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Vinay Divakar

Design and Development of Underwater Acoustic Modem for Shallow Waters and Short Range Communication

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Design and Development of Underwater Acoustic Modem for Shallow Waters and Short Range Communication

M. Sc. [Engg.] in

Electronics System Design Engineering

Submitted by: **Mr. Vinay Divakar**

M. S. Ramaiah School of Advanced Studies

Postgraduate Engineering and Management Programme
Coventry University (U.K.)
#470-P Peenya Industrial Area, 4th Phase, Bengaluru-560 058
Tel; 080 4906 5555, website: www.msrsas.org

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Abstract

The existing underwater acoustic modems are designed for deep oceans and long range communication leading to immense consumption of power and high cost. These long range underwater acoustic modems are not suitable choice for deployment in underwater sensor networks, Hence the problem was chosen to design and develop a underwater acoustic modems that operates in shallow waters of depth below 100m and for a short range of below 100 m. Underwater wireless sensor network is contemporary technology that can be applied in the fields of security, surveillance, military, commercial, industrial and environmental. The major drawback is that the traditional underwater acoustic modems cannot be deployed for underwater sensor networks.

This work focusses on the research and development of the underwater acoustic modem for shallow waters and short range communication. The relevant background theory required understand acoustics and for modelling the unique characteristics of the underwater channel is described in detail. Different concepts to model and implement the functionalities of the transmitter and receiver were explored, while converging to the most suitable choice of concepts. The modelled system is simulated for different channel conditions such as depth, range and induced ambient noise. The results were analysed in order to conclude the performance outcome of the system.

The modelled system can efficiently operate for a depth of 30m, 50m and 70m for a range up to 50m. The hardware was developed using minimum number of components as a proof of concept for efficient data transmission and reception using acoustic signals. The hardware was tested to operate efficiently in air, however hardware tests for underwater is suggested for future work, which will provide much better performance since acoustics is more suitable for communication in water than air.

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Nomenclature

ARQ	Automatic Selective Request
AWGN	Additive White Gaussian Noise
BW	Bandwidth
ADC	Analog to Digital Convertor
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CRC	Cyclic Redundancy Check
CORAL	Common Object Remote Acoustic Link
dB	Decibel
BFSK	Binary Frequency Shift Keying
UASN	Underwater Acoustic Sensor Network
UAM	Underwater Acoustic Modem
DSP	Digital Signal Processing
RF	Radio Frequency
PLL	Phase Lock Loop
ISI	Inter Symbol Interference

CHAPTER 1 - Introduction

In recent year's communication technologies underwater has become an active area of research due to its important applications in military, oceanographic data collection, disaster prevention and pollution monitoring. Communication is an important process that enables exchange of data transfer between two or more entities or nodes.

1.1 Introduction to Underwater Acoustic Modem

The underwater acoustic modem is responsible for gathering sensor information, processing and communicating with other nodes and a group of these nodes communicating underwater using acoustic links creates a network known as "Underwater Acoustic Sensor Network (UASN). In underwater environment, communication using Radio Frequency (RF) is not possible since such high frequencies are easily absorbed in water vanishing the signals and if lower frequencies are used then it requires a very large antenna and high power consumption, which is practically not a wise choice for underwater communications. Therefore, communication using sonar or acoustics was seen to be reliable alternative that suits best the underwater environment using which data communication can happen for longer distances.

1.2 Classification of the Acoustic/Sonar Communication Systems

Acoustic or Sonar Communication Systems are classified into two types i) Passive Sonar System i.e., it only detects and receives acoustic waves from target bodies and does not transmit any acoustic waves (simplex mode), ii) Active Sonar Systems are the once that can receive as well as transmit acoustic waves and these are classified into two modes i.e. full duplex and half duplex communication systems. In full duplex, two way communication is possible in which the sonar waves are emitted and received between two nodes while in half duplex systems emit and receive sonar waves from its own system. Both modes of active sonar systems as well as passive sonar systems makes use of audible frequency range 50 Hz to 20 KHz and in certain applications it can go as high as 50 KHz. Passive sonar communication systems can detect any underwater entities such as moving submarines, crowds of fisheries and some military spying activities. Active sonar communications is used for various underwater tasks such as underwater object identification, fisheries, undersea explorations and military work.

1.3 Motivation

In recent years, communication underwater has become an active area of research due to the big gap between the advancements of communication technology in territorial while the underwater communications/applications had laid low. In order to implement applications underwater such as undersea explorations, assisted navigation, disaster prevention and surveillance requires setting up of wireless sensor networks underwater using acoustic links and this has not been an easy task due to the unique characteristics of water. Therefore it is necessary to design and develop an acoustic modem that can adapt well to the underwater environment.

This thesis proposes design and model of communication system that involves the design and development of an acoustic modem/transceiver for shallow waters and short range communication, that will become the basis for the underwater wireless sensor networks, since the commercially existing acoustic modems are not designed for short range communication, in order to trigger the idea of small, dense and cheap sensor nets, as these commercial acoustic modems are very expensive, they draw high power, bulky and all designed for long range communication. Therefore deployment of 100’s of such commercial modems will be very expensive and unreliable for oceanographic applications. Hence this lead to the motivation for the design of an acoustic modem that consumes low power and is cost effective in order for making it practically possible for deployment of several such acoustic modems setting up a sensor network that can be used for different underwater applications. The design and development of Underwater Acoustic Modem for underwater applications has been chosen to resolve the issues pertaining to the Commercial off-the-shelf (COTS) underwater acoustic modems that are not suitable for shallow waters and short range communication.

1.4 Scope of the work

This work presents software implementation, that involves the design and development of an acoustic modem for shallow waters, and short range underwater applications. The work focuses on modelling of an underwater acoustic channel and, design and development of a transmitter-receiver pair that can communicate efficiently underwater. The performance of modelled system is analysed for different channel conditions. Different attenuation and noise components are modelled representing the underwater channel medium. The Hardware is developed using ultrasonic transducers as a proof of concept for efficient transmission and reception of the data using acoustics.

1.5 Thesis Outline

Chapter 2 describes the background theory related to acoustics and underwater channel. It describes the different characteristics of underwater channel with relevant equations used for modelling it.

Chapter 3 carries out the survey on Underwater Acoustic Communication System by referring journals, white papers, books, patents and related documents.

Chapter 4 defines the problem statement and project objectives followed by methods and methodology adopted to meet the objectives.

Chapter 5 describes the design, modelling and development of an Underwater Acoustic Modem that meets the requirement of shallow waters and short range communication, by invoking the Systems Engineering principles and practices.

Chapter 6 discusses and analyses simulation and hardware implementation results.

Chapter 7 summarizes the research results, concludes the outcome of the project and suggests the scope for future work

CHAPTER 2 – Background Theory

2.1 Introduction

This chapter describes the fundamental theory for acoustics and the physical characteristics of the underwater channel in detail. It describes the important theory required to know for designing of underwater acoustic modems and for modelling the underwater channel.

2.2 Classification of Bandwidths for Underwater Acoustic Communication Systems

Underwater acoustic communication systems can be classified into two types i.e. Long range and Short range-shallow water systems. The long range systems can operate from 20 to 2000km range in deep ocean waters having a bandwidth limit of 500Hz to 10KHz while the short range systems operates over several tens of meters with a bandwidth limit of 10 to 100KHz and shallow water usually refers to a water depth lower than 100m (Akylildiz, Pompili and Melodia, 2005).

Table 2. 1 Bandwidth Availability

	Range [Km]	**Bandwidth [KHz]**
Very Long	1000	<1
Long	10-100	2-5
Medium	1-10	~10
Short	0.1-1	20-50
Very Short	<0.1	<0.1

Underwater acoustic communication links can be classified such as very long, long, medium, short and very short. The Table2.1 shows the available bandwidths for different ranges for underwater acoustic channels. Apart from these they are also classified as vertical links in order to communicate with the nodes present in the vertical plane and horizontal links in order to communicate with the neighbouring nodes present on the same plane. Sine this work focuses on the design of an underwater acoustic modem for short range communication therefore the system will be designed to operate between the bandwidth of 20 to 50 KHz.

2.3 Fundamentals of Underwater Acoustic Communication

Similar to the exchange of data in electrical area, they can also happen in acoustics which can be described by important physical quantities and definitions as follows;

2.3.1 Sound

It is the vibrations of any object can transmit its motion or energy to the surrounding physical medium. This phenomenon results in propagation of vibrations in which the particles vibrates in the same direction as the direction of propagation forming longitudinal waves.

2.3.2 Acoustic Pressure

The Sound Pressure is the force (*N*) of sound on a surface area (m^2) perpendicular to the direction of the sound. The SI-units for the Sound Pressure are N/m^2 or *Pa*. Sound is usually measured with microphones responding proportionally to the sound pressure (*p)*. The power in a sound wave goes as the square of the pressure. It is given by,

$$\mathrm{P} = \mathrm{Po} * \mathrm{c} * 2\pi * \varepsilon \qquad \dots (1)$$

Where, *Po* = fluid density

C = velocity of sound wave propagation

$$\varepsilon = \frac{\mathrm{v}}{2\pi\mathrm{f}} \qquad \dots (2)$$

V = particle velocity

Acoustic pressure (P) is analogues to the potential difference in electrical circuits and $Po * c$ is the called the specific impedance. Another equation that is analogous to ohm's law is the acoustic impedance given by,

$$Z = \frac{P}{U} \qquad \dots (3)$$

Z = Acoustic Impedance that is a function of frequency

P = acoustic pressure

U = Acoustic volume flow

2.3.3 Acoustic Intensity

It's denoted by 'I' with a unit as w/m^2, i.e. the energy per second that crosses the unit area. A plane wave equation is given by,

$$\mathrm{I} = \mathrm{PV} \qquad \dots (4)$$

The equation is viewed as the acoustic power density produced by a source. Generally a reference intensity 'I_r' is defined for each medium. In the case of underwater reference intensity that is produced by a plane wave with root mean square pressure of 1upa.

2.3.4 Speed of Sound

The speed of sound depends on the temperature, salinity and pressure (depth) of the water under the sea surface.

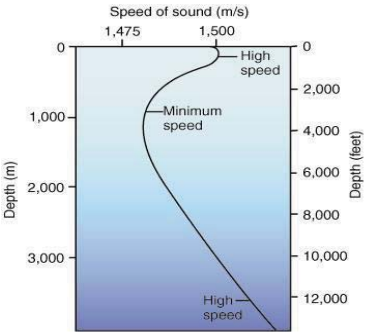


Figure 2. 1. Sound Profiles Underwater

Figure 2.1 shows the variation of the speed of sound as a function of depth of the ocean. The speed of sound ranges between 1400 and 1570 m/s. This is roughly 1.5 km/s (just under 1 mile/s) or about 4 times faster that sound travel through air.

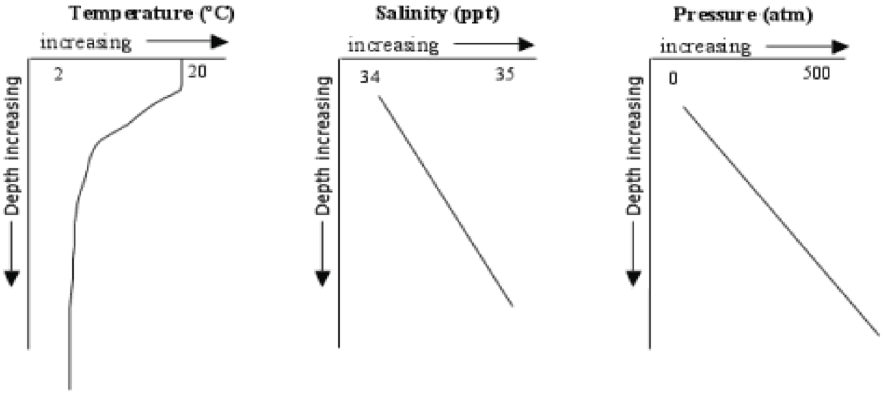


Figure 2. 2. Sound Speed

The speed of sound is affected by the variables of the ocean such as temperature, salinity and depth (pressure). The ocean pressure refers to the weight of the underlying water and not the pressure associated with the sound wave, which is much smaller. In the Figure 2.2, it is seen that the temperature changes a large amount, decreasing from 20 degrees Celsius (°C) near the surface in mid-latitudes to 2 degrees Celsius (°C) near the bottom of the ocean. Salinity changes by only a small amount, approximately 34 to 35 Practical Salinity Units. Pressure increases by a large amount, from 0 at the surface to 500 atmospheres (atm) at the bottom. Therefore the speed of sound in water increases with increase in water temperature, increasing salinity and increase in depth (pressure).

2.4 Underwater Channel Characteristics

The chemical and physical characteristic of underwater, delays and affects the propagation of sound due to common phenomenon such as spreading and absorption, this phenomenon's is responsible for attenuating the acoustic signals underwater. Another major phenomenon attenuating acoustic signal in shallow waters is the multipath fading that causes inter symbol interference at the receiver end and the ambient noise.

2.4.1 Spreading Loss

It does not represent a loss of energy, but refers to the fact that propagation of the acoustic pulse is such that the energy is simply spread over a progressively larger surface area thus reducing its density and it is given by

$$Pl_{spreading}\,(r) = k*10*\log\,(r)\ (dB) \qquad \ldots (5)$$

Where, ‘r’ is the range in meters and ‘k’ is the spreading factor. If there’s a medium in which signal transmission occurs unbounded and spherical spread, then k = 2, i.e. source intensity decreases with the square of the distance ‘r’. In case of bounded spreading, k = 1 (for cylindrical spreading). Spreading loss has a logarithmic relationship with the range ‘r’ and its impact on the acoustic signals underwater is very significant for very short range up to 50m ,hence for shorter ranges, spreading loss plays a larger part compared to the absorption loss.

2.4.2 Absorption Loss

It is the loss that occurs in the form of heat due to viscosity and ionic relaxation of boric acid and magnesium sulphate ($MgSo_4$) molecules, as the sound wave propagates outwards underwater. The effect of viscosity is significant at higher frequencies above 100 KHz, whereas the ionic relaxation effects of $MgSO_4$ affect the frequency range from 10 KHz to 100 KHz. The boric acid affects the lower frequencies up to a few KHz. In general, the absorption coefficient α increases with increasing frequency and decreases as depth increases. Numerous factors and properties of sea water such as acoustic frequency, pressure (depth), temperature, salinity and acidity play a major role in characterizing the absorption co-efficient and is given as

$$\alpha = \left(\frac{A_1 P_1 f_1}{f^2+f_1^2} + \frac{A_2 P_2 f_2}{f^2+2} + A_3 P_3\right) f^3 \qquad \ldots(6)$$

Where f reperesents the frequency in KHz of the sound wave being transmitted, over the channel. A_1 is the boric acid component in the seawater and is given by,

$$A_1 = \left(\frac{8.68}{c}\right) 10^{(0.78pH-5)} \quad \ldots (7)$$

Where pH is the acidity of the seawater. The speed of sound propagation (c) is given by,

$$c = 1412 + 3.2T + 1.19s + 0.0167d \quad \ldots (8)$$

Where T is the temperature in water (°C), s is the salinity in mg/l and d is the depth in meters.

P_1 is the pressure of the boric acid in the sea water, its normalised value for shallow waters is given as 1 Pa. The relation frequency (f_1) of the boric acid is given as,

$$f_1 = 2.8\left(\frac{s}{35}\right) 10^{\left(4-\frac{1245}{273+T}\right)} \quad \ldots (9)$$

The $MgSO_4$ component (A_2) present in the water is given as,

$$A_2 = 21.44\left(\frac{s}{c}\right)(1+0.025T) \quad \ldots (10)$$

Whereas the depth pressure (P_2) in Pa, for the $MgSO_4$ is given as,

$$P_2 = 1 - 1.37\text{x}10^{-4}\, d + 6.2\text{x}10^{-9}\, d^2 \quad \ldots (11)$$

A_3 is the pure water component given as,

$$A_3 = 3.964\text{x}10^{-4}\, T + 1.45\text{x}10^{-7}\, T^2 - 6.5\text{x}10^{-10}\, d^2 \quad \ldots (12)$$

Pure water depth pressure (P_3) in Pa is given as,

$$P_3 = 1 - 3.83\text{x}10^{-5}\, d + 4.9\text{x}10^{-10}\, d^2 \qquad \ldots (13)$$

2.4.3 Path Loss

The total path loss is the combined effect of the absorption loss and spreading loss. For very short range communication below 50 m, the contribution of absorption term is less significant than the spreading term (Burrowes. G and Khan. J, 2011).

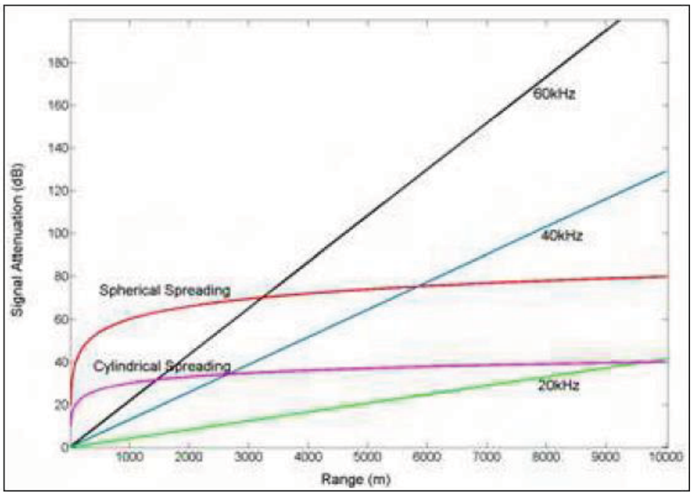


Figure 2. 3. Absorption Loss and Spreading Loss (Burrowes, G and Khan, J, 2011)

According to the model in Figure 2.3, the value of k has the most significant impact on the path loss at shorter ranges. Spherical spreading loss is the decrease in the source level when there are no boundaries such as water surface or sea floor, thus known as unbounded spreading. In reality, the acoustic energy cannot propagate in all directions due to boundaries such as the water surface and sea floor, thus leading to cylindrical spreading. Cylindrical spreading is when the acoustic energy encounters the water surface and sea floor and is trapped within these boundaries radiating horizontally away from the source.

2.4.4 Doppler Effect

The motion in the plane in which the acoustic waves is travelling towards or away from the receiver results in a shift in the carrier frequency. If Transmitter (Tx) and Receiver (Rx) are approaching, the frequency is higher, while if they are moving apart the frequency is lower. The causes for the Doppler Effect are as follows;

i. Apparent shifts in frequencies of transmitted signal due to the motion of Tx/Rx or both, this shift depends on the relative velocity of the Tx/Rx.
ii. Rapid fluctuations in the receiving conditions due to small movements of the receiver.

