A transmission scheme for continuous ARQ protocols over underwater acoustic channels," in *ICC'09 Proceedings of the 2009 IEEE international conference on Communications* 2009.

[70] A. Valera, P. Lee, H. Tan, "Implementation and Evaluation of Multihop ARQ for Reliable Communications in Underwater Acoustic Networks," in *Proceedings of the IEEE OCEANS Conference*, Bremen, Germany, 2009.

[71] Z. Guo, P. Xie, J. Cui, and B. Wang, "On applying network coding to underwater sensor networks.," in *Proceedings of ACM WUWNet'06*, Los Angeles, CA, 2006.

[72] B. Liu,H. Chen, X. Lei, F. Ren, and K. Sezaki , "Internode distance-based redundancy reliable transport in underwater sensor networks " *EURASIP J. Wireless Comm. and Networking 2010,* 2010.

[73] K. Ovaliadi, N. Savage and V. Kanakaris, "Energy Efficiency in Underwater Sensor Networks: a Research Review," *Journal of Engineering Science and Technology Review,* vol. 3, pp. 151-156, 2010.

[74] R. Gitzendanner, F. Puglia, C. Martin, D. Carmen, E. Jones, S. Eaves, "High power and high energy lithium-ion batteries for under-water applications," *Journal of Power Sources* vol. 136, pp. 416-418, 2004.

[75] I. Yardney Technical Products, "Design and performance of lithium ion cells for underwater energy storage and power delivery," 2007.

[76] C.Detweiller, L. Vasilescu, D. Rus , "AquaNodes: an underwater sensor network," in *Proceedings of Underwater Networks'2007*, 2007, p. 85~88.

[77] L. Freitag, M. Grund, S. Singh, James, "The WHOI micro-modem: an acoustic communications and navigation system for multiple platforms," in *Proc. of IEEE/MTS OCEANS Conf.*, Washington, D.C., 2005, pp. 1086–1092.

[78] J. Wills, W. Ye, and J. Heidemann, "Low-Power Acoustic Modem for Dense Underwater Sensor Networks," in *Proceedings of the First ACM International Workshop on UnderWater Networks (WUWNet)*, Los Angeles, California, USA, 2006, pp. 79-85.

[79] M. Molins and M. Stojanovic, "Slotted FAMA-A MAC protocol for underwater acoustic networks," in *Proc. of MTS/IEEE OCEANS'06*, 2006.

[80] V. Rodoplu and M. Park, "An energy-efficient MAC protocol for underwater wireless acoustic networks," in *Proceedings of MTS/IEEE OCEANS*, 2005, pp. 1198 - 1203.

[81] D. Pompili, T. Melodia, I. Akyildiz, "A Distributed CDMA Medium Access Control for Underwater Acoustic Sensor Networks," in *Proc. of*

Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net), Corfu, Greece, 2007.

[82] A. A. Syed, W. Ye, and J. Heidemann, ", "T-Lohi: A New Class of MAC Protocols for Underwater Acoustic Sensor Networks," in *Proceedings of INFOCOM'2008*, 2008, p. 231~235.

[83] E. Sözer, M. Stojanovic, and J. Proakis, "Underwater Acoustic Networks," *IEEE J. Oceanic Eng.*, vol. 25, pp. 72-83, 2000.

[84] P. Xie,J. Cui, and L. Lao, "VBF: vector-based forwarding protocol for underwater sensor networks," in *Proceedings of the IFIP Working Conference on Networking*, Coimbra, Portugal, 2006.

[85] C. J. Huang, Y. Chen, I. Chen, K. Hu, and J. Liao, "A Clustering Head Selection Algorithm for Underwater Sensor Networks " in *Proceedings of the 2008 Second International Conference on Future Generation Communication and Networking*, 2008 pp. 21-24.

[86] W. Heinzelman, A. Chandrakasan and H. Balakrishnan, "An Application-Specific Protocol Architecture for Wireless Microsensor Networks," *IEEE Transactions on Wireless Communications*, vol. 1, pp. 660-670, 2002.

[87] M. C. Domingo and R. Prior, "A Distributed Clustering Scheme for Underwater Wireless Sensor Networks," in *Proceedings of 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2007)*, Athens, Greece, 2007.

[88] Wenz and G. M., "Acoustic Ambient Noise in the Ocean: Spectra and Sources," *The Journal of the Acoustical Society of America*, vol. 34, 1936.

