ANALYSIS OF USING OFDM FOR SHORT-RANGE, MULTI-USER, UNDERWATER ACOUSTIC COMMUNICATIONS

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By
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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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Acoustic waves are being used in several underwater applications, such as SONARs, underwater communication systems. Most of already developed and deployed underwater communication systems use narrow band communication and lacks layered communication approach. In this thesis, we propose a spread spectrum, layered architecture for underwater communication system, such as for SCUBA divers. The communication device shall be designed such that divers can communicate with each other in shallow water, short range in a multi-user fashion and provide not only voice communication but also data transmission as well. The device shall use Orthogonal Frequency Division Multiplexing (OFDM) as a spread spectrum technique. The OFDM technique is selected from other spread spectrum techniques due to it's inherent ability to combat the channel impairments and flexibility of implementing the communication system using software defined radio (SDR). The spread spectrum system shall operate in 100 kHz to 300 kHz frequency band using wideband acoustic transducers. In this work, we studied a layered architecture for the communication device. We mainly studied the application layer, data link layer and physical layer in order to analyze the achievable data rate and performance. In this work, we tried to find the optimal communication parameters to achieve guaranteed communication performance for possible scenarios. The communication parameters are set in order to achieve best performance for the worst condition. Using the optimal parameters, the system shall occupy 5 users voice and data communication at the same time using the entire frequency band at the same time, however with certain Grade of Service (GOS) the capacity shall be increased. The capacity of the system shall further be increased if the system uses adaptive communication parameters that are adapted to changing channel and user conditions. The system using adaptive communication parameters shall provide at most 16 users' voice and data communication using the entire frequency band at the same time.

Keywords: Underwater Acoustic Communications, Spread Spectrum Communications, Orthogonal Frequency Division Multiplexing (OFDM), Coded OFDM (COFDM), Layered Communication Architecture

ÖZET

KISA MENZİL, ÇOKLU KULLANICILI, SUALTI AKUSTİK İLETİŞİMİ İÇİN OFDM KULLANIMI ANALİZİ

Kemalettin Kerem Öktem
Elektrik ve Elektronik Mühendisliği Bölümü Yüksek Lisans
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Akustik dalgalar, SONAR, sualtı iletişim sistemleri gibi birçok sualtı uygulamasında kullanılmaktadır. Geliştirilmiş ve kullanılmakta olan sualtı iletişim cihazlarının büyük çoğunluğu dar bant iletişim kullanıp, katmanlı bir iletişim yapısına sahip değildir. Bu tezde, tayf yayma tekniği kullanan, katmanlı bir yapıya sahip, SCUBA dalgıçlarının kullanabileceği bir sualtı iletişim sistemi tasarlamayı ön görüyoruz. İletişim sistemi dalgıçlar arasında, sığ suda, ve kısa menzilde bir çok kullanıcıya hizmet verecek şekilde, ses iletişiminin yanı sıra veri iletişimini de olanak sağlayacak şekilde tasarlanacaktır. İletişim cihazı Dikken Frekans Bölüşümlü Çoğullama (OFDM) tayf yayma tekniğini kullanacaktır. OFDM tekniği diğer tayf yayma tekniklerine göre tercih edilmesinin sebebi, OFDM'in iletişim kanalından kaynaklanan sinyal bozulmalarına karşı yapısal koruma sağlaması ve fiziksel uygulamasının sayısal tabanlı radyo kullanarak daha kolay gerçekleştirilmesidir. Tayf yayma tekniği, 100 kHz ile 300 kHz arasında geniş bant akustik dönüştürücüler kullanılarak yapılacaktır. Bu çalışmada katmanlı bir iletişim sistemi inceledik. Başlıca, sistemden elde edilebilecek veri hızı ve performansını inceleyebilmek için uygulama, veri link ve fiziksel katmanlar üzerinde çalışmalar yapıldı. Bu çalışmada, iletişim sistemi parametrelerini optimize ederek olası senaryolar için en iyi performansı yakalayabilmek amaçlanmıştır. İletişim sistemi parametreleri kötü koşullarda en iyi performansı sağlamak için optimize edilmiştir. Bu optimal iletişim parametrelerini kullanarak, sistem aynı anda aynı frekans spektrumunu kullanarak, 5 kullanıcının ses ve veri iletişimine izin vermektedir, bu kapasite belli bir Servis Derecelendirmesi (GOS) ile arttırılabilir. İletişim sisteminin kapasitesi, değişen kanal ve kullanıcı durumlarına uygunluk gösterebilen iletişim parametreleri kullanarak daha da arttırılabilir. Sistem değişken parametreler kullanarak en fazla 16 kullanıcının aynı anda aynı frekans bandını kullanarak ses ve veri iletişimine izin verebilmektedir.