Note that the Power Spectral Density (PDF) is the direction of the waves reaching the receiver is uniformly distributed between 0 and 2π. The Doppler shift (Δf) of the received signal is given by,

$$\text{fc} = \frac{\Delta \text{v}}{\text{c}} \qquad \ldots (14)$$

Where 'fc' is the original signal frequency and Δv is the relative velocity between the Tx and Rx or nodes.

2.4.5 Multipath Fading

Fading basically means distorting a signal over a certain propagation medium. It happens mainly due to multipath propagation also known as multipath induced fading. In multipath fading, signal will reach the receiver not only via the direct path but also as a result of reflections from other objects underwater. In underwater multipath is governed by two objects

i. Sound reflection at the surface, bottom and any objects present underwater.
ii. Sound refraction in water.

This can lead to inter-symbol interference (ISI). In this case, one may need to use appropriate error protection scheme to minimize the effect of ISI.

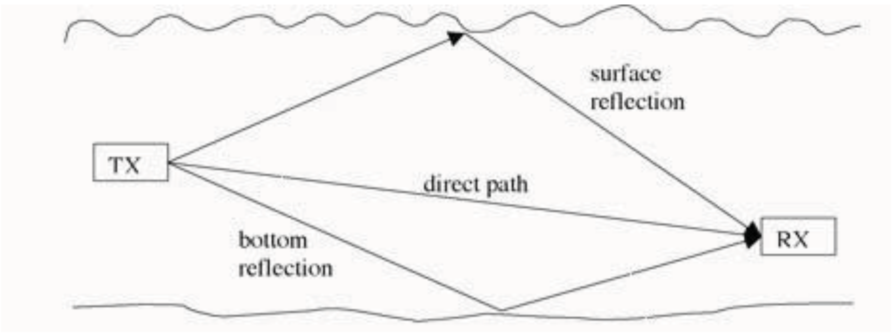


Figure 2. 4. Multipath Fading

The Figure 2.4 shows the reflections caused as the transmitted waves bounces either at the surface or bottom of the sea and reaches the receiver along multiple paths. This effect most commonly occurs in shallow water environments. Sound refraction in water is a consequence of sound speed variation with depth, therefore it is mostly evident in deep waters.

2.4.6 Ambient Noise

For underwater acoustic modem (UAM) operating at a frequency range of interest (10 KHz to 100 KHz), the ambient noise power spectral density (psd) decreases with increasing frequency. Ambient noise is basically caused due to external factors that interfere with the signal transmission. The four different types of ambient noise are described as follows (Simanjuntak L, 2004);

- Turbulence Noise

It's the noise generated by the rapid movement of water layers over each other's at various speeds. The turbulence noise is significant at the bottom of the sea. Only low frequencies of ($f < 10$ Hz) are affected by turbulence noise. The formula for turbulence noise psd in dB re uPa is given as;

$$10 \log N_w(f) = 17 - 30 \log f \qquad \dots (15)$$

- Wave Noise

Wave noise can be defined as the motion caused on the sea surface driven by different wind speeds. This has a major influence on frequency range of 100 Hz to 10 KHz. The empirical formula for the wave noise in psd, dB re uPa is given as;

$$10\log N_w(f) = 50 + 7.5\sqrt{w} + 20\log f \qquad \ldots (16)$$

- Shipping Noise

Shipping noise is caused by shipping activities carried out on the sea ocean surface, and has an impact on interfering with the transmitted signals in shallow waters. The shipping noise will vary depending on the level of boating activities in the oceanic area. The shipping noise is mainly dominant in the frequency range of 10 KHz to 100 KHz. The psd of shipping noise in dB re uPa is given as;

$$10\log N_s(f) = 40 + 20(s - 0.5) + 26\log f - 60\log(f + 0.03) \qquad \ldots (17)$$

- Thermal Noise

It's caused due to the molecular bombarding of the receiver. This noise dominates in the frequency region above of 100 KHz. Thermal noise in dB re uPa per Hz as;

$$10\log N_{th}(f) = 15 - 20\log f \qquad \ldots (18)$$

2.5 Bit Error Rate (BER)

As the name implies, BER is defined as the rate at which errors occur in a transmission system. BER is one of the key parameters to access the full end to end performance of a system. The definition of BER can be expressed by a simple formula i.e.

$$\text{Bit Error Rate, BER} = \frac{\text{Number of errors}}{\text{Total number of bits sent}}$$

$$\text{Bit Error Rate, BER (\%)} = \frac{\text{Number of errors}}{\text{Total number of bits sent}} * 100$$

If the medium between the transmitter and receiver is good and has high SNR, then the BER will be low, the main reason that causes BER is the presence of noise in the data channel.

2.6 Conclusion

The Bandwidth (BW) availability underwater is severely limited to KHz. While designing any systems for underwater applications, different characteristics of the underwater channel needs to be considered such as spreading loss, absorption loss, multipath fading, propagation delay and ambient noises. The reliability of the communication systems are tested based on the signal strength required to achieve a particular BER.

CHAPTER 3-Literature Review

3.1 Introduction

This chapter describes the previous and recent existing designs of acoustic modems for underwater wireless sensor networks and also gives a broad understanding related to this project work based on the literatures, conferences papers, books, journals and publishers. It also serves as a reference based on which the thesis work can be carried out.

3.2. Literature review on Underwater Acoustic Modems for Short Range Communication

The work of Bridget Benson et al focuses on the development of a short range underwater acoustic modem. Commercially available omnidirectional waterproof ultrasonic transducers are very expensive. In this work, a piezoelectric homemade transducer is used. The modulation scheme used is FSK due to its simplicity. The system supports data rates up to 200 bps with a BER of 10^{-2} for a low SNR of 10 dB The overall cost of the system is 600$. The transmission distance of the system is greater than 350m. Hardware platform used is FPGA (Benson et al, 2010).

The research work of Akylildiz, Pompili and Melodia describes the state of art of underwater sensor networks along with some research challenges for deployment of underwater acoustic sensor networks (UASN). It describes the different applications of the underwater acoustic sensor networks such Some of the major challenges in the design of UWASN’s have been mentioned such as Bandwidth (BW) limitation, high bit error rates followed by shadow zones, limitation in battery power and fouling corrosion. Different UWASN architectures or topologies such as two dimensional static and three dimensional underwater sensor networks have been described. This paper also describes some of the main differences between the territorial sensor networks and UWASN’s with respect cost, deployment, power and memory. An internal architecture of an underwater sensor node that consists of a sensor, sensor interface circuitry, microcontroller, power supply and acoustic modem has been described in detail and they have mentioned a way to make the system waterproof by using PVC housing. Some major challenges faced by the designers with respect to deployment of a low cost, low scale UWASN's has been listed and briefed. This research gives a good insight related to several design issues to consider for developing an acoustic modem (Akylildiz, Pompili and Melodia, 2005).

In the work of Wills, Yi and Heidemann, the primary aim was to design and develop an inexpensive modem that is affordable for purchase and for deployment of many sensor nodes. The target price of this system is said to be 100$ and the modem is mainly designed for short-range communication of range 50m-500m.The digital hardware platform used is a simple 8-bit Atmel Atmega 128L microcontrollers and this design makes each of the sensor node development cost cheaper. The modulation scheme used for data transmission here is FSK. A BER of 10^{-5} was seen when the transmitter and receiver were kept close to each other. (Wills, Wei Ye and Heidemann, 2006).

The CORAL communication subsystem is designed for one way communication. According to Pandya et al, the acoustic transducer used is an US Navy design whose operating specifications were found experimentally rather than in a component datasheet. The hardware platform used is a microcontroller that can be interfaced to any sensor for any specific application. The system was tested for shallow underwater with only two transducers placed in the water while the other circuitry was kept outside. The optimal operating frequency of the transducer underwater was found to be 1.7 KHz. The transmission efficiency was tested for a distance of 20cm and was seen to be same as observed for tests conducted for very short distance of 1.2cm. The SNR under water observed was 250 that is maximum for a frequency of 3.8 KHz. In this system, a signal voltage of 5V is being used to demonstrate low power system. However several environmental issues such as harmonics, acoustic reflections and medium noise limited the performance of the interface circuitry posing a challenge, therefore much more work is needed to solve these issues for the practical deployment of the CORAL modems (Pandya et al, 2005).

In the work of Jurdak et al, a software modem has been designed and developed that is coupled with generic microphones and speakers. This system eliminates the need for hardware requirements needed to carry out the modulation and demodulation schemes while the software itself takes care of it reducing cost and making it available for deployment of underwater acoustic sensor networks. The system makes use of software designed 8 frequency FSK modulation and demodulation schemes. A capacity of 24 bps can be transmitted underwater without any errors while it can support data rates up to 48 bps. The transmitter used is a Tmote Invent speaker's whose SNR measured indicated that this speakers supported a error free bit rate of at least 24 bps up to a distance of 13m. The FSK software modem was designed for 8 frequencies that showed high signal quality i.e. 1000,1200,1300,1500,1600,1700,1800 and 2000Hz. The minimum SNR noticed for all these frequencies within a range of 13m are 6.95dB providing data rates up to 24 bps that was error free channel capacity. The paper also describes some of the fundamentals of underwater acoustics parameters and issues to consider while designing an acoustic communication system. In short, this system consists of underwater network of sensor nodes that communicates with each other's through acoustic links eventually delivering the data to the water surface node connected to a laptop placed on a surface buoy. This laptop uses broadband radio connection to internet to transmit the received data to the station where that is analysed and interpreted using tools (Jurdak et al, 2007).

In the work of Num and Sunshin An, they developed a low power based acoustic modem that basically operates with 3.3V power supply and has a capability of digital data communication. The modulation scheme used in this work is amplitude shift keying (ASK).The system tested to show a data rate of 100 bps, the communication distance of the modem is approximately 3m, however the exact range of the acoustic modem could not be found due to the lack of test facilities. The system has made use of piezo-transducers i.e. Sounder/ projector/speaker at the transmitter and hydrophones at the receiver end, however some problems that needs to be considered for this modem for future work is directional property, reflection and refraction. In addition, this acoustic modem will become the basis for the underwater wireless sensor networks (Num and Sunshin, 2007).

The work of Jeon and Park mainly focuses on the design and implementation of an acoustic modem for underwater sensor networks that has good performance and efficiency. This modem was tested experimentally in water tank, a pond and offshore ocean for various distances and data rates and the bit error rate was observed. The modem used an Atmega128 microcontroller and waterproof piezo-transducer that operates at a frequency of 30 KHz. Two modems were tested in water tank for a depth of 0.7m and for communication distances of 0.2m, 0.5m and 1m for which a maximum of 4kbps data rate was achieved with no errors. The modem was then tested in the pond which is a length of 40m and width of 60m for depths of 1 to 5m, a maximum data rate of 5Kbps was achieved for a distance of 1m and a data rate of 1 Kbps at 30m. The modem was also tested offshore located on the southern sea of Korea and it could achieve a maximum data rate of 1Kbps for a transmit distance of 20m. The system uses a 14.8 volt Li-on battery to supply power to the modem circuitry and the implemented hardware (MCU). No quantifiable details or plots of the bit error rate and SNR have been reported. The performance of the modem was best seen in the pond therefore according to Jun-Ho-Jeon and Sung-Joon-Park, it was concluded that the modem operates better in open space such as pond with small multipath than a limited water tanks. Therefore in overall, the system supports data rates of up to 5 Kbps and can operate up to a range of less than 30m (Jun-Ho-Jeon and Sung-Joon-Park, 2010).

3.3 Summary of Literature Review

From the section 3.1, it is noticed that the maximum SNR was achieved is 250 but for a very short range of 20cm underwater based on the work of Pandya et al. The maximum data rate is achieved is 200bps for a range over 300m based on the work of

Benson et al, but the trade off in this modem is the high power consumption at the receiver end and low SNR. The SNR achieved is 6.95dB for data rate of 24 bps for a range of 13m based on the work by Jurdak et al. Therefore based on the literature review it was identified that the performance parameters such as SNR, range, BER and power consumption plays an important role during the design and analysis of an underwater acoustic modem. Based on the literature review it is identified that lower order modulation schemes provides robust communication, and the hydrophones/projectors adds up to the high cost of the system, therefore an alternate ultrasonic transducer needs to be used that is low cost and offers short range communication. The System needs to be simulated for the underwater channel, therefore it is necessary to model the underwater acoustic channel to simulate the modelled system and analyse its performance.

CHAPTER 4 –Problem Definition

4.1 Problem Statement

The aim of the project is to Design and Develop an Underwater Acoustic Modem for shallow waters (<100m) and short range (<100m) communication.

4.2 Project Objectives

- To conduct literature review on acoustic signals, existing underwater acoustic modems, underwater channel characteristics, modulation schemes, and error detection, correction schemes.
- To arrive at a system level specifications and functional block diagram of the low rate underwater acoustic transceiver system.
- To model the underwater acoustic channel and integrate noise models to the designed acoustic modem for analysing the system performance.
- To design, model and simulate the underwater acoustic modem using appropriate simulation tool for the desired specifications.
- To realize the designed system in hardware for low data rate communication
- To test and analyse the performance of the developed system

4.3 Methods and Methodologies adopted to meet the project objectives

- Literature survey on the Underwater Acoustic Communication System has been carried out by referring journals, white papers, books, patents and related documents.
- Conducted Literature survey on acoustic signals, existing underwater acoustic modems, underwater channel characteristics, modulation schemes, and error detection, correction schemes.

- Need analysis has been performed to identify deficiencies in the existing modems, based which the target system requirements are identified to overcome the deficiencies.
- Different modulation and error detection concepts were explored and analyzed, converging to the most suitable concepts.
- The functional block diagram and system design specifications were identified based on the literature survey and chosen concepts feasibility.
- The Underwater acoustic channel has been modelled using suitable software tools such as MatLab/Simulink.
- The chosen concepts for the transmitter and receiver implementation was modelled and simulated for the underwater channel using software tools.
- The simulation results were analyzed to identify the performance outcome of the modelled system.

CHAPTER 5 – System Engineering Based Design and Development of Underwater Acoustic Modem

5.1 Introduction

In this phase, need for a new underwater acoustic modem (system) in the presence on the available commercial acoustic modems, is analysed. The underwater acoustic modems (UAM), developed by the researchers for academic projects were studied. Thus the deficiencies with respect to commercial modems and areas having scope for improvement in the research based UAM's, are identified.

5.2 Need Analysis

The intention for developing this underwater acoustic modem (UAM) is to overcome the deficiencies in the presently underwater commercial acoustic modems. The significant deficiencies identified in the underwater commercial acoustic modems are as follows

- The physical structure of these commercial modems is bulk and also heavy in weight
- Since these modems are basically designed for long range communication, therefore they consume immense amounts of power, hence the overall power consumption is high
- The cost of development of one such commercial modem is very high, therefore not a cost effective option for deployment of underwater sensor networks
- These modems are generally designed for deployment in the deep oceans, thus making it difficult to access these modems, and frequent charging or replacement of the batteries is necessary which includes high maintenance cost.

The stated deficiencies can be overcome

- The target system should be designed for short range communication (<100 m).
- The target system should be designed for shallow waters of depth (<100m).

- The cost of development per node should be low for making it reliable for deployment of underwater sensor network using several such low cost nodes.
- The target system should be small in size i.e. the size per node should be small.
- The overall power consumption per node or system should be low in order to increase the lifetime of the system, and reduce the maintenance cost
- The system should be able to efficiently transmit and receive data adapting the underwater environmental characteristics.

5.3 Concept Exploration

The harsh and changing environment in underwater acoustic channel has significant impact in attenuating and altering the information being transmitted. This leads to the loss and corrupting of signal information, thus leading to high probability of Bit Error Rate (Rate) at the receiver end. The data link performance of the acoustic modem depends on the type of modulation schemes used and also on the strength of error detection, protection capability. Even though, higher order modulation schemes with the modulation order of 4 and above can provide higher data throughput in air, but however for underwater, from (Burrowes and Khan, 2011), it is identified that higher order modulation schemes are not robust schemes for data communications underwater, as the signal levels increases, the system becomes more susceptible to noise and ISI. A robust data link performance can be achieved underwater using the simpler lower rate modulations schemes, and this thought has occupied researchers approach to use the BPSK and BFSK schemes for several decades. A brief to the two approaches is discussed in the following sections.

5.3.1 Binary Frequency Shift Keying (BFSK)

In FSK, the frequencies of the carrier signals are used to the represent the binary data 1 or 0.A simple way to think about BFSK is to consider two carrier frequencies f_1 and f_2. The two carrier frequencies keep switching based on the binary input data, where the data 1 is represented by f_1 and data 0 is represented by f_2. Another scheme similar to

BFSK is the OOK scheme in which a binary data 1 is represented by a carrier frequency. which is the ON-state and binary data 0 is OFF-state not being represented by any carrier frequency i.e. the presence or absence of a single frequency is used to modulate digital data, thus the name On-Off Keying (OOK).

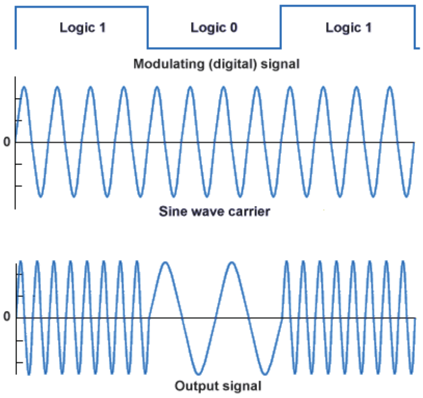


Figure 5. 1. Concept of BFSK Scheme

The Figure 5.1, shows the digital data 1's and 0's, being represented by two different frequencies in the output signal. There are two implementations of BFSK, one is non-coherent BFSK which may have discontinuity in phase when one signal element ends and the next begins. In coherent BFSK, the phase continuous through the boundary of two signal elements.