[89] S. C. Webb, "The equilibrium oceanic microseism spectrum," *J. Acoust. Soc. Am.*, vol. 92, pp. 2141-2158, 1992.

[90] L. M. Brekhovskikh and Y. P. Lysanov, *Fundamental of ocean acoustics*: Springer, 1982.

[91] *8-PSK Modulation*. Available: http://en.wikipedia.org

[92] F. Daneshgaran,M. Laddomada, and M. Mondin "An Extensive search for good punctured rate k/k+1 recursive convolution codes for serially

concatenated convolution codes," *IEEE transaction of information theory*, vol. 50, pp. 208-217, 2004.

[93] T. M. Inc, "MATLAB, The Language of Technical Computing (version 7.7.047)," ed, 2008.

[94] L. Inc. *Underwater Acoustic Modem Models*. Available: http://www.link-quest.com

[95] G. Begin, D. Haccoun, and C. Paquin, "Further Results on High - Rate Puncturing G Convolutional codes for viterbi and sequential decoding," *IEEE transaction on Communications*, vol. 38, pp. 1922-1928, 1990.

[96] W.Lee, J. Kim, J. Lee, Y. Jang, K. Dho, "An improved ARQ scheme in underwater acoustic sensor networks," in *Proc. MTS/IEEE Oceans*, Kobe, Japan, 2008, pp. 1-5.

[97] A. F. Harris and M. Zorzi, "On the Design of Energy-efficient Routing Protocols in Underwater Networks," in *Proceedings of SECON'2007*, 2007, pp. 80-90.

[98] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," in *Proceedings of the 1st ACM International Workshop on Underwater Networks (WUWNet '06)*, Los Angeles, Calif, USA, 2006, pp.41–47

PUBLICATIONS

- Published journals papers:

1. **Ammar Elyas Babiker,** Mohd Nordin Bin Zakaria,” Energy Efficiency Analysis of Error Correction Techniques in Underwater Wireless Sensors”, *Journal of Engineering Science and Technology*, Vol.6(1), PP.17-28, 2011.

2. **Ammar Elyas Babiker**, Mohd Nordin Bin Zakaria, Hassan Yousif Ahmed, Brahim Belhaouari Samir, ” An Efficient Energy Adaptive Hybrid Error Correction Technique for Underwater Wireless Sensor Networks”, *World Academy of Science, Engineering and Technology,* Vol. 75 PP. 1390-1396, March 2011.

- Refereed Conferences:

3. **Ammar Elyas Babiker**, Mohd Nordin Bin Zakaria,” An Efficient Energy Two Mode Error Correction Technique in Underwater Wireless Sensor Networks”, Proceeding of International Symposium on Information Technolgy 2010 (ITSIM 10, 15 – 17 June 2010, Kuala Lumpur, Malaysia.

4. **Ammar Elyas Babiker**, Mohd Nordin Bin Zakaria, Hassan Yousif Ahmed, Brahim Belhaouari Samir,” Packet Acceptance Rate- Based Adaptive Energy Efficient Error Correction Technique for Underwater Wireless Sensor Networks”, Proceeding of 3rd International Conference on Underwater System Technology: Theory and Applications 2010 (USYS'10), 1st & 2nd November 2010, Cyberjaya, MALAYSIA, 137-142.

- Accepted Book Chapter Proposal

5. **Ammar Elyas Babiker**, M. Nordin B. Zakaria, Hassan Yousif Ahmed, Brahim Belhaouari Samir," Energy Efficient Communications for Underwater Wireless Sensors Networks". In the book titled “Energy Efficiency and ICT", ISBN 979-953-307-854-9

- Accepted Conference Papers

6. **Ammar Elyas Babiker**, M. Nordin B. Zakaria, Hassan Yousif Ahmed, Brahim Belhaouari Samir, “Applying Variable Error Correction Technique to the Design of Bounded Distance Routing Protocol for Underwater wireless Sensors Networks’, accepted in International conference on sensor networks, information and ubiquitous computing, Singapore, 28-30 September 2011.

7. **Ammar Elyas Babiker,** M. Nordin B. Zakaria, Hassan Yousif Ahmed, Brahim Belhaouari Samir, “PAR-Based Adaptive Redundancy Reliable Transport protocol for Underwater Wireless Sensor Networks, Accepted in the 17th Asia-Pacific conference on communications, Sabah- Malaysia, 2-5 October 2011.