Anahtar Kelimeler: Sualtı Akustik Haberleşmesi, Tayf Yaymalı Haberleşme, Dikken Sıklık Bölüşümlü Çoğullama (OFDM), Kodlanmış OFDM (COFDM), Katmanlı İletişim Sistemi.

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And science and all the scientists who believe in the sovereignty of wisdom.

With my eternal gratitude.

To my parents Güzide and Bahri

And to my Brother Alp

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Chapter 1

Introduction

Oceans and its belongings have been a great interest of human being. Scientists believe that life on Earth began from the sea and continued over the soil; therefore, investigations over how the earth, universe and life started on Earth should start from the oceans and the seas.

It was made possible to gain extensive information about the oceans and seas, after it was understood that ocean could support signal transmission. The foundation of possibility of signal transmission in oceans made life for military, scientific and industrial life easier for underwater specific applications. There are several places and applications where underwater acoustic communication is used, namely; from military point of view, submarines and submersibles could communicate over long distances and scan the open waters, from scientific point of view, scientist could gather much greater information about the ocean and from industrial point view, people could use underwater remote controller vehicles instead of divers.

In SCUBA diving activity, SCUBA divers use hand gestures during SCUBA diving. In most situations, the available alphabet of the gestures are enough, however it is sometimes hard to express feelings and in emergency cases more than gestures are needed; therefore a digital communication device would provide SCUBA divers a better way of communication, safer and much better SCUBA diving sessions.

In this thesis, we investigated an underwater acoustic communication system, which uses Orthogonal Frequency Division Multiplexing (OFDM) spread spectrum technique to achieve high data rate in good and bad channel conditions. The underwater communication system has multi-user capability and provides not only voice traffic but also other digitized data as well.

The outline of the theses is as follows. In Chapter 1, we address the need for underwater acoustic communication and we also provide already developed and deployed underwater acoustic communication devices. We also provide communication system architecture that has to be used for the underwater communication system. In Chapter 2, we present the underwater acoustic channel, the frequency response, Doppler shift, multipath signal propagation and acoustic noise. In this chapter, we also investigate the acoustic medium impairments in frequency range of interest and specifications, such as range of mobility. In Chapter 3, we state our underwater communication system architecture that is composed of physical, data link, network and application layer. In this chapter, we state that the system shall use OFDM as the spread spectrum technique. We detailed the system architecture on physical layer, data link layer and application layer; while providing preliminary information on the network layer and Medium Access Control (MAC) layer. The system specifications and needs are stated in this chapter. In Chapter 4, the simulation procedure for finding suitable communication parameters is introduced. The physical layer and the data link layer of the communication system methods are explained. In Chapter 5, simulation results are explained and discussed. The effects of communication parameters on the communication system performance is discussed. Finally, in Section 6, conclusion and future work are stated. Communication system parameters, achievable communication performances are stated.

1.1 Ocean Transmission Medium

The underwater communication and underwater acoustics are active branches, which have several applications in military, commercial, industrial and scientific areas. Some of applications of underwater acoustics for military usage, are active and passive SONARs; for civilian usage, are bathymetric sounders, fishery sounders, sidescan and multibeam SONARs, sediment profilers, acoustic communication systems, positioning systems [1, pp.8-10].

Underwater communication may rely on several techniques; namely wired, electromagnetic, optical and acoustical [2].