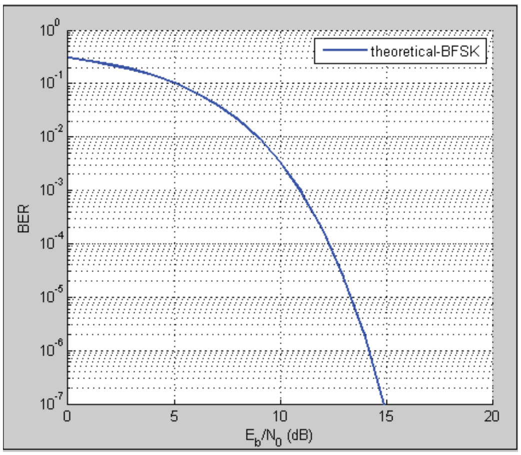
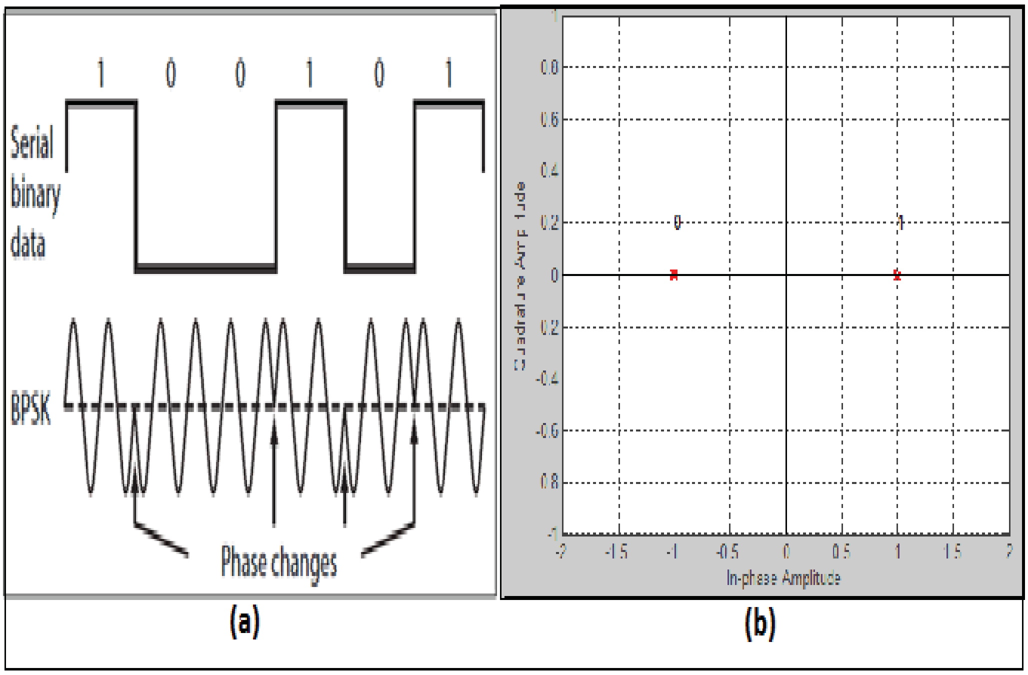


Figure 5. 2 Performance Curve of BFSK

The Figure 5.2, shows the ideal data link performance of the BFSK scheme for the AWGN channel. The plot shows the BER that can be achieved for different levels of Eb/No values in dB. Theoretically, a BER of 10^{-5} can be achieved for an Eb/No of 12 dB for a given AWGN channel, however in practice the value of Eb/No required to achieve a BER of 10^{-5} will be more than the theoretical value and it depends on the channel conditions and induced noise by the receiver itself.

5.3.2 Binary Phase Shift Keying (BPSK)

In PSK, the phase of the carrier is varied to represent the binary data 1s and 0's while the peak amplitude and the frequency remain constant.



(a) (b)

Figure 5. 3. Concept of BPSK Scheme

The simplest PSK in which, only two signal elements exists, one with a phase of 0° and the other with a phase of 180°. The Figure 5.3a gives a conceptual view of the BPSK. The Figure 5.3b shows the constellation diagram, that shows the amplitude and phase of the signal element particularly when two carriers are being used (one in phase and one quadrature), the Figure 5.3b shows the data points or symbols that are 180° out of phase with each other. BPSK also uses only an in-phase carrier and it creates two signal elements, one with amplitude 1 and other with -1. In simple terms, it can be stated as, the binary data 1 is represented with amplitude of 1V in phase and 0 is represented by a amplitude of -1V that is out of phase by 180°.

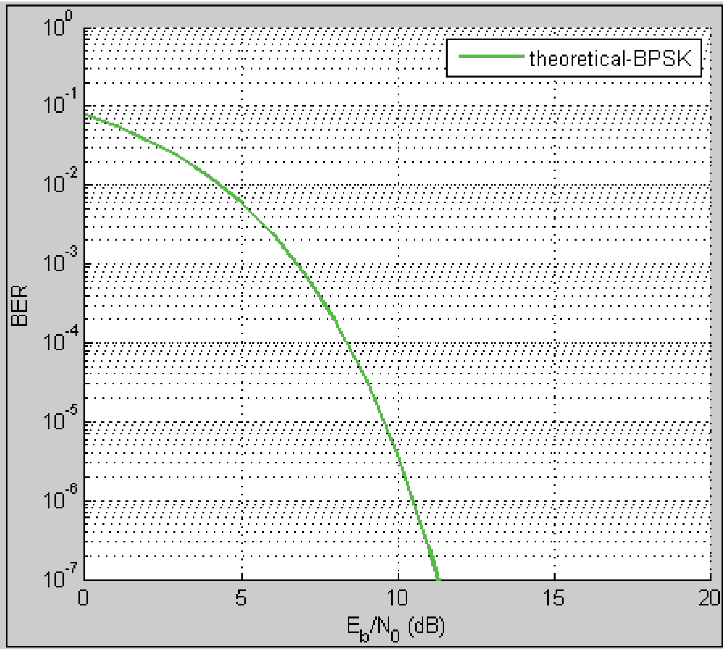


Figure 5. 4. Performance Curve of BPSK

Figure 5.4, shows the ideal data link performance of the BPSK scheme for the AWGN channel. The plot shows the BER that can be achieved for different levels of Eb/No values in dB. Theoretically, a BER of 10^{-5} can be achieved for an Eb/No of 9 dB for a given AWGN channel, however in practice the value of Eb/No required to achieve a BER of 10^{-5} will be more than the theoretical value and it depends on the underwater channel conditions.

Note: The theoretical BER v/s Eb/No curves were plotted for BPSK and BFSK using the BER Tool available in the Matlab-Simulink.

5.3.3 Error Protection and Detection

In any communication system, before transmitting the modulated data, it is important to make sure, the data packets or frames are protected against errors in the transmission channel (underwater channel), and the receiver should be in a position to detect maximum errors occurred in the received packets. This process is known as error detection capability. This technique basically adds some redundancy or extra bits to the data forming a codeword and making it robust to transmit receive and detect errors in the received data packets. There are two actions that can be initiated to minimize the BER when errors are detected at the receiver end, and they are as follows;

- The receiver can have error correction capability on detection of bit errors and improve BER performance. In this case the receiver should be able to identify the type of errors occurred i.e. single bit or burst errors and have a mechanism to interpret and correct these errors. This is also known as the forward error correction.
- The receiver must have a strong error detection capability, when errors are detected in any of the received data packets or frames, the receiver will send a retransmission request of that particular data frame to the transmitter to minimize the BER. This is also known as error detection by retransmission.

The most prominent error detection schemes are the block coding, simple parity check code and Cyclic Redundancy Check. A conceptual brief to different error protection coding schemes are described as follows;

5.3.3.1 Simple Parity Check Code

The most familiar error-detecting code is the simple parity check code. In this code, a k-bit dataword is changed to an n-bit codeword, where n=k+1, the extra one bit appended is called the parity bit. The bit is a 1 or a 0 depending on the parity. There are two types of parity check i.e. add parity and even parity. In add parity check, the data chunk is appended with either a 0 or 1 bit, making an add number on 1’s in the codeword.

In even parity check, the data chunk is appended with a 0 or 1 bit, making an even number of 1's in the code word. A conceptual view of the even parity check is described below;

Simple Even parity check Scenario: Assume the sender transmits a (k) 4-bit data word 1011. Since the number of 1's in the dataword is add, a 1 bit is appended to it making it codeword (n) of 10111, thus the codeword (n) is transmitted. As the data packet received at the receiver is corrupted due to the transmission channel. Three cases can be considered as follows;

i. Case 1: The received data packet is 10111, thus the receiver performs XOR operation on all the 5 bits sequentially, resulting a syndrome of 0, which means the data received is not corrupt, hence the dataword 1011 is created.
ii. Case 2: A single bit error occur forming codeword 10011, since the number of 1's is odd in the received codeword, the syndrome results a 1, meaning dataword is corrupted, therefore discarded.
iii. Case 3: Three bits are changed in the codeword due to errors forming 01011. The syndrome is 1, since the number of 1's is even and thus the corrupt data packet is not created.

5.3.3.2 Cyclic Redundancy Check (CRC)

The CRC is well known error protection and detection scheme in which the data packets are appended with redundancy bits before transmission. Unlike the simple parity check code, in CRC more than 1 redundancy bits can be appended to the data packet. The CRC makes use of the modulo 2 arithmetic division, in which the generator polynomial G(x) is the divisor and the message bits F(x) is the dividend, the remainder obtained will be the CRC error checking bits appended to the data packet before transmission.

CRC Scenario**:** Assume the sender transmits a 4 bit data F(x) = 1001011 and uses a polynomial of G(x) = 1011 (x^3+x+1). The sender and receiver agree upon an arbitrary binary pattern G(x) = 1011. Shift F(x) to the left by 1 less than the number of bits in G(x). Now, F(x) = 1001011000. Let F(x) is the dividend and G(x) be the divisor. Perform “modulo 2 divisions”. After performing the division, the quotient is ignored. A 100 is obtained as the remainder R(x), which becomes the actual CRC checksum. Add the remainder to F(x), giving the message M (x):

1001011 (F) + 100 (R) = 1001011100 = M(x)

At the receiver, the codeword M(x) is decoded and checked by using the reverse process. In the XOR division, decoding the codeword M(x) by the G(x) gives a remainder of R(x) = 0000, this means that the received codeword M(x) has the data packet intact and hence no error has occurred, however in case if the remainder obtained after division is not 0000 at the receiver end, then it just means that an error has occurred in the data packet and thus the corrupt data packet is discarded.

Table 5. 1 Standard CRC Polynomials

Name	Standard Uses
CRC-1	Single Parity Check
CRC-4	International Telecommunication Union (ITU)
CRC-6	CDMA-2000 A, CDMA 2000 B (Mobile Networks)
CRC-8	WCDMA-Mobile Networks
CRC-10	ATM, CDMA 2000-Mobile Networks
CRC-11	FlexRay
CRC-12	Telecom Systems
CRC-15	CAN
CRC-16 and CRC-32	IEEE-Telecommunications

A much deeper insight to CRC scheme has been described in detail (Forouzan, 2007). There are general standards of CRC polynomials used for different applications. The

Table 5.1 shows the different CRC polynomials standards set and used for telecom applications.

5.4 Concept Definition

The most suitable modulation schemes for underwater explored are BFSK and BPSK. In order to choose the right modulation scheme, it is necessary to understand the performance of these two schemes in the underwater channel.

5.4.1 Modulation Scheme

The BPSK and BFSK are modulation schemes that has shown potential in the field of underwater acoustic communication. From Figure 5.2 and Figure 5.4, it is seen that, BPSK offers better signal to noise ratio compared to that of BFSK, however non-coherent BFSK was the only alternative technique that could sustain the rapid phase variations occurring in the shallow water (Istepanian and Stojanovic 2002, 142).Hence in this research non-coherent BFSK modulation scheme is chosen, as it has several advantages over BFSK as follows;

- BPSK modulation scheme is very sensitive to phase variations, it’s highly susceptible to multipath effects causing ISI, while non-coherent BFSK is immune to channel phase variations as it tracks only frequencies to detect the original data.
- The requirement to track phase in the receiver, to retrieve original data from the carrier signal increases the complexity of the receiver design, therefore using non-coherent BFSK scheme simplifies the receiver design and there is no need for the use of a PLL circuit.

5.4.2 Error Protection and Detection

In concept exploration, the two error protection and detection schemes identified are the simple parity check code and the CRC. For underwater acoustic channel, one must understand that the coding schemes with higher error detection and correction capabilities will require more overhead and bandwidth. This results in lower information transmission rates. The simple parity check is easy to implement, however it has some serious drawbacks as follows; let's consider the same scenario (even case) as in section 5.3.3.1, the dataword is 1011.

- If the received word is 10110, the syndrome results a 1, note that although none of the data bits are corrupted, yet the dataword is discarded of being corrupt. The reason is that the simple parity check code is not sophisticated enough to show the position of the corrupted bit.
- If the received codeword is 00110, the syndrome result is 0 since the number of 1's is even, thus the corrupt dataword 0010 is accepted. The reason is the dataword is wrongly created due to the syndrome value. Therefore simple parity check decoder cannot detect an even number of errors. Hence the simple parity check can detect only odd number of errors and can detect only one single bit error.
- Another serious drawback is the redundancy. For a noisy and harsh channel such as the underwater channel, the simple parity check code offers very little protection to data packets, since redundancy in this scheme is just a single bit appended to each data packets and this can make the data bits exposed to some serious ISI. Hence for preventing the ISI caused due to the multipath in shallow under waters, it is necessary to have certain amount of redundancy between each data packets. Therefore the concept of simple parity check is eliminated, since it's not suitable for underwater acoustic communication.

Error correcting codes such as the hamming, RS and convolution codes are generally more complicated than error detection; more difficult to implement, and have lower code rates, but have powerful error correcting capabilities. Increased coding complexity for better error correction will cause longer delays at the source and destination for encoding and decoding process. These schemes are basically more suited for satellite and deep space communication where the essential bandwidth is unlimited and correction of errors by the concept of retransmission is not feasible

(Shelton, 1999). The error correcting capabilities can also be used for long range underwater acoustic communications, since retransmission on error detection is not a feasible option. For shallow water applications, the effects of multipath is very significant, therefore a certain amount of redundancy is a must to avoid ISI and the fewer bits used for coding redundancy, the less error protection is provided. A trade-off must be made between bandwidth availability and the amount of error protection required for the communication. The underwater acoustic channel is highly susceptible to single bit errors and burst errors, therefore the CRC scheme is the most suitable concept for error detection of the data packets, the advantage of CRC is that it has a very good performance in detecting single-bit errors, double errors, odd number of errors and burst errors. The CRC concept can be easily implemented in software and hardware. Hence using CRC will certain level of protection to data bits from ISI caused due to multipath and also provide excellent error detection capability. From Table 6.1, it is seen that several standards of CRC exists such as CRC-10, CRC-12, CRC-16 and CRC-32, these standards are suitable for communications in air, since the bandwidth of the air channel is much more compared to that of underwater channel. These CRC standards will not be suitable for underwater communication since the bandwidth available is severely limited. Therefore the use of high redundancy CRC's for underwater communications is eliminated, instead CRC polynomials such as CRC-3, CRC-4 (ITU) and CRC-6 (CDMA 2000) is considered, since these schemes provide sufficient redundancy between adjacent data packets while consuming lesser bandwidth providing sufficient data rates and excellent error detection capability. The Underwater Acoustic Modem (UAM) being designed is for short range applications, therefore the concept of retransmission of corrupt data frames using the Selective Repeat Automatic Repeat Request (ARQ) is more feasible concept. However the implementation of Selective ARQ is out of the scope of this project. This research mainly focuses on implementation of the error detection mechanism for the system using CRC.

Table 5. 2 Design Specification

Parameters	Specification
Modulation Scheme	BFSK
Receiver	Non-coherent BFSK Detection
Error Protection and Detection	Cyclic Redundancy Check (CRC-6)
Bandwidth (BW)	3200 Hz
Frequency Separation (Δf)	1 KHz
Data rate (N)	1600 bps (1300bps + Redundancy)
Redundancy Bits	~300 bps
Transmit signal Power (P)	0.1 W
Operating frequency	40 KHz
Sampling Time ,T_s	1/1600
Symbol period,T_{sym}	0.625 ms
Frames per second	100 Fps
Operating Range (R), meters	Below 100 m
Operating Depth (D), meters	Below 100 m

The Table 5.2 describes the design specification of the system to be modelled. It is seen that the system to be modelled must meet this requirements. The system should operate at a constant low power of 0.1W. The modulation scheme used is BFSK and the receiver is modelled based non-coherent BFSK.

5.5 Advanced Development

This phase deals with the software implementation of the system. It describes the approach towards modelling an underwater acoustic channel and the underwater acoustic modem. The system is simulated for different channel conditions and its end to end performance is analysed.

5.5.1 System Block Diagram

The system block diagram is describes the process of communication between the transmitter and receiver.

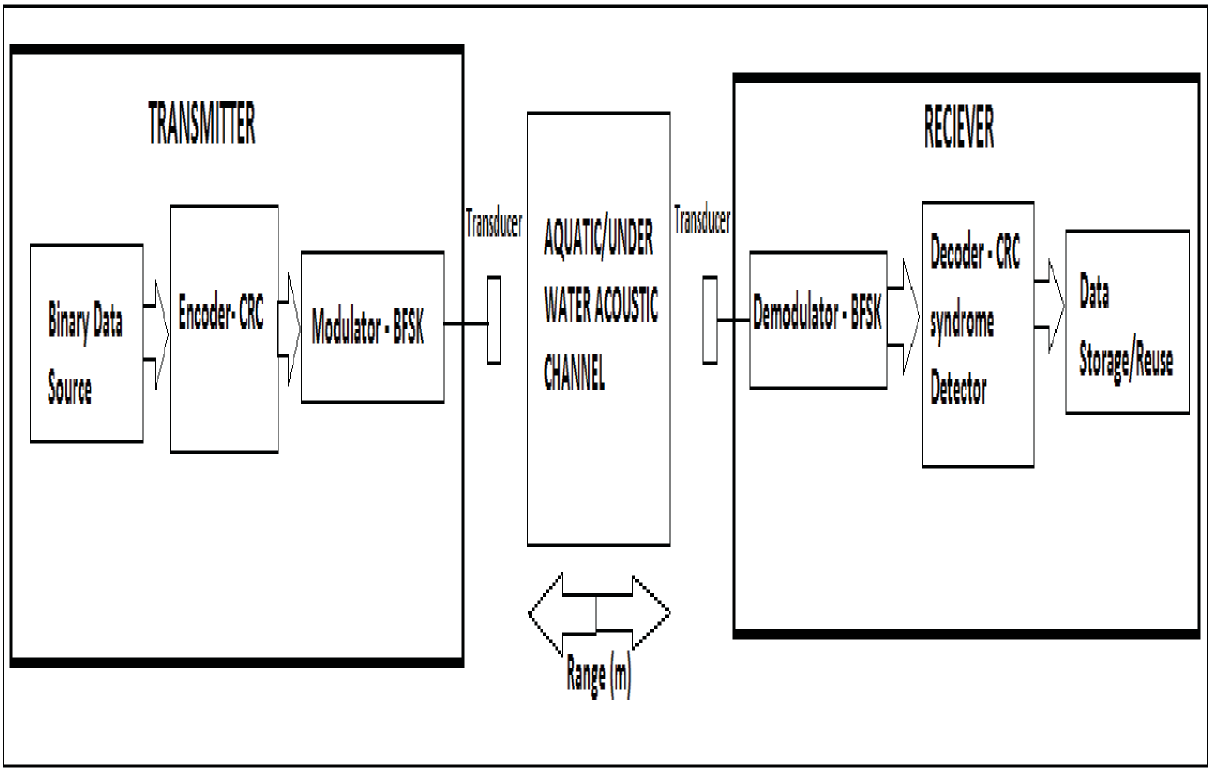


Figure 5. 5. Block Diagram of System

It also has an aquatic channel block. A software implementation of this system is developed, to be able to run simulations and compare or predict the systems behaviour. The Figure 5.5, shows the aquatic channel block breakdown into several internal blocks. and represents the relevant functions that has to be modelled and implemented at the transmitter and receiver.