Wired communication is possible in most situations however; is limited with the wire infrastructure. Electromagnetic radiation, is an already established technique in air wireless communication, however the usability of the electromagnetic (EM) waves underwater is limited with the transmission frequencies. The reason EM waves cannot be used for underwater communication efficiently is the high absorption of electromagnetic energy in a conductive medium like sea water, which is about $45\sqrt{f}$ dB per kilometer, where f is frequency in Hertz [3]. Because of this high propagation absorption the communication can be done in extreme low frequencies (30 Hz – 300 Hz), which require long antennas and high transmission powers [2]. Optical waves are another way of underwater communication technique. The optical waves do not suffer as much absorption as EM waves however; they are affected by scattering and require high pointing precision [2]. The acoustic waves are the possible and most feasible means of underwater communication. By using the acoustic waves, desired communication performance and data rate can be achieved [2], [3]. Like wired, EM or optical communication, acoustic waves are affected by many problems even if the effects are not as severe as the others.

The acoustic waves have orders of magnitude lower propagation speed than other communication ways, namely EM waves; this in turn creates latency of packets. The range is limited by both transmit power and signal attenuation, which is a function of both range and frequency. Strong reflections from the surface and the bottom create multipath signals arriving at the receiver, thus creating multipath fading. Since acoustic wave's wavelength in water is large, the Doppler shift becomes a dominant factor, which should be addressed in the system design [2], [3], [4], [5].

Even though, underwater acoustic communication has its own problems, it is the most suitable communication technique to achieve required data rate and performance [2].

1.2 Interest in Underwater Ocean and Acoustic Systems

Underwater acoustic systems are used in various fields, such as underwater environment monitoring, collection of scientific data, remote control of autonomous underwater vehicles (AUV), speech transmission between divers, underwater imaging, also known as SONARs, military communication and applications.

Before the development and deployment of underwater acoustic systems, scientific exploration of underwater was possible by placing stationary sensors that could only record data. The recorded data could only be gathered after the sensors are brought off the water. With the advances in underwater acoustic communication systems, underwater sensors can gather data, transmit them to a surface buoy and the surface buoy can relay the data to the shore via an RF link. This way, the underwater exploration could be done almost in real time and since the data is not store in sensors, data loss is prevented until sensors fail [4].

Similarly, for systems that collect underwater data, wires can be used to connect the underwater sensors to the buoy. Using wires for sensor-buoy link has the possibility of link breakage. Therefore, instead of using wires for sensor-buoy link, acoustic links can be established. The use of acoustic link can provide flexibility to the sensor network.

1.3 Emerging Needs for Underwater Acoustic Links

Today wireless communications, such as Wi-Fi (802.11x) family networks, are all fighting for higher data rate. The data rate and performance are what users are looking for their applications in their lives. For underwater acoustic networks same principle works, however the data rate requirements are not as challenging as their air counterparts.

Underwater communication data and error rate requirements depend on the type of application. In [2] it is stated that for control signaling, that might include navigation, status information and various on/off controls of an underwater robot would require up to about 1 kbps, with high reliability; for telemetry data collected from an underwater equipment from hydrophones, seismometers one to several tens of kbps with not so stringent reliability; for speech signals, that may be transmitted between divers and/or surface station several kbps with relaxed reliability and for a video signal transmission couple of 100 kbps with an error rate on the order of 10^{-3}, 10^{-4} is required.

The underwater acoustic system should be designed according to the data and error rate requirements. Since data and error rate is crucial in critical and high data bandwidth demanding applications, our concern in this work is to find, a communication system that would provide as much data rate as possible with high performance.

We shall be investigating a communication scheme to achieve at first sight a suitable data rate that SCUBA divers need for voice communication, then the proposed system can be used with modification in other areas, such as underwater acoustic networks. The communication scheme shall have multi-user capability and shall be used at short range, in shallow water. Since the communication shall allow multi-users communication at the same time, wide bandwidth is required. A wide bandwidth on the order to 200 kHz would be achieved if the frequency of transmission is high. The frequency band that shall be used is between 100 kHz and 300 kHz using a wide bandwidth acoustic transducer.

1.4 Developed and Deployed Underwater Communication Systems

With the advances in underwater acoustics and electronics that would support complex algorithms, modulations and equalization techniques, communication system performances grew and several new applications areas became possible. In scientific and commercial applications, underwater acoustics are used to remotely control robots, take images of underwater, enable voice communications and enable underwater acoustic sensor networks to transmit monitored underwater environment data.