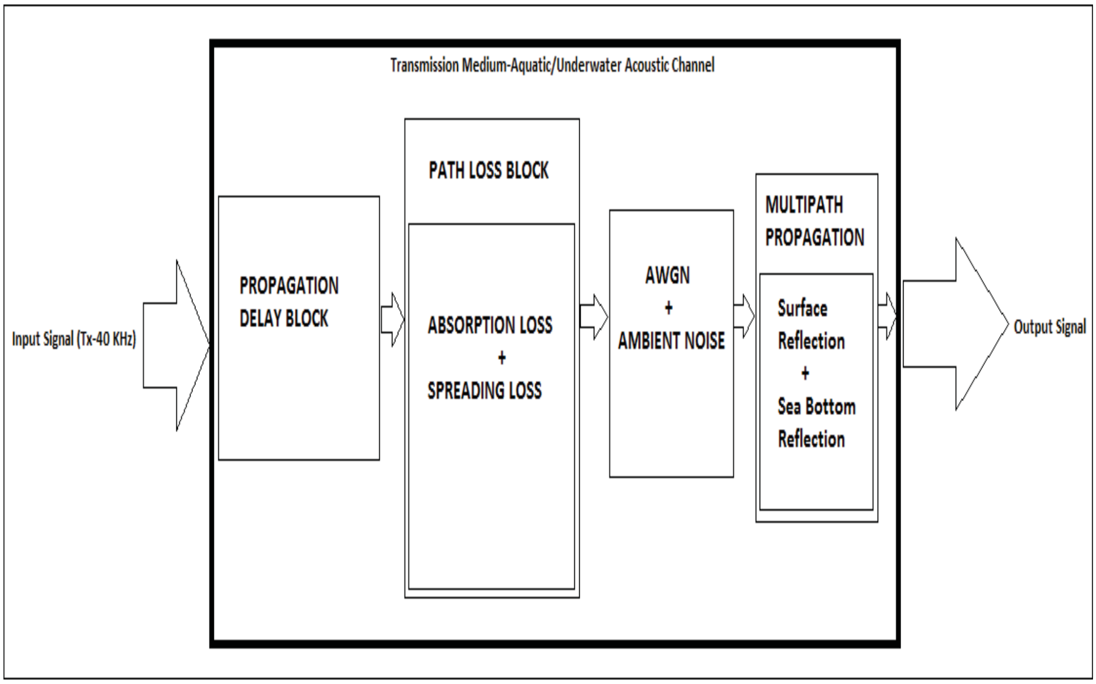


Figure 5. 6. Underwater Acoustic Channel

The path loss block deals with the modelling of absorption and spreading loss. The propagation delay block propagates the sound in the underwater channel based on the temperature, salinity and depth variability's. AWGN block generates additive white Gaussian noise with flat PSD. Ambient noise block adds up the noises occurring due to external factors, to the transmission signal. The multipath block is modelled to characterize the reflection occurring from the surface and sea bottom. The aquatic channel is modelled using equations discussed in section (2.4).

5.5.2 Software tool used for simulations

Matlab/Simulink was the chosen tool to develop all the simulation models. This tool offers great versatility to modelling communication systems, especially the physical layer design. Another speciality of this tool is it has a variety of ready to use blocks, which greatly simplifies and speeds up the software development process.

5.5.3 Underwater Acoustic Channel Model

Modelling of the communication channel is significant in the detection theory. It is important to conduct statistical approximation of the real environment of the underwater acoustic channel. It has been a difficult task to model a communication channel that has exact statistical representation of the underwater channel, due to its homogeneity and non-stationary nature. One of the common noise models used in the scientific and engineering world is the Addictive White Gaussian Noise (AWGN) to represent communication channels. It does provides the researchers with a fairly good approximation of the real environment, but it does not mimic specific characteristic of underwater channel such as, absorption loss, spreading loss, ambient noise, multipath fading and propagation delay.

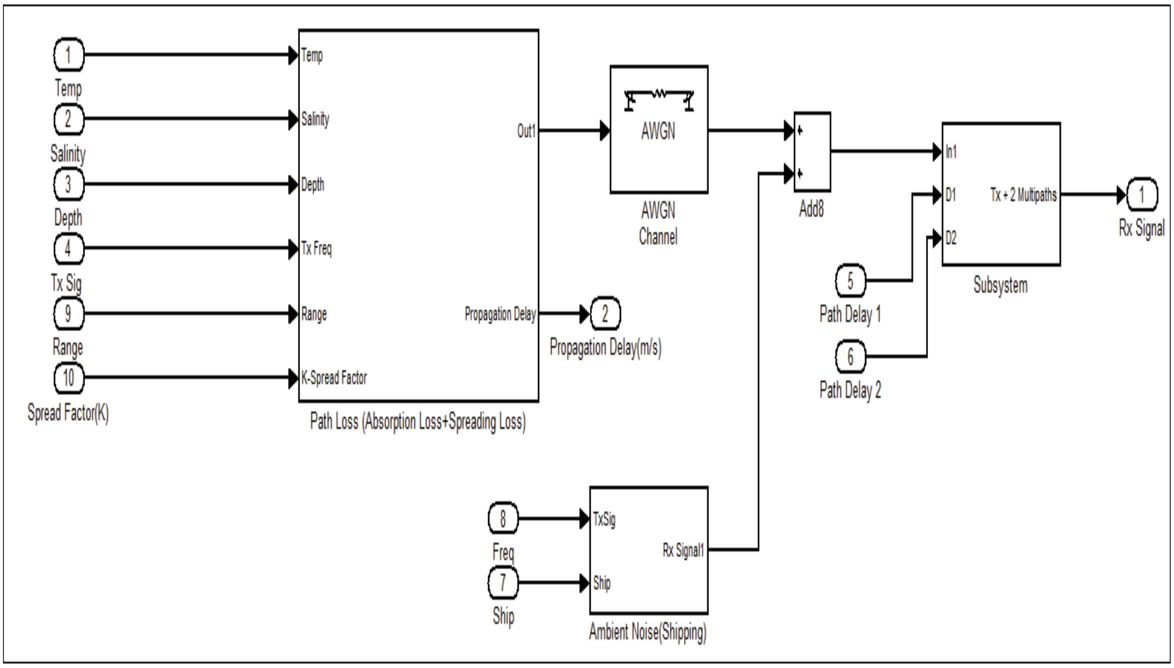


Figure 5. 7. Underwater Acoustic Channel Model

Therefore in this research, statistical noise models representing these specific effects of the underwater channel are considered. The AWGN is also considered as a part of the underwater channel, as to test the performance of the system for the worst possible medium. The Figure 5.7 shows the underwater acoustic channel model. The underwater channel is influenced by path loss i.e. Absorption loss and Spreading loss, AWGN, Ambient noise, Propagation delay and multipath propagation.

5.5.3.1 Propagation Delay

The delays experienced in a underwater acoustic communication link is much higher than in air link. Nominal speed of sound underwater is 1500 m/s, which is 100 times slower than the speed of electromagnetic waves i.e. $3x10^8$ m/s.

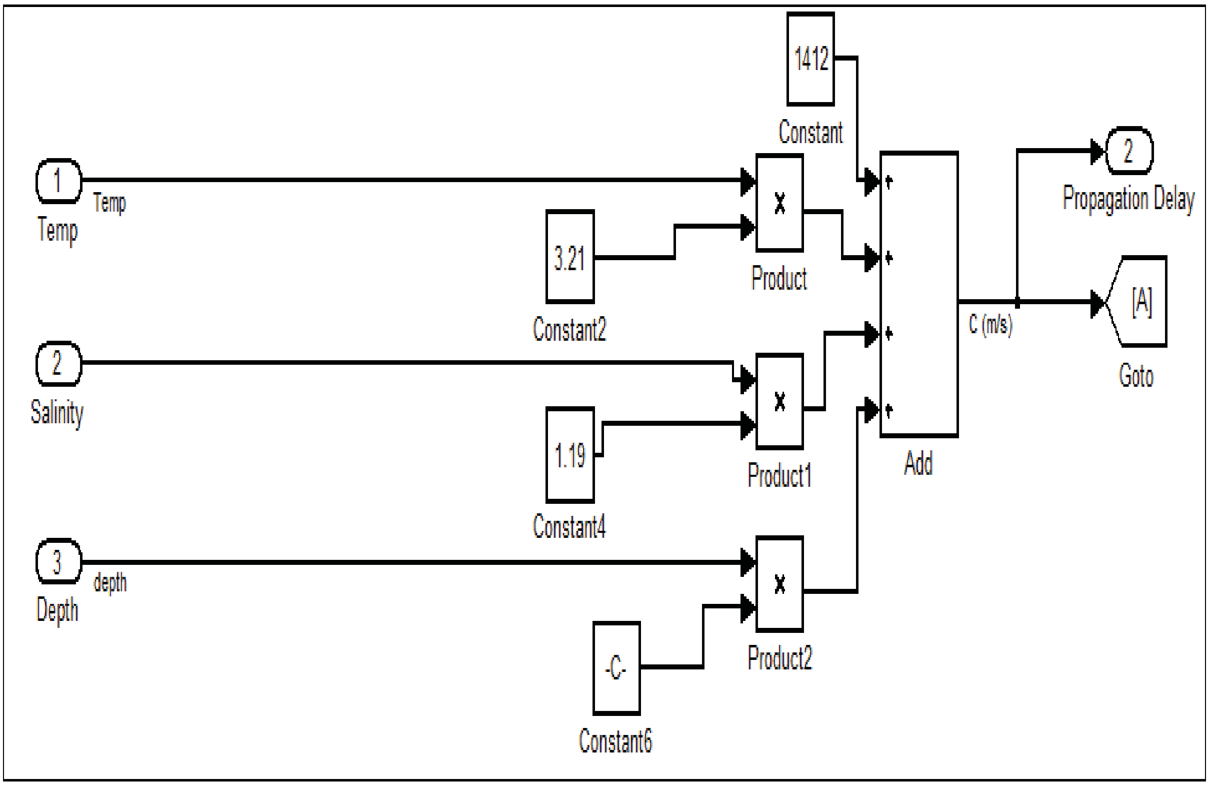


Figure 5. 8. Acoustic Propagation Delay Model

The model shown in Figure 5.8 causes propagation delays, which becomes a major complication for applying the feedback techniques in correcting the channel distortions. The propagation delay was modelled based on the equation (8).

5.5.3.2 Path Loss

The Figure 5.9 represents the model that represents the boric acid (A_1) component of the absorption loss model.

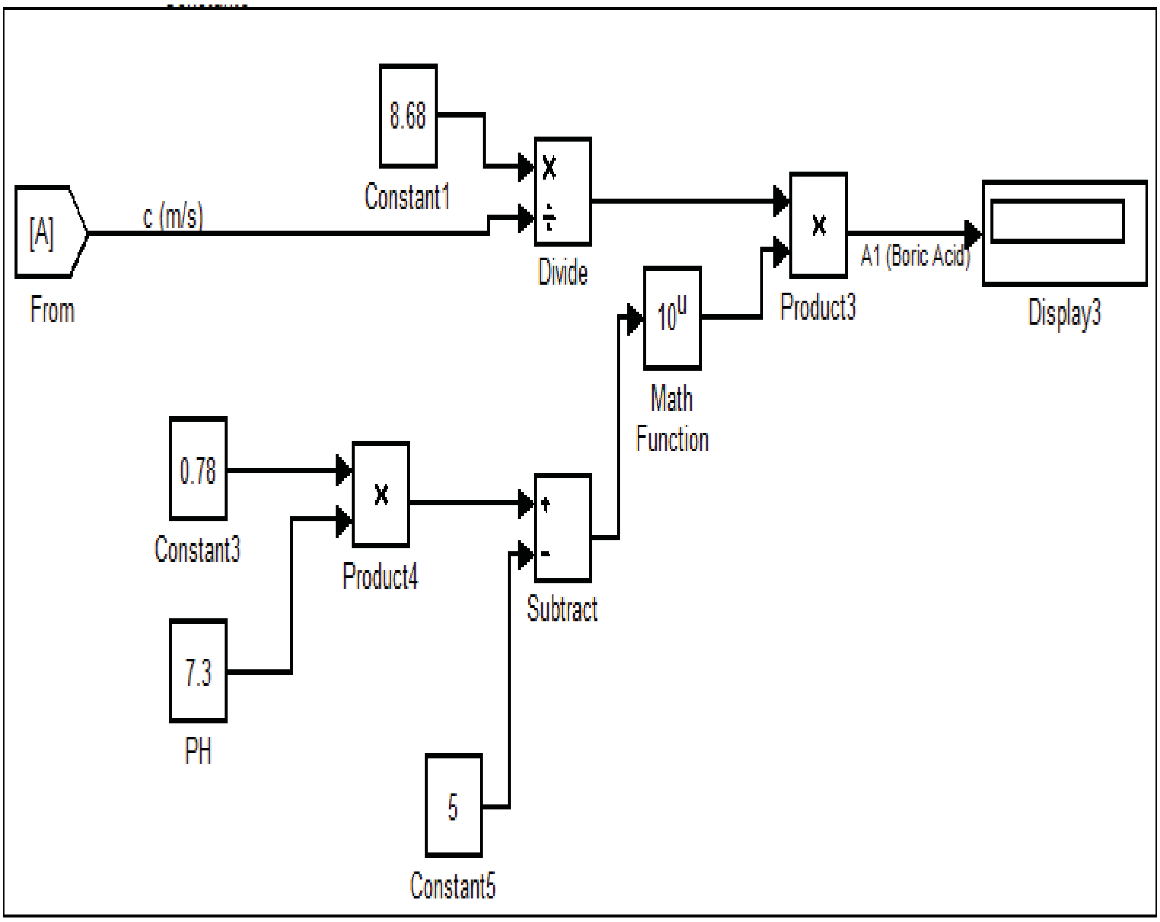


Figure 5. 9. Boric Acid Component Model

The output of the boric acid component (A_1) depends on the propagation speed of sound underwater (c). This component was modelled based on the equation (7).

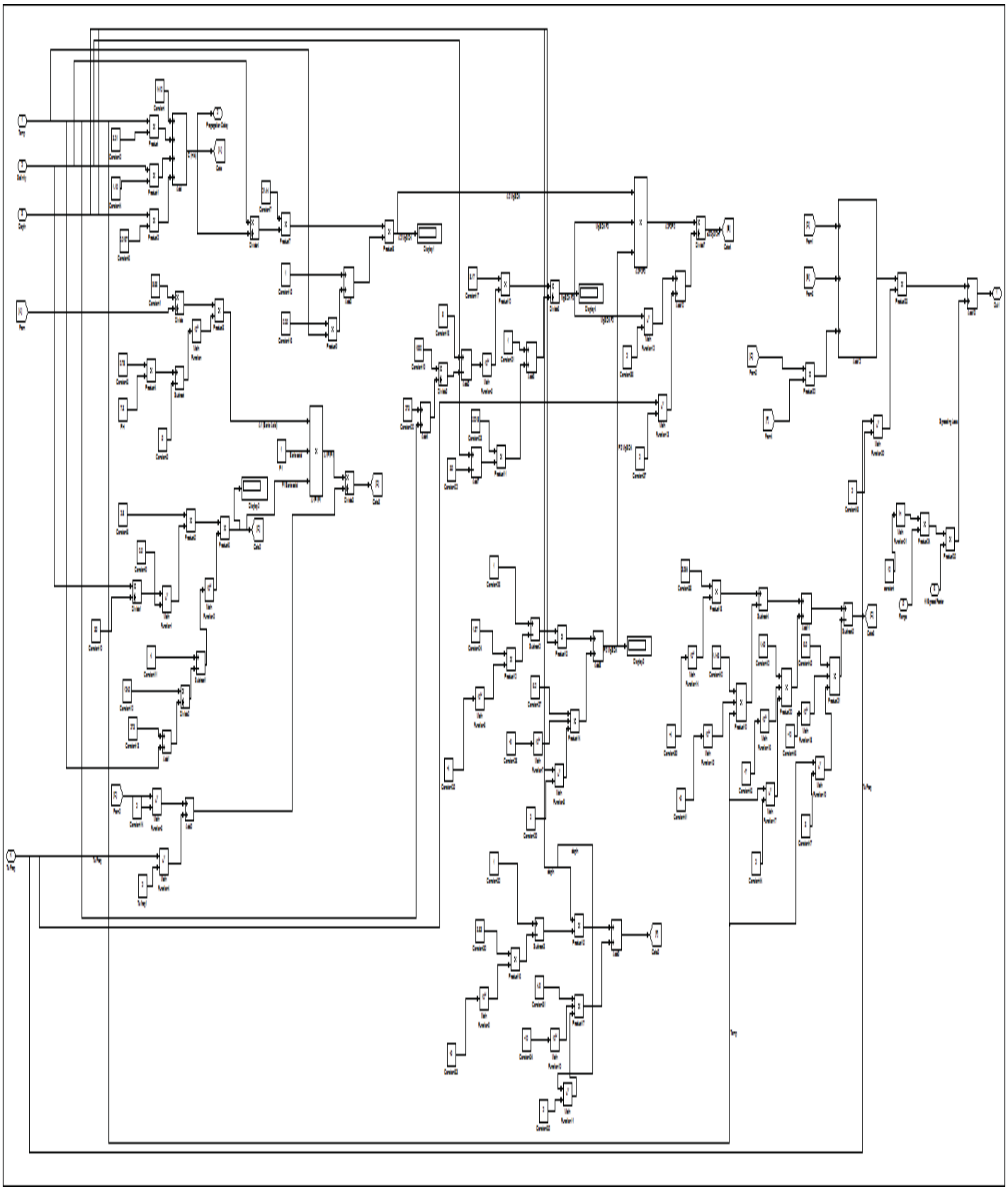


Figure 5. 10. Path Loss (Absorption Loss + Spreading Loss) Model

The Figure 5.10 represents the path loss model that constitutes absorption loss and spreading loss. The absorption loss is modelled based on the equation (6). The absorption loss equation consists of other components, which are modelled similar to the boric acid (A_1) as shown in Figure 5.9.