One of the first underwater communication systems is an underwater telephone, which was developed in 1945 in United States for communicating with submarines [3]. The underwater telephone uses single-sideband suppressed carrier amplitude modulation (SSB-SC AM) in the frequency range of 8-11 kHz, the range capability of the system is several kilometers. Commercially available SCUBA diver communication device SCUBA-PHONE produced by ORCATRON is another example of an analog communication device that uses SSB-SC AM that operates at 30 kHz and has a range of 3 km [6].

After the development of first underwater acoustic device, with the help of developments in electronics, digital acoustic systems started to be built. The first digital systems were based on non-coherent modulation using frequency shift keying (FSK) [2], [4]. In order to mitigate the problem of multipath signals, combining at the receiver, guard times are inserted between data burst. The insertion of guard times results in reduction of data rate. Despite the fact that FSK is far from a bandwidth efficient communication scheme, moderate data rates and robust performance makes it an easy and less expensive technique for underwater acoustic communication. A representative system using non-coherent Multiple FSK (M-FSK) provides 5 kbps data rate, in the 20-30 kHz band [7]. The system successfully used for telemetry over a 4 km shallow water horizontal path and 3 km vertical path. It was also used in 700 m shallow water path with 10^{-2}-10^{-3} probability of error.

Low bandwidth efficiency makes non-coherent communication an inappropriate scheme for high data rate and performance requirements. The need for high data rate resulted in usage of coherent modulation techniques [2], [4]. Today with the availability of powerful electronics, coherent communication systems using phase shift keying (PSK) or quadrature amplitude modulation (QAM) can be built. Coherent modulation, despite being more complex and costly, is bandwidth efficient and can support greater data rates. Like non-coherent systems multipath propagation degrades the performance, in order to mitigate the multipath problem, equalizers are employed at the receivers with certain update algorithms. A representative coherent modulation system in [8] is tested in vertical path at short range of 60 m and achieved 500 kbps, using 16-QAM. The transmission is at 1 MHz with 100 kHz bandwidth. The performance degradation due to multipath propagation was resolved with adaptive equalizer at the receiver under least mean square error (LMS) algorithm.

Apart from narrowband single carrier communications systems, spread spectrum techniques, which are gaining much attention and popularity for wireless networking and air communication, are used for underwater acoustic communication. There are types of spread spectrum communication, Frequency Hopped Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS) [9, pp.329-338], [10]. Orthogonal Frequency Division Multiplexing (OFDM) is another spread spectrum technique, however this technique can be considered as a spread spectrum technique that combines properties of Frequency Division Multiplexing (FDM) and Multi-Carrier modulation (MCM) [11, pp.20-24].

The spread spectrum systems are used in underwater applications due to their inherent resistance to the channel impairments, like multipath and Doppler shift. In DSSS, the narrow band data is multiplied with a higher frequency bit sequence (chips) to have a larger bandwidth signal. DSSS has the capability of resolving multipath signals, is jam resistant due to large bandwidth occupancy, has the ability to transmit under the noise floor to gain counter detection and has the inherent security due to spreading sequence [9, pp.329-338], [10]. In FHSS systems, the narrow band data is transmitted through different frequency bands in a determined pattern. FHSS communication technique with carefully selection of the hopping sequence and parameters can reject multipath propagation, is jam resistant with suitable error correction coding and has inherent security due the predetermined frequency hopping sequence [9, pp.329-338], [10]. OFDM is a special type of FDM, in which in a certain time interval, the bit sequence is transmitted in parallel at the same time from different frequencies that are orthogonal to each other [11, pp.33-47].

A representative DSSS communication system in [12] uses DPSK and has a 10 kHz spread bandwidth using 16 chips/bit has 625 baud data rate. Similarly, in [13], an OFDM underwater acoustic communication system is depicted. The OFDM system operating in the 8-16 kHz band has 11.89 kbps data rate.

In our work, we chose to use spread spectrum communications and designed the system with suitable properties and parameters. The reason for the choice is that, spread spectrum communications' inherent properties to deal with channel impairments. The advantages of spread spectrum communication can be designed for use in underwater to achieve better data rate and performance.