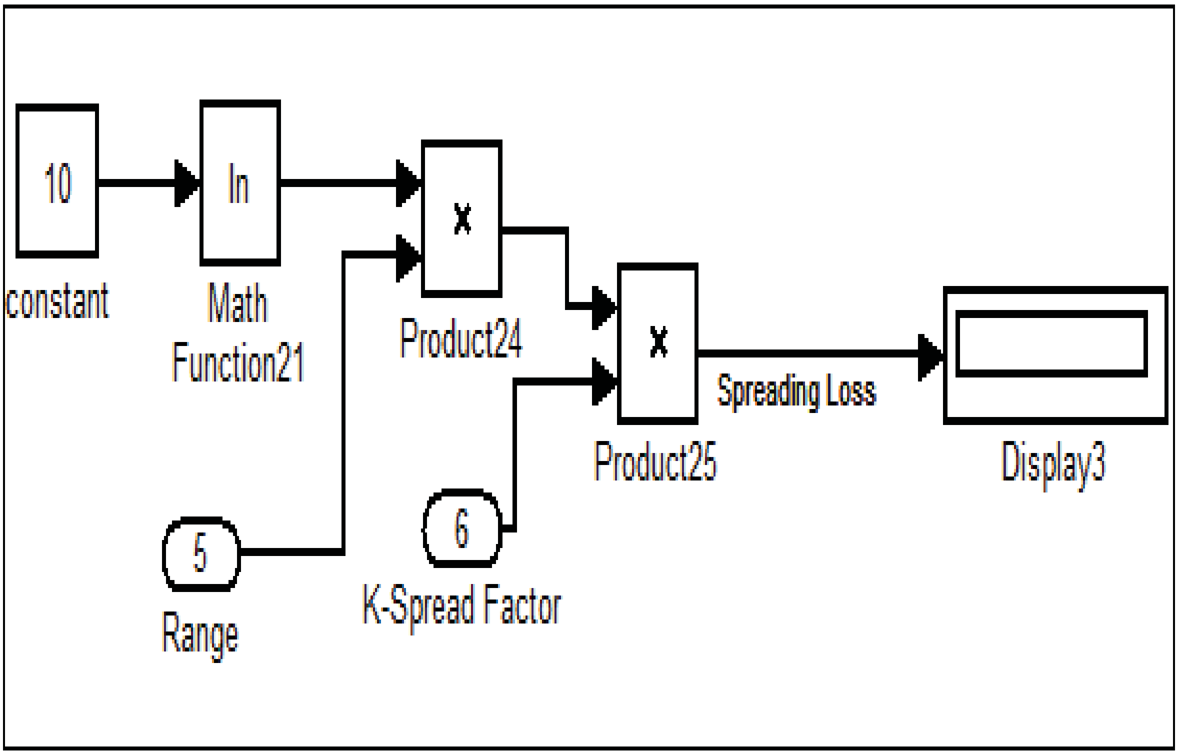


Figure 5. 11. Spreading Loss Model

The Figure 5.11 represents the spreading loss model that contributes to the path loss based on the equation (5). The output of spreading loss model depends on the input parameters such as the spreading factor (K) and range (R) in meters.

5.5.3.3 Ambient Noise

The Figure 5.12, represents the ambient noise models for turbulence noise, shipping noise, wave noise and thermal noise. In this research, one of the common ambient noise is used i.e. shipping noise.

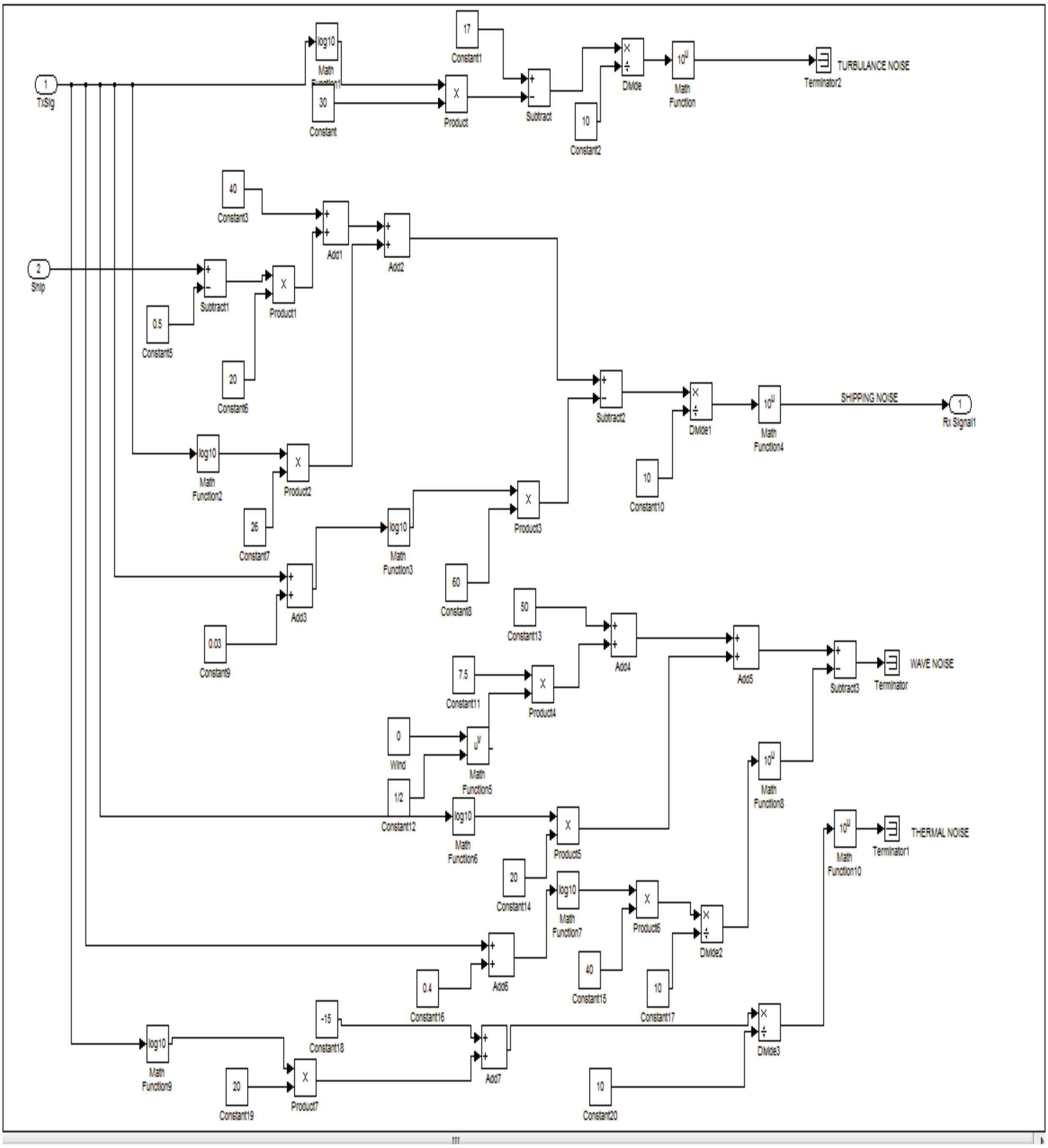


Figure 5. 12. Ambient Noise Models

A transmit signal frequency used is 40 KHz, therefore only the shipping noise can interfere during data transmission. The other noises does not have any impact on this signal frequency as discussed in section 2.4.6. Hence in the Figure 5.12, it is seen that all the individual noise models are terminated while allowing only the shipping noise to corrupt the signal. The left over noise models can be used for future works to simulate the system for different transmit signal frequencies.

5.5.3.4 Multipath Propagation

The Figure 5.13 represents the multipath propagation model. In this case two delayed paths are considered. The delays are introduced in terms of samples.

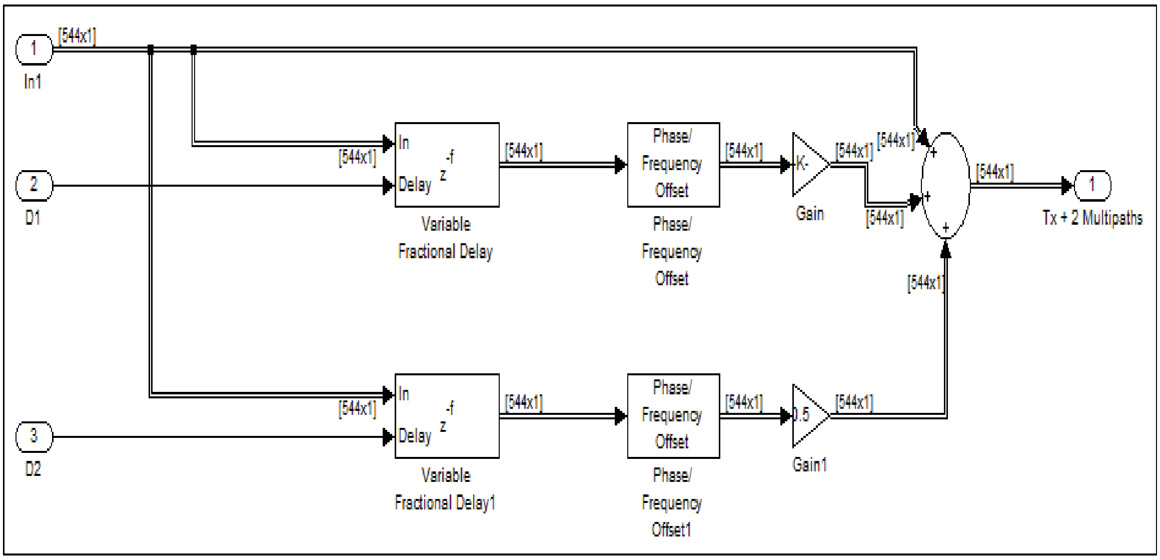


Figure 5. 13. Two Multipath Delays

The phase and frequency offsets for the delayed multipath are introduced. The first path delay is considered as the reflection from the surface and the second delay is the reflection caused due to the sea bottom. The variable delay block is used to introduce the delays to the direct signal in terms of samples or ms. The Phase/Frequency offset block is used to introduce the shift in the carrier frequency due to Doppler spread. The change in phase is not going to affect the system, since the receiver is based on Non-coherent BFSK.

5.5.3.4 System Model in Matlab/Simulink

The system is divided into 3 main parts; the transmitter, underwater channel and the receiver. The Figure 5.14 describes the system modelled in Matlab/Simulink. The data source block generates a stream of binary input data frames 16 bits each at a rate of 100Fps i.e. 1600bps.

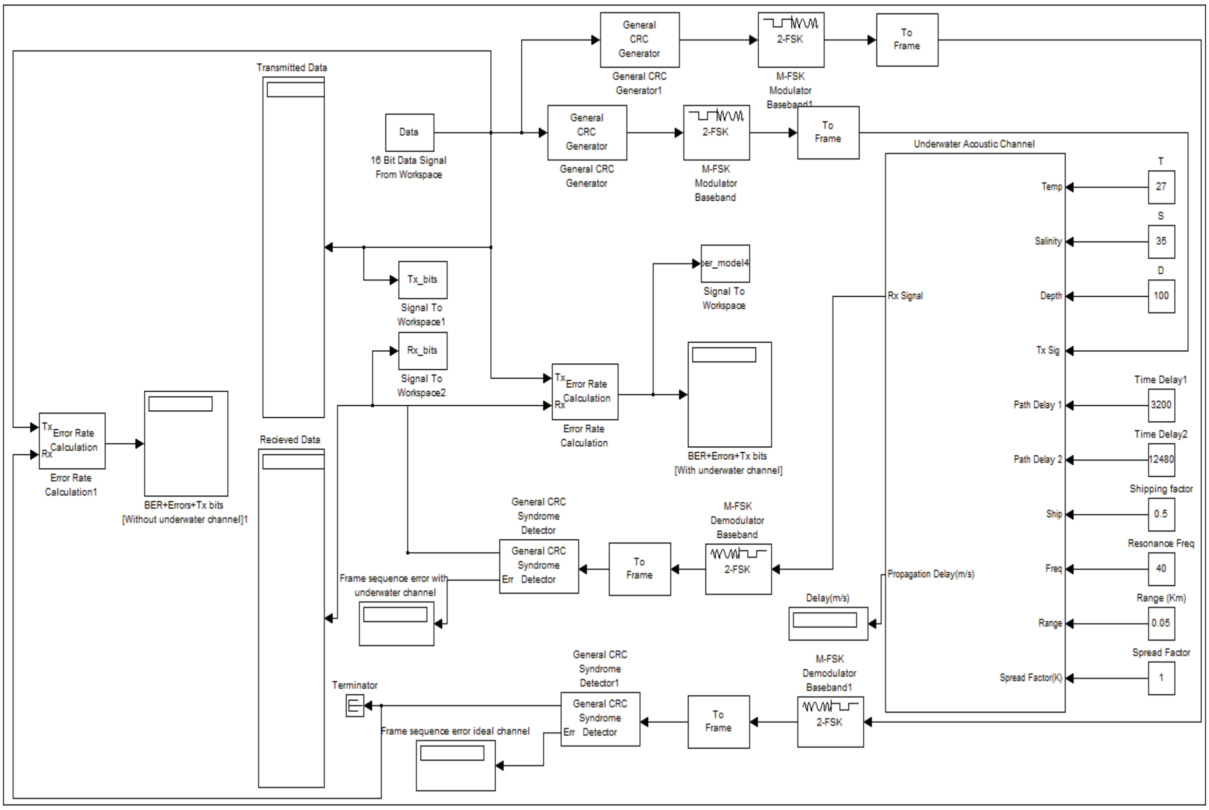


Figure 5. 14. System Model in Simulink

The data frames are encoded by the CRC block and then the digital data is modulated by the BFSK to transmit the signal. During transmission the signal is corrupted by the underwater channel. At the receiver, the signal is demodulated by Non-coherent BFSK, and decoded by the CRC detector to detect errors and extract the data to be stored.

Transmitter: The transmitter consists of the data source, encoder and modulator, they design parameters are described as follows;

- Data Source (signal from workspace): A 16 bit/2 bytes binary data is generated from the Matlab workspace. The 16 bit data input is generated in a cyclic repetition continuous form. The data rate is R_b = 1600 bps (1300bps + Redundancy). Thus the sample time (T_s) is given by,

$$T_s = 1/R_b$$
$$T_s = 1/1600 \text{ s}$$

A margin of 300 bps is kept for the addition of the redundancy to the datawords for robust transmission. Therefore it takes Ts = 0.625ms to sample each bit.

- Encoder (Cyclic Redundancy Check): The binary data is encoded using the CRC technique for a robust transmission. A CRC generator block is used to break down the length of the message evenly into data frames, and append the appropriate CRC or redundancy based on the generator polynomial G(x). In this case CRC-6 has been used as it had proven to provide better performance compared to the other CRC standards. The mask parameters are as follows;

Generator Polynomial: [6 4 2 0] i.e. $G(x) = x^6+x^4+x^2+1$
Initial States: 0
Checksums per frame: 2

The initial state of the internal shift register is specified by the Initial states parameter as 0.The number of checksums that the block calculates for each input frame is specified by the Checksums per frame parameter. The Checksums per frame value must evenly divide the size of the input frame i.e. 16bit = 8bit+8bit. If the value of Checksums per frame is 2, the block does the following: Divides each input frame into 2 subframes of equal size, Prefixes the Initial states vector to each of the 2 subframes, applies the CRC algorithm to each augmented subframe, Appends the resulting checksums at the end of each subframe and Outputs concatenated subframes.

- Modulator (BFSK): A BFSK baseband modulator block is used to modulate the input binary data frames for transmission. For BFSK, the bandwidth(BW) is given by,

$$BW = 2xR_b = 2x1600bps = 3200\text{ Hz}$$

The frequency separation (Δf) between the mark and space frequency was selected as 1000Hz. In BFSK, only two signal levels are possible i.e. either 1 or 0, therefore M = 2. The output data type is double. The simulated is based on single rate processing, in which the block accepts the input as the column vector input signal.

Underwater Acoustic Channel: The signal is transmitted through the underwater acoustic channel. The underwater acoustic channel block consists of the several internal models characterizing the underwater channel effects as discussed in section (5.5.3). The output of the underwater channel is the received signal and the propagation delay of the signal. The system is simulated keeping some parameters of the channel constant such as, Temperature (T) is 27°C, Salinity (s) is 34 mg/l and signal power is 0.1W. The ultrasonic transducer used in this research has a resonance frequency of 40 KHz, therefore a transmit signal frequency of 40 KHz is used for the simulations. In the Figure 5.7, it is seen that, the transmit signal is first affected by path loss with the spread factor k=1, then attenuated by the AWGN and shipping noise followed by two multipath delays.

Receiver: The receiver extracts the data from the received signal. It consists of a demodulator, detector and data storage.

- Demodulator (BFSK): The BFSK baseband demodulator block is used to extract the original data from the carrier signal. The receiver only tracks the change in carrier frequencies to retrieve the binary data, and does not track the phase changes, this is known as Non-coherent BFSK. The main reason to choose Non-coherent BFSK is to make the receiver immune to any phase changes occurring in the received carrier waves. The block parameters are similar to that of modulator. The number of signal levels M=2 and for a frequency separation (Δf) of 1000Hz.

- Detector (CRC Syndrome): The CRC syndrome detector performs the XOR (Modulo 2) division on the received data frames with the $G(x) = x^6+x^4+x^2+1$. The error frame check sequence results are displayed at the output of the detector for data frame checksum of 2. If the received dataframe is valid, a result of 0 is displayed for frame check, but if the dataframe is invalid, then the result is 1 and the invalid data frame is discarded. Therefore using CRC greatly reduces the receiver complexity and also provides excellent error detection capabilities.

5.6 Engineering Design

This chapter deals with hardware implementation of underwater acoustic modem. This research mainly focuses on implementation of the hardware as a proof of concept, for data being transmitted and received underwater, using acoustics for academic purpose. Therefore to keep the cost and complexity low, minimum components had been used in order to develop the transmitter and receiver.

5.6.1 Block Diagram and Description of the System

The Figure 5.15, shows the block diagram of the hardware system. It shows the different components involved in implementing the functionalities of the transmitter and receiver.

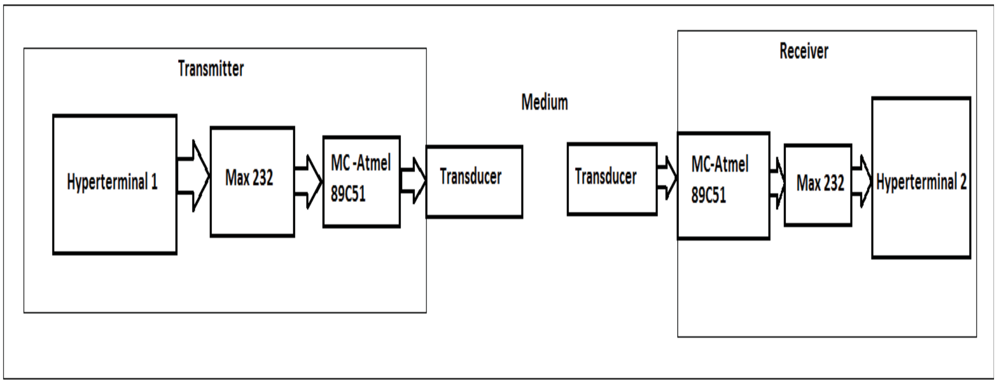


Figure 5. 15. Hardware System Block Diagram

In the transmitting end, A PC is used to input the data to the max 232 through RS-232. The max 232 IC is used for interfacing the microcontroller to the PC. The max 232 converts the RS 232 input to TTL voltage output that is most suitable to operate with the microcontroller. The microcontroller transmits the input data it received from the max 232, to the receiver through ultrasonic transducer. In the receiver, the microcontroller receives the transmitted data from the receiver ultrasonic transducer. The max 232 converts the output of the microcontroller from TTL to RS-232 which is used by the PC to display the transmitted data. The details of the different components used for the hardware implementation is described as follows;

- Ultrasonic Transducer:

In this research, a china made, low performance cheap ultrasonic transducers were chosen for acoustics over hydrophones and projectors, as they are too expensive.

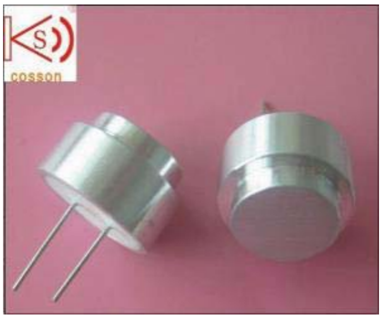


Figure 5. 16. Ultrasonic Transducer

The Figure 5.16, shows the cosson KS-P1640H12TR (waterproof type) ultrasonic transducer that costs 35 INR. These transducers were mainly considered for its low cost and for academic purpose, however using high end hydrophones and projectors will provide excellent performance compromising the high cost.

The Table shows the design specifications of the transducer. It operates at a centre frequency of 40 KHz and it has a sensitivity of -75 dB.

- Max 232N serial level converter:

The MAX232 IC is used to convert the TTL/CMOS logic levels to RS232 logic levels during serial communication of microcontrollers with PC. The controller operates at TTL logic level (0-5V) whereas the serial communication in PC works on RS232 standards (-25 V to + 25V). This makes it difficult to establish a direct link between them to communicate with each other.

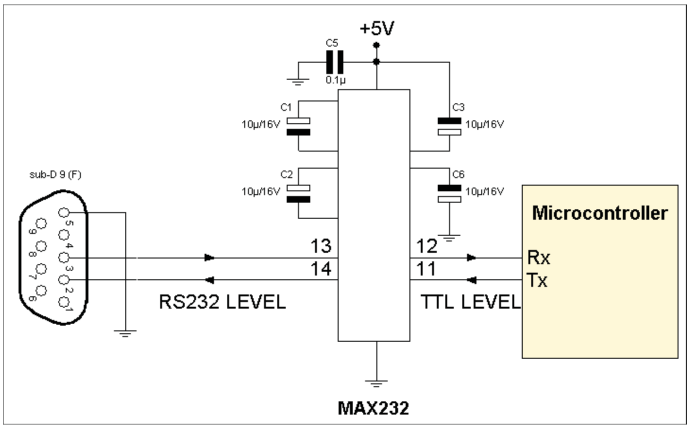


Figure 5. 17. Schematic for IC MAX 232N

The Figure 5.17 shows the schematic on how to interface a microcontroller to PC RS232 port using MAX232. This is a standard configuration used when we want to translate the RS232 logic levels (-15V, +15V) to 0V and 5V logic levels and vice versa.

- Microcontroller

In this project, an 8-bit PIC16F877A microcontroller is used. The operating speed for DC is 20 MHz clock input and DC – 200 ns instruction cycle.

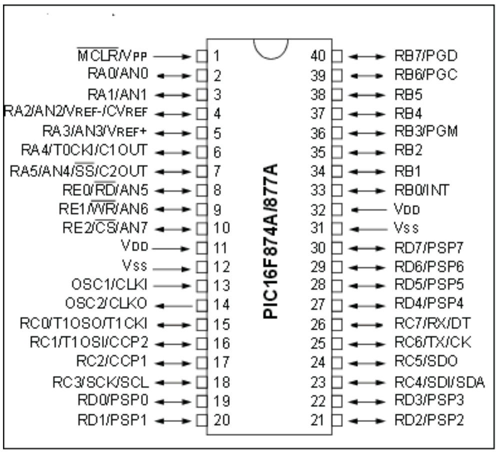


Figure 5. 18. Pin Configuration of PIC16F877A

It can support up to 8K x 14 words of Flash Program Memory and 368 x 8 bytes of Data Memory (RAM). The Figure 5.18, shows the pin configuration for the 40 pin PIC16F877A microcontroller.

5.6.2 Hardware Set up

The Figure 5.19 shows the hardware set up of the transmitter circuit. The transmitter circuit consists of a transformer to step down the AC supply voltage 230V to 12V. The 12V is further stepped down to 5V using a voltage regulator (IC L805). A USB to RS-232 is used to interface the microcontroller to PC.

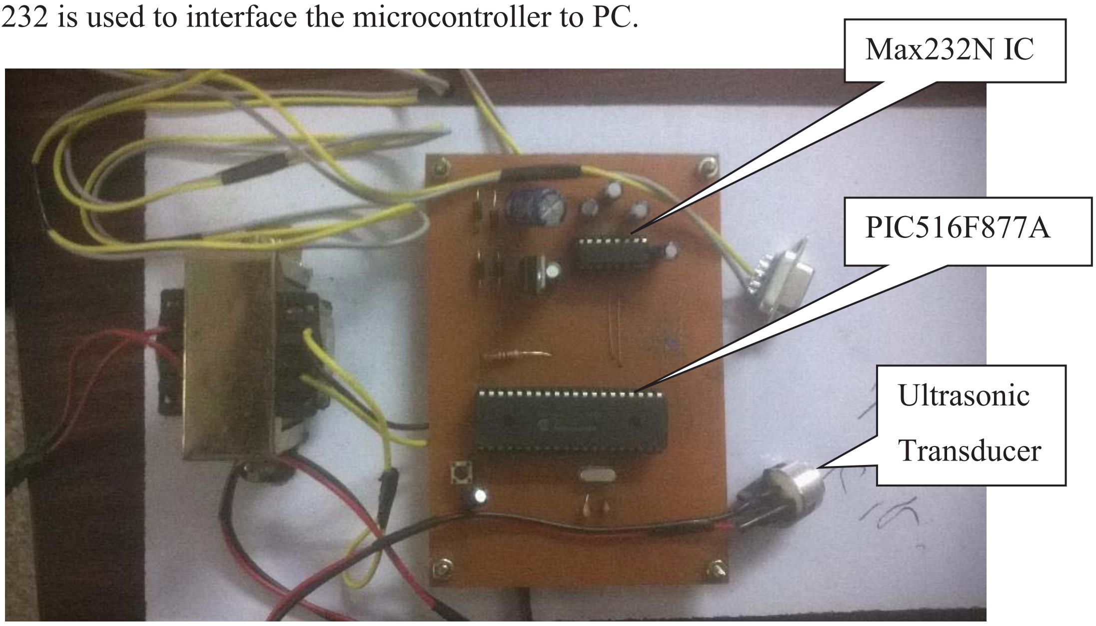


Figure 5. 19. Transmitter Hardware

The input data is given from the PC, the MAX 232 IC is responsible to convert the RS-232 input voltages to TTL output of 0 and +5V that is suitable to operate with the microcontroller. Based on the inputs from the MAX 232, the microcontroller triggers the ultrasonic transducer to transmit the character or text data.

]

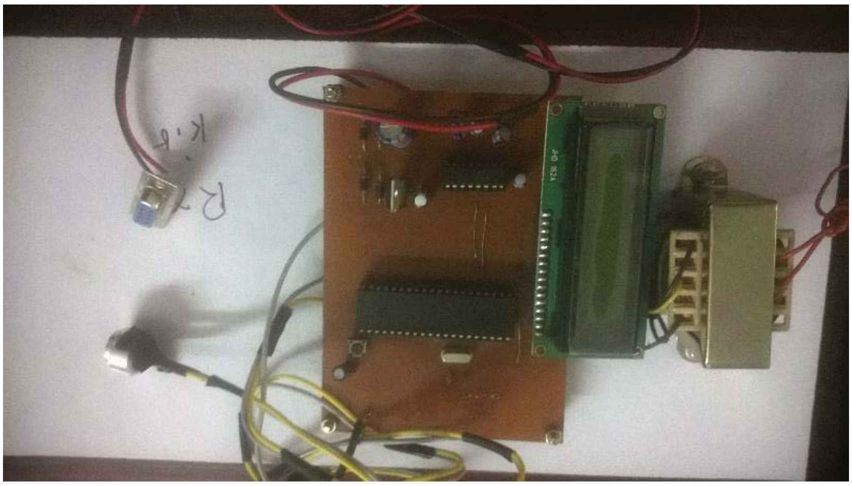


Figure 5. 20. Receiver Hardware

The Figure 5.20 shows the hardware set up of the receiver circuit. The ultrasonic transducer receives the transmitted data, the microcontroller converts the received analog signal to convert to digital using ADC. The output of the microcontroller is in TTL/CMOS logic, hence the MAX232 converts the output of microcontroller to RS232 voltage form that is recognized by the PC and displayed on the HyperTerminal.

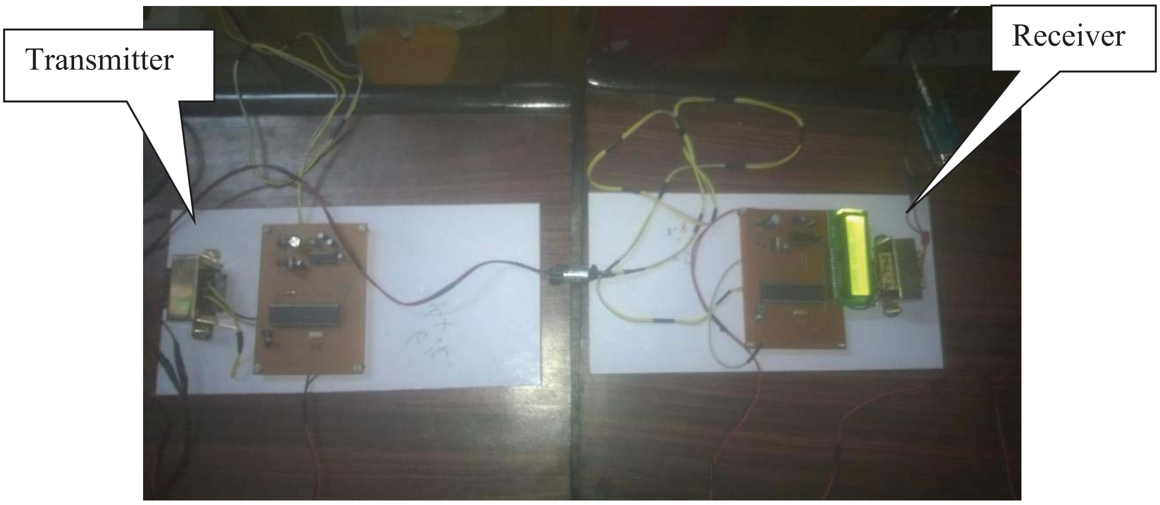


Figure 5. 21. Complete System Hardware

Figure 5.21 shows the complete hardware set up of the system consisting of the transmitter and receiver. It is seen that the transducer are placed facing very close to each other, the reason for this is, the transducers used for this research offers just range of 0.4m . An LCD display is used at the receiver to indicate the data once it is received.

5.7 Conclusion

- In the Need analysis phase, the customer problems and deficiencies with respect to the existing modems are identified, based on which the target system requirements are identified. Based on the output of need analysis, the problem was defined as the modem needs to operate for shallow waters and short range communication.
- In concept exploration, different modulation schemes and error detection techniques are identified, then these concepts are analyzed while converging to the most suitable concept. In concept exploration, higher order modulations and lower order modulation schemes such as BFSK and BPSK were identified. In concept definitions BFSK modulation scheme was chosen due to its several advantages over the other schemes. In concept exploration, error detection techniques such as simple parity check and CRC were identified. In concept definition, the CRC scheme was chose due to its excellent performance in error detection over simple parity scheme.
- The different characteristics of the underwater channel is modelled and integrated to resemble the complete underwater acoustic channel. The transmitter and receiver functionalities are modelled using Non-coherent BFSK scheme and CRC. The polynomial used for the CRC is CRC6. The different parameters involved in the design and modelling of the system has been discussed.
- In the engineering design phase, the components to implement the hardware for the system is identified. The transmitter and receiver circuit is developed.

CHAPTER 6 – Results and Discussion

6.0 Introduction

It is necessary to understand how the system behaves for different conditions of the underwater channel. The systems performance is checked for different ranges and depths underwater with respect to some constant parameters such as

- Temperature (T) = 27ºC
- Salinity(S) = 34 mg/l
- Transmit Signal Frequency, f = 40 KHz

Since the requirement is that the modem should operate for short range communication and shallow waters, hence in this research, the system is simulated for a short ranges of 10m, 30m, 50m and if the system supports it can go up to 100m, and for shallow depths of 10m, 30m, 50m and 70m. The system is simulated for different mediums. Monte-carlo simulations are performed to plot the BER vs Eb/No curves using the bertool in Matlab/Simulink. The required BER for the system needs to be in the range of 10^{-3} to 10^{-5} for a data rate of 1600 bps.

6.1 Model 1-Simulations with Additive White Gaussian Noise (AWGN)

The Figure 6.1 shows the BER vs Eb/No curve for the system simulated with the AWGN channel.

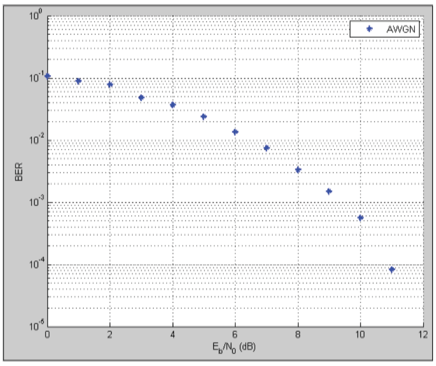


Figure 6. 1. Model 1 - AWGN

From the Figure 6.1, it can be seen that, for a BER of 10^{-5}, the required EbNo is 11 dB For a BER of $10^{-4,}$ the required EbNo is 10 dB and for a BER of $10^{-3,}$ the required EbNo is 6 dB, therefore as the Eb/No increases the BER decreases.

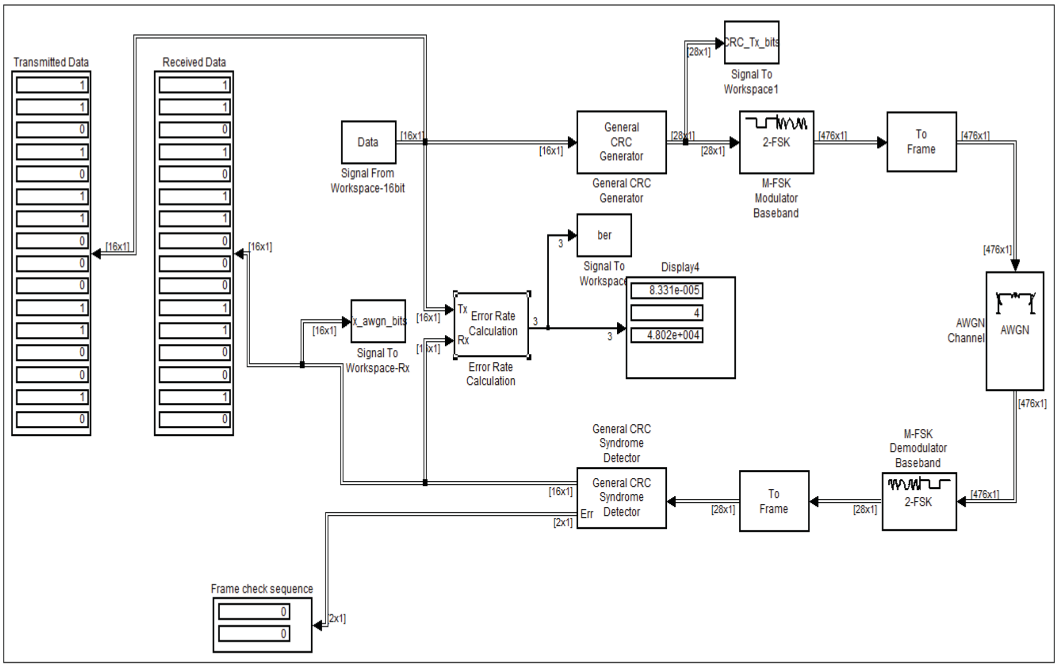


Figure 6. 2. System with AWGN Channel

The Figure 6.2, shows the system simulation with AWGN channel for EbNo of 11 dB achieving a BER of 10^{-5}. The frame check sequence display result is 0, indicating that the received data packets are valid. The received data and transmitted data displays, shows that the received data or bits exactly matches the transmitted data. The signal to workspace block at the receiver end has been used to extract continuous received data.

Table 6.1 Performance with AWGN Channel

BER	Eb/No (dB)
10^{-5}	11
10^{-4}	10
10^{-3}	9

The Table 6.1, shows the bit error rates (BER) achieved for the corresponding power levels (Eb/No) required to transmit the bits. Here the system is showing excellent performance for AWGN medium.

6.2 Model 2 – Simulations with AWGN and Path Loss

The Figure 6.3, shows the system with AWGN and path loss. The path loss is very much dependent of the distance between the transmitter and receiver and the depth of the water.

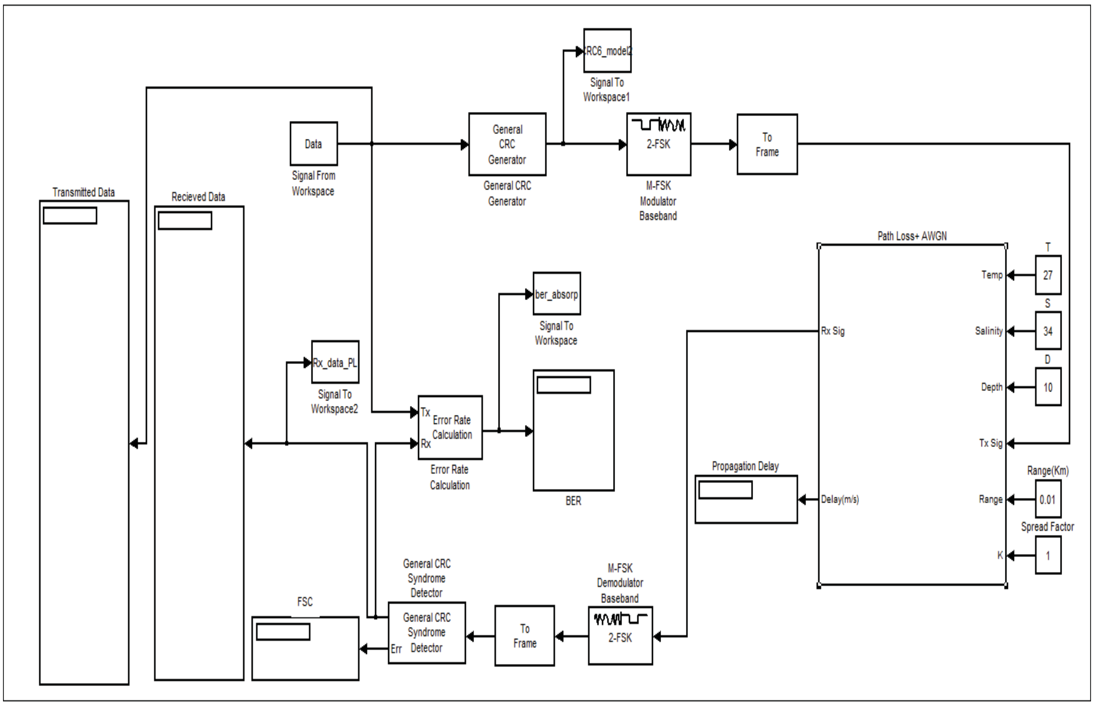


Figure 6. 3. System with AWGN and Path Loss

Hence the end to end performance of the system is tested for inputs with different ranges and depths. The performance results obtained through simulations are as follows;

- Simulation for Depth of 10 meters:

In this case, the modem is placed 10 meters (m) deep into the water and its performance is analysed for different short ranges of 10m, 30 m and 50 m.