1.5 Underwater Communication System Architecture

The design of an information network is of the form of a layered architecture [14, pp.49-57]. Underwater acoustic communication systems, specifically underwater acoustic networks, operate in a layered structure. The already developed air communication network layers and structures are not suitable for underwater acoustic communications due to long propagation times acoustic waves therefore, the layer and structures are modified. The basic architecture of an underwater communication system, in terms of layers consists of physical layer, data link layer, network layer and application layer [5]. Figure 1.1 depicts the basic architecture of the underwater communication system's layered architecture.

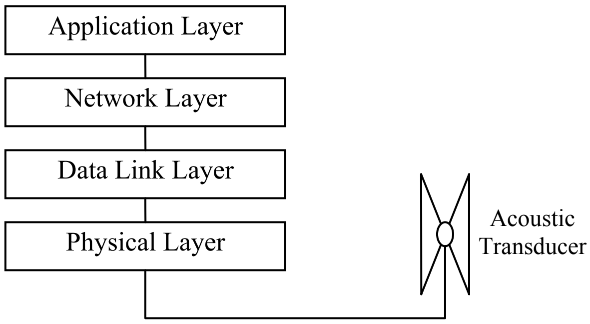


Figure 1.1: Layered architecture of underwater acoustic communication system

1.5.1 Physical Layer

The physical layer at the transmitter, converts (modulate) information bits, or more generally symbols, into analog signals and at the receiver side the received signals, which are corrupted by noise and affected by channel impairments, is converted (demodulate) to information bits or symbols [5].

1.5.1.1 Modulation

The signals to be transmitted are modulated to a higher frequency, such that suitable communication is obtained. The modulation technique is chosen such that required bit rate, performance is achieved. The modulation methods also determine the required bandwidth and the methods should be such that communication is least affected by the channel impairments. There are several modulation schemes; FSK, in which data is encoded in different frequencies, PSK, in which the data is encoded into the phase of the signal, ASK, in which the data is encoded onto the amplitude of the signal and QAM, in which the data is encoded not only on the phase of the signal but also on the amplitude of the signal [9, pp. 294-328], [15, pp.340-398].

FSK implementation is easier than the other methods due to non-coherent demodulation; however has low bandwidth efficiency due to the insertion of the guard interval. PSK systems require coherent demodulation and the bandwidth efficiency is better than the FSK modulation however, the complexity of the system grows, albeit with high data rate. ASK has an easier implementation, however since, the data is encoded in the amplitude, due to channel impairments of underwater such as multipath, range and frequency dependent frequency response, the modulation scheme is not a good solution for underwater applications. QAM is a high bandwidth efficient modulation scheme, however it is not considered for underwater communications due to multipath propagation and frequency response.

1.5.1.2 Multiple Access Methods

In a network topology, users share the transmission medium. Whenever users have information to send, they should transmit to the shared medium. This scheme is well suited to a one transmitter and one receiver system, however in real life many users share the same transmission channel, therefore users have to share the available frequency and time in an efficient manner. This is accomplished by multiple access methods, like Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA) and Orthogonal Frequency Division Multiple Access (OFDMA) [9, pp.447-461], [11, pp.33-47].

FDMA divides the available frequency spectrum into sub bands, which are assigned to different users. Each user can transmit its own data in its allocated band. FDMA is an easy to implement scheme, however is not suitable for underwater communications. The available underwater spectrum is limited by range and frequency; therefore either there will be small number of channels available for each user or the data rate in each band will be too low to achieve desired communication. On the other hand, the bandwidth of the channels may be greater than the coherence bandwidth, in which case the users are vulnerable to frequency selective fading [4], [5].

Time Division Multiple Access (TDMA) divides the time interval, called a frame, into time slots. Each time slot is assigned to a different user. In TDMA method strict time slot synchronization is required and since propagation delays are large in underwater communications, synchronization is hard to achieve; therefore TDMA is not a suitable technique to be used for underwater acoustic communication [4], [5].

Code Division Multiple Access (CDMA) on the other hand allows users to operate simultaneously over the entire frequency band at the same time. Different users are differentiated by assignment of different codes that are used to spread the messages. Each user's code is selected such that they are orthogonal. This way receiver can reject the unintended users signal. In CDMA method the users' bandwidth is much larger than the narrowband bandwidth; therefore this provides resistance to frequency-selective fading. CDMA appears to be a promising multiple access method for shallow water acoustic networks [4], [5].

Orthogonal Frequency Division Multiplexing (OFDM) or Coded-OFDM (COFDM), like CDMA allows multiple users to operate simultaneously over the entire frequency band at the same time. In OFDM, serial information data is transmitted in parallel like FDMA, however each frequency band is orthogonal to each other. OFDM is a burst and wait communication technique, whose implementation is easy with Fast Fourier Transform (FFT) algorithms. The channel impairments are addressed with use of guard time and cyclic extension [11, pp.20-24], [11, pp.33-47].

1.5.2 Data Link Layer

In the data link layer, packetized information bits/symbols are formed into frames and error control coded [5]. The error control coding is applied to the information data in order to recover the corrupted data due to noise in the channel and channel impairments. Also in the data link layer, medium access control (MAC) is applied to coordinate the access of users' to the shared medium. The function of the MAC protocol is to orchestrate the devices in order to maximize the available data rate and to avoid collisions [9, pp.463-469], [14, pp.432-448]. There are several MAC protocols, namely; ALOHA, slotted ALOHA, carrier sense media access (CSMA), carrier sense media access with collision avoidance (CSMA/CA), multiple access with collision avoidance (MACA), MACAW, automatic repeat request (ARQ).

From the MAC protocols, CSMA/CA and MACA medium access protocols are well developed protocols, which are used in Wi-Fi wireless Ethernet. The protocol provides desired data rate and has the ability to deal with *hidden* and *exposed node* problems, which are faced in wireless networks, using special packet exchange. The CSMA/CA and MACA protocols avoid collisions; this in turn increases the overall channel efficiency [4], [5], [9, pp.463-469], [14, pp.432-448]. Along with increase in channel efficiency, by using special packet exchange, channel properties, range can be determined and proper signal level, equalizer parameters can be adjusted to have the most reliable communication [4]. The details of the CSMA/CA and MACA protocols are discussed in APPENDIX A.

1.5.3 Network Layer

The major function of the network layer is to route the packets from the source to the destination [4], [5]. Routing is the algorithm to find the route of a packet from the source to the destination. In a static network or a dynamically changing network (ad-hoc networks) the routes that packets have to travel should be properly be set before packets are transmitted.

The routing is done according to an optimization criterion, which may be based on shortest path, least congested path, minimum energy consumption path [4], [5]. The criterion may be based on overall energy consumption, in which case the optimum system would have the largest network lifetime. There are several routing algorithms that are used with ad-hoc networks, destination sequence distance vector (DSDV), temporally ordered routing algorithm

(TORA), dynamic source routing (DSR), ad hoc on-demand distance vector (AODV) [5].

One of the routing algorithms should be chosen for underwater acoustic ad-hoc network deployment. The choice should consider the long propagation delay caused by the slow propagation speed of acoustic waves, variability of the network, power availability and data rate. The underwater communication system shall operate in an ad-hoc network architecture, due to several advantages of ad-hoc networking. In an ad-hoc network architecture, since each node hops its packets using neighbors, not only the energy of each node is conserved but also the range of the network is increased. Network topologies and advantages of ad-hoc networking are discussed in APPENDIX B.

Chapter 2

Underwater Acoustic Channel Properties

The underwater acoustic communication relies on generation of acoustic waves with a suitable acoustic transducer, travel of the waves through the ocean and reception of the acoustical waves with the receiving acoustic transducer.

The propagation of sound in water is a mechanical phenomenon and depends on the mechanical properties of the medium. In particular, the inertial and elastic properties of an elemental volume are of interest. A net force across a volume element results in an acceleration opposed by inertial properties, and mechanical strain is created in the element related to applied force and the elastic properties of the medium. The total energy involved in these mechanical effects includes the kinetic energy of motion and the stored potential energy represented by internal strain [16, pp.17-18].