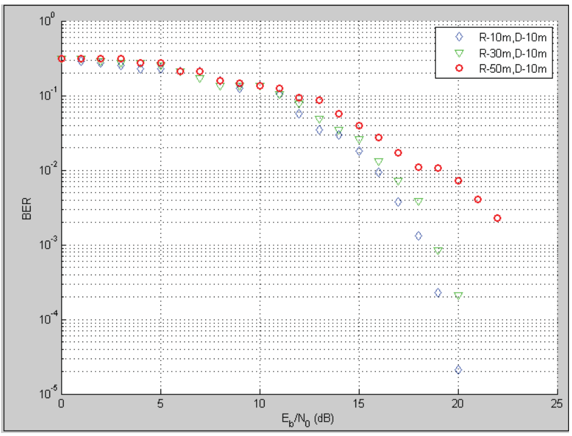


Figure 6. 4. Performance with AWGN and Path Loss (Depth 10 m)

Figure 6.4, shows the BER vs Eb/No curves obtained from simulating the system for depth of 10m, for different ranges of 10m, 30m and 50m. It is seen that the bit errors increases as the range increases from 10m to 50m, however still the system is able to achieve a BER of 10^{-3} for an Eb/No of 18 dB upto a range of 30m.

Table 6. 2 Performance Results for Depth 10 m

Depth (m)	Range (m)	BER	EbNo (dB)
10	50	10^{-3}	22
	30	10^{-3}	18
		10^{-4}	19
	10	10^{-5}	20
		10^{-4}	19
		10^{-3}	18

The Table 6.2 shows the results of the simulation. The required Eb/No ranges from 18 to 22 dB for a range of 10m to 50m.

- Simulation for depth of 30m

In this case, the system's performance is tested for a depth of 30m with respect to different ranges.

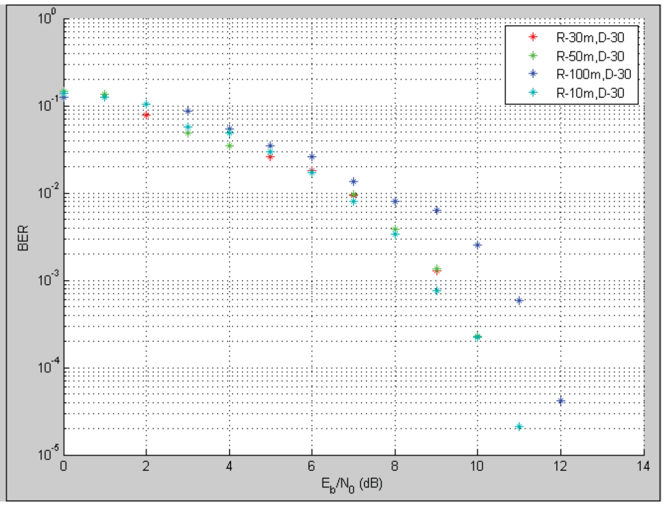


Figure 6. 5. Performance with AWGN and Path Loss (Depth 30 m)

Figure 6.5, shows the BER performance curves of the system placed under water at a depth of 30m for different ranges. An Eb/No of 12 dB can attain a transmission range up to 100m for a BER of 10^{-5}.

Table 6. 3 Performance Results for Depth 30 m

Depth (m)	Range (m)	BER	Eb/No (dB)
30	100	10^{-5}	12
		10^{-4}	11
		10^{-3}	10
	50, 30 and 10	10^{-5}	11
		10^{-4}	10
		10^{-3}	9

The Table 6.3 shows the results of the system simulation for a depth of 30m. The Signal strength has improved by almost 10 dB compared to depth of 10m, for a range of up to 50m achieving a BER of 10^{-5}.

- Simulation for depth of 50m

The Figure 6.6, shows the BER performance curves of the system placed under water at a depth of 50m for different ranges.

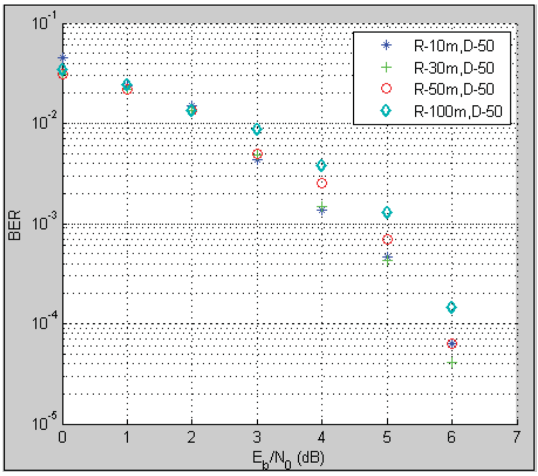


Figure 6. 6. Performance with AWGN and Path Loss (Depth 50 m)

An Eb/No of 6 dB is sufficient to attain a transmission range of 100m for a BER of 10^{-4}. The Table 6.4, shows the simulation results of the system for a depth of 50m.

Table 6. 4 Performance Results for Depth 50 m

Depth (m)	Eb/No (dB)	Range (m)	BER
50	6	10	10^{-5}
		30	10^{-4}
		50	10^{-4}
		100	10^{-4}

The system provides excellent performance for a low Eb/No of 6 dB. The effects of absorption loss decreases as the depth increases and this leads to an improvement in the performance of the system.

6.3 Model 3-Simulation with AWGN, Path Loss and 2 Multipath delays

The system's performance is tested for AWGN, Path Loss and two multipath. Figure 6.7, shows the system model with the underwater channel fused with a 2 multipath delays.

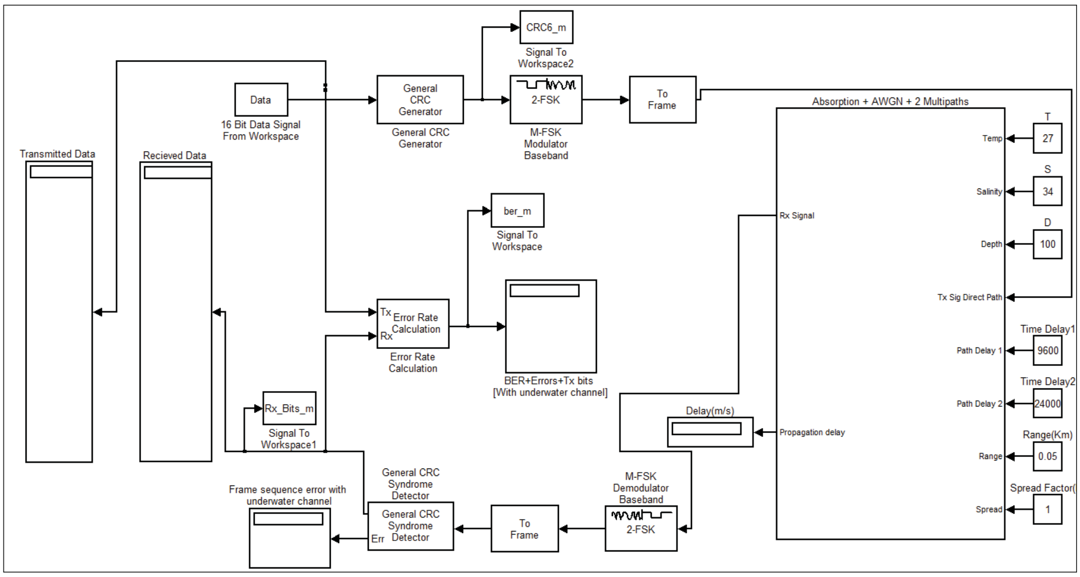


Figure 6. 7. System with AWGN + Path Loss + 2 Multipath delays

The parameters of the two delay signals used in the simulations are as follows;

1. Delayed Signal1 : Time shift, T_1 : 9600 samples ($4T_s$)
   Phase shift, φ: 30 degrees
   Frequency shift, F_{D1}: 20 Hz (2 m/s)
   Gain, α_1: 0.25

2. Delayed Signal1 : Time shift, T_1 : 9600 samples ($4T_s$)
   Phase shift, φ: 30 degrees
   Frequency shift, F_{D1}: 40 Hz (4 m/s)
   Gain, α_1: 0.5

- Simulation for depth of 100m

Figure 6.8, shows the Eb/No vs BER curves for the system simulated for a depth of 100m.

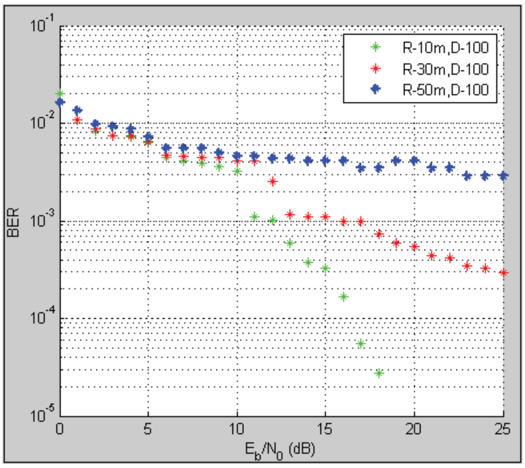


Figure 6. 8. Performance for Depth of 100 m

It is seen that the system performs well for a range of 10m for a BER of 10^{-5}. It also provides good performance for a range of 30m and 50m, however the required power Eb/No is high.

Table 6.5 Performance Results for Depth 100 m

Depth (D) in meters	Range in meters	Eb/No	BER
100	10	18	10^{-5}
		16	10^{-4}
		12	10^{-3}
	30	24	10^{-4}
		16	10^{-3}
	50	25	10^{-3}

The Table 6.5, shows the simulation results for the system when multipath is induced. It is seen that the BER increases and also the power requirement for a range of 30m and 50m, however for a range of 30m, a BER of 10^{-3} is achieved for an Eb/No of 16 dB.

- Simulation for depth of 50m

The Figure 6.9 shows the Eb/No vs BER performance curve for a depth of 50m. It is seen that for a range of 30m and above there is a requirement of high power for a BER of 10^{-3}.

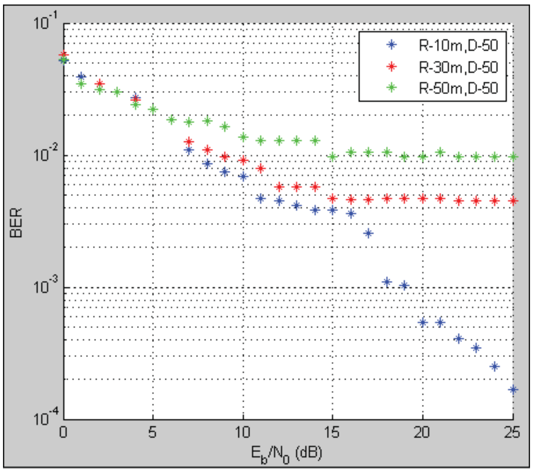


Figure 6. 9. Performance for Depth of 50 m

Table 6.4 Performance Results for Depth 50 m

Depth (D) in meters	Range in meters	Eb/No	BER
50	10	24	10^{-4}
		19	10^{-3}
	30	25	10^{-3}
	50	25	10^{-3}

The Table 6.4, shows the results of the system simulation. The system can achieve a BER of 10^{-3} for an Eb/No of 19 dB, with a transmission range of 10m.

- Simulation for depth of 10 m

The Figure 6.10 shows the Eb/No vs BER performance curve for a depth of 10m. It is seen that as the depth decreases to 10m from 50m. The performance of the system degrades as the underwater channel conditions for this depth is not suitable data transmission.

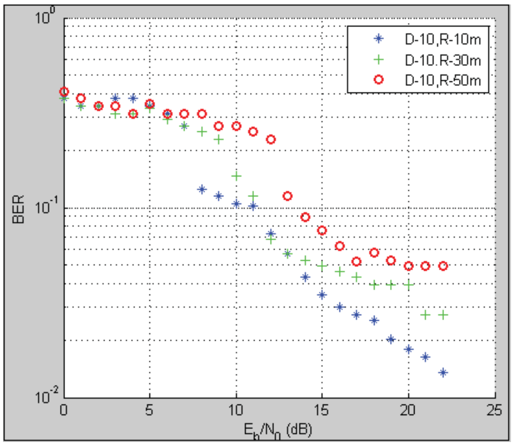


Figure 6. 10. Performance for Depth of 10 m

The performance of the system degrades as the underwater channel conditions for this depth is not suitable data transmission.

Table 6.5 Performance Results for Depth 10 m

Depth (D) in meters	Range in meters	Eb/No	BER
10	10	22	10^{-2}
	30	22	10^{-2}
	50	22	10^{-2}

The Table 6.5, shows the simulation results when multipath is induced into the channel. It is seen that the performance of the system is heavily degraded with high BER and power requirement.

6.4 Model 4-Simulation with AWGN, Path Loss, 2 Multipath delays and shipping noise (Complete underwater acoustic channel)

The Figure 6.11 show the system model with the complete underwater acoustic channel. One of the ambient noises encountered is the shipping noise.

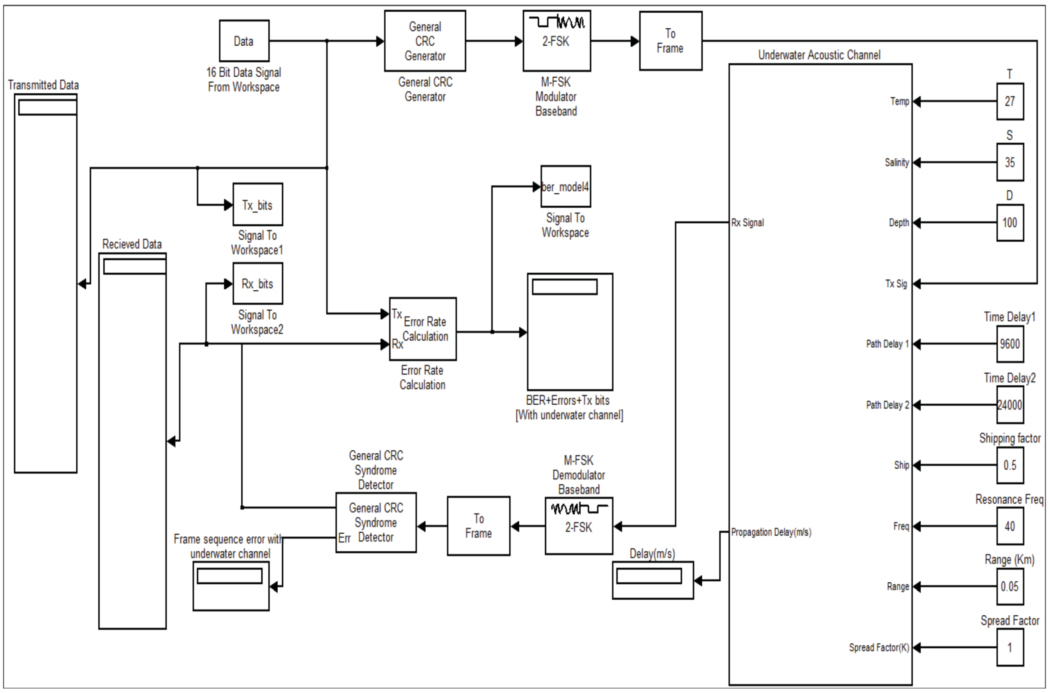


Figure 6. 11. System with AWGN + Path Loss + Two Multipath delays + Shipping Noise

The shipping noise is induced in the channel based on the equation (), that has a factor “s” that defines the level of shipping activity. A s=0, indicates a no shipping activity, s=0.5, indicates a low shipping activity and s=1 indicates a high shipping activity factor.

- Simulation for depth of 10m

Figure 6.12 shows the Eb/No vs BER curves of system for depth and range of 10m corresponding to different shipping activity factor.

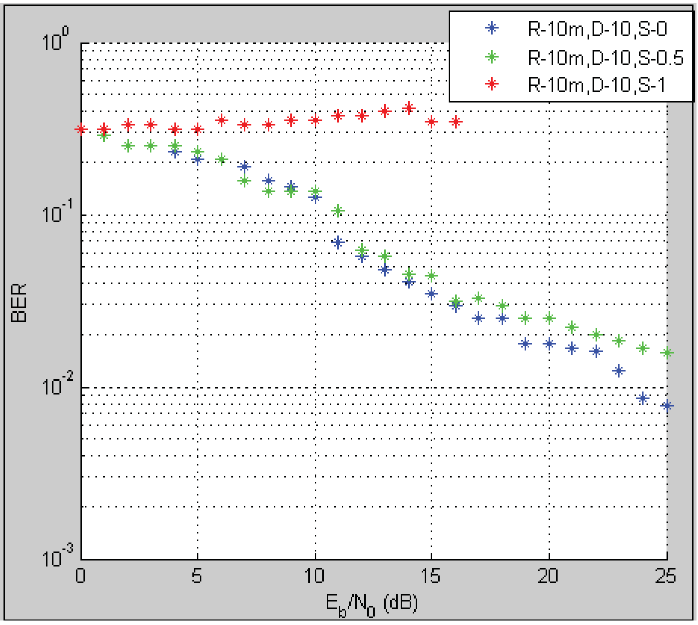


Figure 6. 12. Performance for Depth of 10 m

Figure 6.12, it is seen that the performance of the system is totally degraded for depth of 10m, giving a BER of 10^{-2}.