A localized variable source of mechanical force imposes unbalanced forces on neighboring volume elements. The propagation of the resulting motion-strain effects away from the source results in a longitudinal compression wave that transmits mechanical, or acoustic, energy away from the source [16, pp.17-18].

For an oscillating source, the wave consists of regions of compression, where the pressure exceeds the original equilibrium value, and regions of rarefaction with pressure less than the original value. These regions move, or propagate, away from the source at a constant rate determined by the properties of the medium [16, pp.17-18].

In ocean, sound transmission is affected by such factors as temperature, pressure, chemical composition, and details of the surface and bottom boundaries [16, pp.17-18].

2.1 Shallow Underwater Acoustic System Operational Properties

In this work, the underwater communication device shall be used in shallow water at maximum depth of 100 m, which is decided such that a SCUBA diver shall not in any circumstance pass beyond 66 meters with ordinary SCUBA equipment due to health safety regulations [17], [18]. The range shall be at most 100 meters, which should be maintained for health concerns and safety. The transmission frequency is around 200 kHz, having 200 kHz bandwidth provided by specially designed wide bandwidth acoustic transducer. The relative motion between divers is assumed to at most 1 m/s, which is decided by most likely motion of divers.

2.2 Underwater Acoustic Channel Properties

The communication system has to be designed to provide desired data rate and performance. The acoustic channel properties, such as propagation speed, wavelength, frequency response, loss due to spherical spreading and attenuation, loss due to surface and bottom reflections and noise has to be defined and precisely calculated, in order to achieve the desired data rate and performance.

The underwater acoustic medium has various difficulties, in terms of communicationwise problems. These problems are related to range, depth and site of the device's operational environment. The environment can be classified with respect to range and depth. The underwater acoustic frequency response is both frequency and range dependent; therefore the transmission frequency creates a limit on the range. The underwater acoustic communication range is classified by short range, less than 100 m, medium range, between 1 km-10 km, and long range, over 10 km – 100 km range [2]. The available bandwidth changes with the range and is more than 100 kHz for short range communication, in the order of 10 kHz for medium range communication and a few kHz for the long range communication [2]. The depth is classified by shallow and deep water. Even if the definition of shallow and deep water is not strict, shallow water can be considered depths less than 100 m, whereas deep water can be considered beyond the continental shelves [2]. Of the shallow and deep water communication, shallow water is more problematic than the deep water, due to possible strong reflections from the surface and bottom, strong ocean current and wind driven waves.

The underwater communication can be done within two paths, vertical and horizontal. Communication, which is done in horizontal direction is a problematic one due to the multipath reflections from the surface and the bottom along with a line of sight (LOS) path, whereas in vertical communication path only LOS communication is present. In vertical path communication, higher data rates can be achieved without much of a device complexity, however in horizontal path communication, complex equalizers are needed or guard intervals should be inserted to mitigate the multipath reflection problem, in order to achieve desired data rate. In vertical channels there is little multipath, whereas in horizontal path the multipath spread is extremely long [2].

2.2.1 Acoustic Waves' Propagation Speed and Wavelength

Acoustic wave's propagation speed is a function of several parameters, temperature, depth and salinity. Temperature is a function of depth, time, location and weather conditions. In [16, pp.126-130], [19] the propagation speed of acoustic waves is found from experimental and theoretical considerations and is defined as:

$$c = 1449 + 4.6T - 0.055T^2 + 0.0003T^3 + (1.39 - 0.012T)(S - 35) + 0.017z \qquad (2.1)$$

In (2.1), c is the speed of sound in underwater (m/sec), T is the temperature (°C), S is the salinity (parts per thousand) and z is the depth (m).

In [19], the propagation speed of sound is calculated and found to be between 1450 m/s and 1540 m/s. In our simulations and calculations, the propagation speed of sound is taken to be 1500 m/s for convenience.

The wavelength of the transmitted waves is given by [9, pp.107]:

$$\lambda = \frac{c}{f} \qquad (2.2)$$

For underwater acoustic medium, the wavelength are orders of magnitudes shorter than the EM waves in air. The wavelength at 100 kHz, 200 kHz and 300 kHz are 15 mm, 7.5 mm and 5 mm respectively. The short wavelength is a consequence of the slow propagation speed of the acoustic waves.