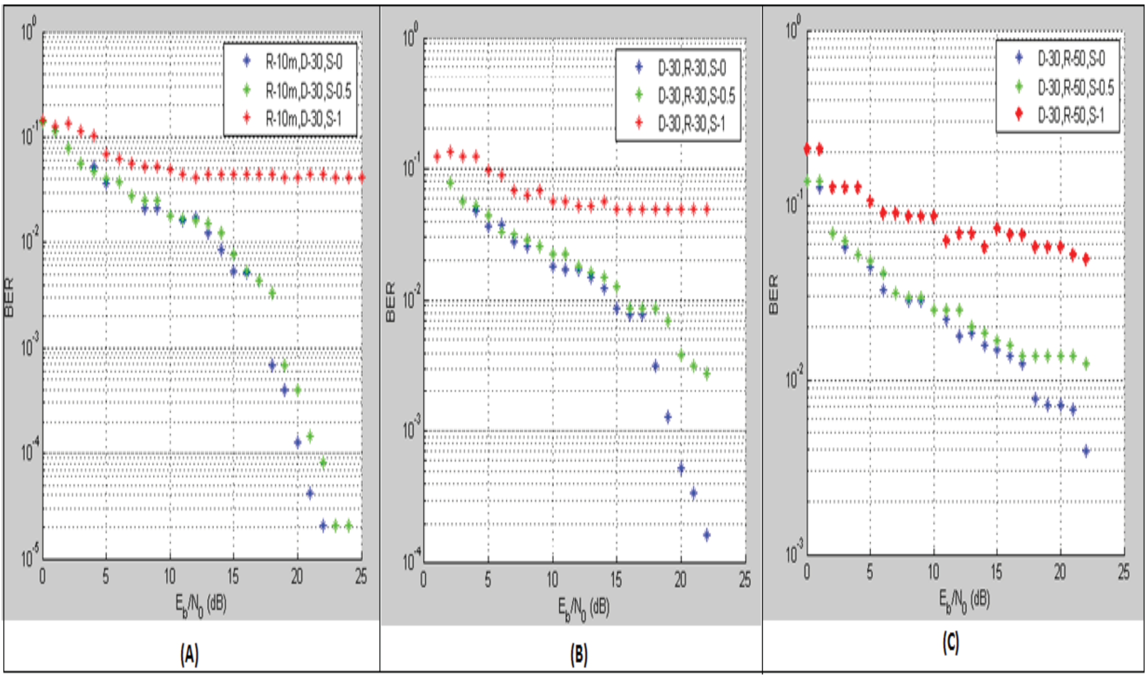
Table 6.6 Performance Results for Depth of 10 m

Depth (m)	Range (m)	Shipping Factor (S)	Eb/No (dB)	BER
10	10	0	23	10^{-2}
		0.5	25	10^{-2}
		1	17	10^{-1}

The Table 6.6, shows the simulation results of the system for a depth of 10m. It is seen that the BER is degraded and the required Eb/No exceeds the power budget of 22 dB.

- Simulation for a depth of 30m

Figure 6.13 shows the performance curves of the system for a depth of 30m with respect to different shipping activity factors and ranges.



(A) (B) (C)

Figure 6. 13. Performance for Depth of 30 m

The Figure 6.13a shows the performance of the system for range of 10m, Figure 6.13b shows the performance for range of 30 m and Figure 6.13c shows the performance of the system for range of 50m. It is seen that, as the range increases, the required Eb/No to achieve a BER of 10^{-4} also increases. The system performance is degraded when the shipping activity is high.

Table 6. 7 Performance Results for Depth of 30 m

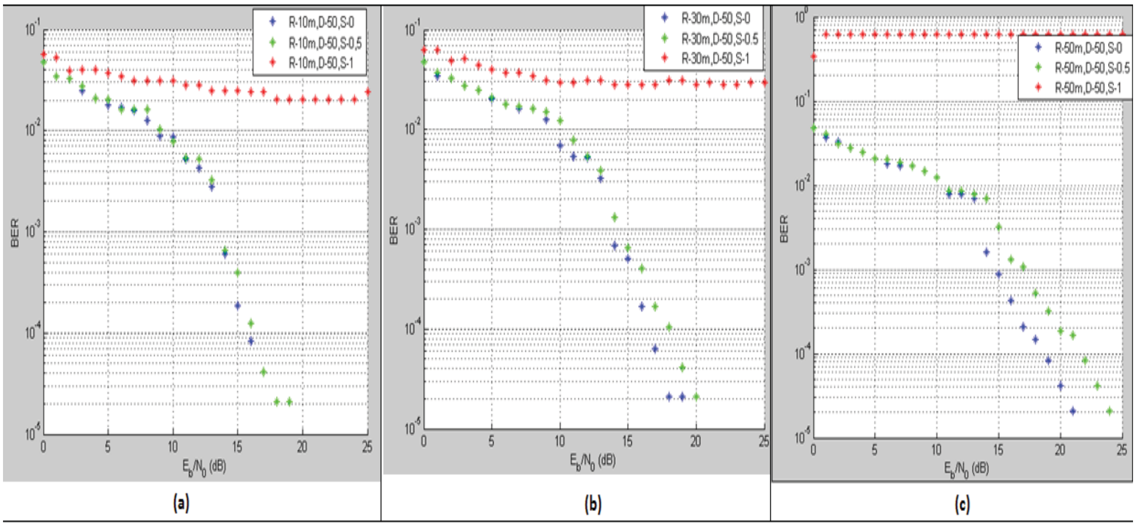
Depth (m)	Range (m)	Ship Factor (S)	Eb/No (dB)	BER
30	10	0	22	10^{-5}
			20	10^{-4}
			17	10^{-3}
		0.5	23	10^{-5}
			21	10^{-4}

			18	10^{-3}
		1	4	10^{-1}
	30	0	22	10^{-4}
		0.5	22	10^{-3}
		1	5	10^{-1}
	50	0	23	10^{-2}
		0.5	23	10^{-2}
		1	6	10^{-1}

The Table 6.7, shows the simulation results of the system for a depth of 10m and different ranges. It is seen that the system provides decent performance for low shipping activities and up to a range of 10m.

- Simulation for depth of 50m

Figure 6.14 shows the Eb/No vs BER curves of system for depth of 50m and different ranges with respect to the shipping activity factors.



(a) (b) (c)

Figure 6. 14. Performance for Depth of 50 m

The Figure 6.14a shows the performance of the system for range of 10m, Figure 6.14b shows the performance for range of 30 m and Figure 6.14c shows the performance of the system for range of 50m.It is seen that the systems performance is still degraded for high shipping activity, however the system provides good performance up to a range of 30m for low shipping activities.

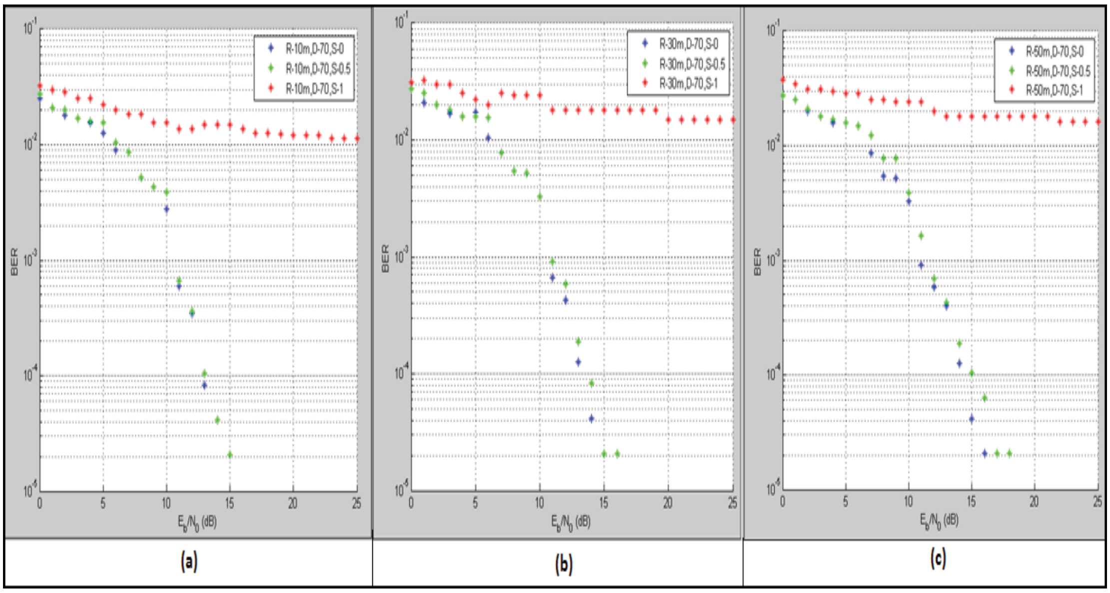
Table 6.8 Performance Results for Depth of 50 m

Depth (m)	Range (m)	Ship Factor (S)	Eb/No (dB)	BER
50	10	0	18	10^{-5}
			15	10^{-4}
			13	10^{-3}
		0.5	18	10^{-5}
			21	10^{-4}
			16	10^{-3}
		1	13	10^{-2}
	30	0	18	10^{-5}
			16	10^{-4}
			13	10^{-3}
		0.5	20	10^{-5}
			18	10^{-4}
			14	10^{-3}
		1	13	10^{-1}
	50	0	21	10^{-5}
			18	10^{-4}
			14	10^{-3}
		0.5	23	10^{-5}
			21	10^{-4}
			17	10^{-3}
		1	6	10^{-1}

The Table 6.8, shows the simulation results corresponding to the Figure 6.14. It is seen that the required Eb/No to achieve a BER of 10^{-4} is reduced compared to the results of system when placed at a depth of 10m and 30m, Therefore as the depth increases the effects of multipath, absorption loss and shipping noise is minimized improving the performance of the system.

- Simulation for depth of 70m

In order to reduce the required Eb/No to achieve a BER of 10^{-4}, the system was simulated for a depth of 70m. Figure 6.15 shows the Eb/No vs BER curves of system for depth of 70m and range up to 50m corresponding to different shipping activity factors.



(a) (b) (c)

Figure 6. 15. Performance for Depth of 70 m

From Figure 6.15, it is seen that the system is showing excellent performance for low shipping activities, compared to the response obtained, when system was simulated for depths of 10m, 30m and 50m. The Figure 6.15a shows the performance of the system for range of 10m, Figure 6.15b shows the performance for range of 30 m and Figure 6.15c shows the performance of the system for range of 50m.

Table 6.9 Performance Results for Depth of 70 m

Depth (m)	Range (m)	Ship Factor (S)	Eb/No (dB)	BER
70	10	0	14	10^{-5}
			12	10^{-4}
			10	10^{-3}
		0.5	15	10^{-5}
			13	10^{-4}
			11	10^{-3}
		1	17	10^{-2}
	30	0	15	10^{-5}
			13	10^{-4}
			11	10^{-3}
		0.5	15	10^{-5}
			14	10^{-4}
			14	10^{-3}
		1	20	10^{-2}
	50	0	16	10^{-5}
			14	10^{-4}
			11	10^{-3}
		0.5	17	10^{-5}
			15	10^{-4}
			11	10^{-3}
		1	22	10^{-2}

The Table 6.9, tabulates the simulation results corresponding toe Figure 6.15. It is seen that the system can achieve a BER of 10^{-5} for a low Eb/No of 17 dB. For a short range of 10m, the system shows a BER of 10^{-4} for an Eb/No of 14 dB.

Table 6. 10 Final System Performance Specifications

Depth (m)	Range (R)	Eb/No (dB)	BER
10	10	23	10-2
30	30	20	10-4
50	30	18	10-4
70	50	17	10-5

The Table 6.10 shows the final performance outcome of system. From the Table 6.10, it's seen that, system achieves excellent performance for a depth of 30 m and above, up to a range of 50m with a BER of 10-4 for a maximum required Eb/No of 20 dB, for a low shipping factor of 0 and 0.5.

6.5 Hardware Implementation Results

The hardware/system set up is tested for the transmission and reception of the data. Figure 6.1 shows the complete hardware system to be tested. It consists of two laptops, one is used at the transmitter to generate data and the other is used at the receiver end to display the received data.

Figure 6. 1. Complete Integrated Hardware

In the PC’s hyper terminals is used to generate and display the received data. The system consists of the transmitter circuit and the receiver circuit with the transducer placed facing close to each other as shown in the figure 6.1. The system was tested in air for a close range of 1cm.

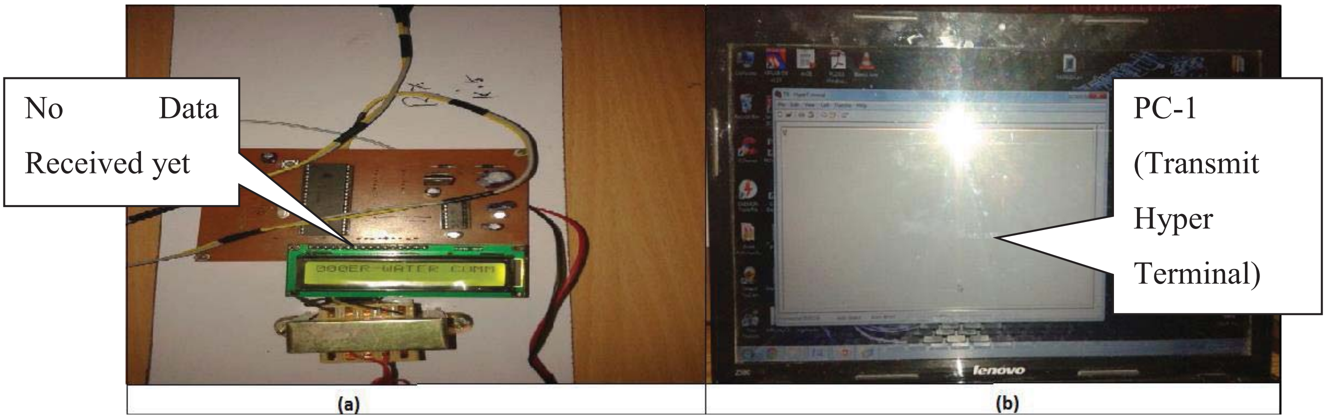


Figure 6. 2. Transmission Process

Figure 6.2 shows the initiation of the transmission. Figure 6.2 a, shows the LCD display on the receiver indicating ASCII value of 000ER indicating that no data has been received yet. Figure 6.2b, shows the transmitter's side PC HyperTerminal, in which a character 'V' is typed that needs to be transmitted.

Figure 6. 3. Data Reception Process

Figure 6.3 shows the data reception process. When the transmitted data is received by the receiver, the LCD displays the received data in ASCII indicating that the data has been received as shown in Figure 6.3a. Figure 6.3b, shows the receiver side laptops HyperTerminal that displays the received character 'V'.

6.6 Conclusion

The System was simulated for different channel conditions. The performance of the system is analysed with respect to range, depth, Eb/No and BER. The system showed excellent performance for depths of 30m and above, up to range of 50m as shown in Table 6.10. However the systems performance is degraded for depth of 10m and for high shipping activities. The hardware was tested in air for a very close range, the hardware efficiently transmitted and received data through the ultrasonic transducers.

CHAPTER 7 – Conclusion and Scope for Future Work

The summary and conclusions are derived from the design, model, simulations and implementation of an underwater acoustic modem for shallow waters and short range communication. The scope for the future improvements for the proposed system is discussed in this chapter.

9.1 Summary

An underwater acoustic modem is used to transmit and receive data. The BW availability is severely limited to KHz range and due to the unique characteristic of the underwater channel, communication underwater has been a difficult task and leads to high BER. In the Need analysis phase, the customer problems and deficiencies with respect to the existing modems are identified, based on which the target system requirements are identified. Based on the output of need analysis, the problem was defined as the modem needs to operate for shallow waters and short range communication. In the concept exploration phase, different modulation and error detection schemes were identified and converged to choosing the concepts as non-coherent BFSK modulation scheme and Cyclic Redundancy Check (CRC) scheme. The underwater channel, transmitter and receiver is modelled in the advanced development phase using the software tool MATLAB/Simulink. The systems performance was analyzed for different channel conditions mentioned as model 1, model 2, mode 3 and model 4. The simulation results for the different channel conditions are summarized as follows;

- Model 1 - The system provides excellent performance of BER 10^{-5} for a signal strength of 11 dB, for AWGN channel.
- Model 2 – For a depth of 10m, the system can operate upto a range of 30m for a signal strength of 19 dB. As the depth increases to 50m, systems range extends to 100m for a low signal strength of 6 dB
- Model 3 – Multipath are very significant shallow waters, therefore for a depth of 10m, the systems performance is degraded with high BER. For a depth of 50m,

system operates efficiently for range of 10m, BER of 10^{-4} for signal strength of 19 dB. For a depth of 100m, the system can achieve a BER of 10^{-4} for Eb/No of 18 dB with range 10m.

- Model 4 – For a depth of 10m, the system performance is degraded. For a depth of 30m, with s-0, 0.5, the system can operate efficiently up to a range of 30m with BER 10^{-4} for EbNo of 20 dB. For a depth of 50 m, the system shows excellent performance for a range upto 30m with BER of10^{-4}, for EbNo of 18 dB. For a depth of 70m, the system is operating at its best for a range up to 50m, BER 10^{-5} for a Eb/No of 17 dB.

The hardware was developed using the ultrasonic transducer. Minimum number of components had been used to develop the hardware such as the PICC16877A, Max232 IC, serial port, transformers and voltage regulators. The hardware was tested to operate in the air with the transducers kept very close to each other and efficient transmission and reception of the data was observed, however due to the lack of test facilities, the BER of the system could not be measured.

9.2 Conclusion

- The performance of the system improves as the depth increases, since, as the depth increases the effects of multipath, absorption loss and shipping noise is minimized.
- The systems performance is degraded when operated at a depth of 10m and the system cannot operate efficiently while the shipping activities are at peak i.e. S-1.
- The system performed efficiently for a depth of 10m up to model-2, but the introduction of multipath (4ms and 14.33ms), degraded the signal strength drastically while the systems performance degraded. Therefore multipath significantly affects the performance of the system for shallow waters.
- The requirement of Eb/No to achieve a BER of 10-4 can be further reduced by increasing the depth of the system placed underwater, above 100m, but this will conflict with the requirement of the system to operate at shallow waters.

- Therefore using the CRC-6 scheme and Non-coherent BFSK scheme to design an underwater acoustic modem, can achieve a good performance operating at shallow depths of 30m, 50m and 70m, providing a transmission range up to 50m.
- The Hardware system was tested to efficiently transmit and receive data through sound in air and the range was seen to be very less in millimeters, as the sensors was of low quality and offered a range of just 0.4mm.

9.3 Recommendation for Future Work

- Errors can be minimized further by using, error correction by retransmission of the non-critical data frames using the Selective ARQ (Automatic Repeat Request) protocol.
- In order to correct some critical data, an error correcting scheme can be used in conjunction with CRC, to correct critical data on spot and transmit. This will provide excellent error detection as well correction capabilities.
- The hardware systems performance can be improved by using a high end sensors such as hydrophones and projectors in order to improve the transmission range and data efficiency.
- In this research the hardware was tested to perform in air. The hardware tests shall be conducted underwater in future.
- Error correction techniques can be implemented in order to improve the performance and minimize BER.

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