2.2.2 Absorption of Sound in the Ocean

Underwater acoustic waves have more complex path loss profile as compared to EM waves. The acoustic waves in underwater spread to the medium spherically; therefore spherical attenuation is part of the total attenuation. Apart from the spherical attenuation, there is also frequency and range dependent attenuation [1, pp.11-59], [16, pp.126-156], [19]. The total path loss defined in [16, pp.126-156] is given as:

$$PL = 20\log R + \alpha R \tag{2.3}$$

Where α is the absorption loss in the ocean in dB/m and R is distance in meters. The absorption loss is defined in [1, pp.11-59] and Francois-Garrison modeled this loss as in (2.4), (2.5), (2.6) and (2.7).

$$\alpha = A_1 P_1 \frac{f_1 f^2}{f_1^2 + f^2} + A_2 P_2 \frac{f_2 f^2}{f_2^2 + f^2} + A_3 P_3 f^2 \tag{2.4}$$

The contribution of $B(OH)_3$ is:

$$\begin{gathered} A_1 = \frac{8.86}{c} 10^{(0.78 pH - 5)} \\ P_1 = 1 \\ f_1 = 2.8\sqrt{\frac{S}{35}}\, 10^{\left(4 - \frac{1245}{T+273}\right)} \\ c = 1412 + 3.21T + 1.19S + 0.0167z \end{gathered} \tag{2.5}$$

The contribution of Magnesium Sulphate $Mg(SO)_4$ is:

$$\begin{gathered} A_2 = 21.44 \frac{S}{c}(1 + 0.025T) \\ P_2 = 1 - 1.37x10^{-4} z + 6.2x10^{-9} z^2 \\ f_2 = \frac{8.17x10^{\left(8 - \frac{1990}{T+273}\right)}}{1 + 0.0018(S - 35)} \end{gathered} \tag{2.6}$$

The contribution of pure water viscosity is:

$$P_3 = 1 - 3.83x10^{-5} z + 4.9x10^{-10} z^2$$
$$T < 20°C:$$
$$A_3 = 4.937x10^{-4} - 2.59x10^{-5} T + 9.11x10^{-7} T^2 - 1.5x10^{-8} T^3 \quad (2.7)$$
$$T > 20°C:$$
$$A_3 = 3.9464x10^{-4} - 1.146x10^{-5} T + 1.45x10^{-7} T^2 - 6.5x10^{-10} T^3$$

In (2.4), (2.5), (2.6) and (2.7), z is the depth (m), S is the salinity, T is the temperature (°C), f is the frequency (kHz) and *pH* is the acidity of the medium. In order to find absorption loss (α), instead of using complex equations, analytical graphs in [1, pp.11-59] and [16, pp.126-156] can be used. The absorption loss is shown in Figure 2.1.

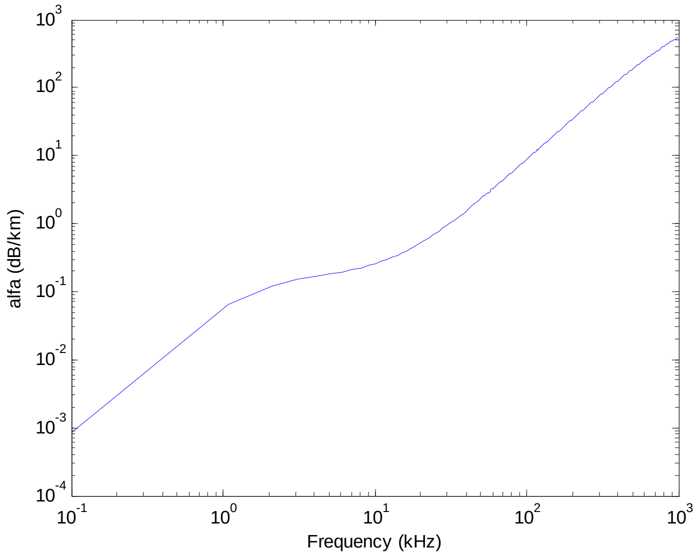


Figure 2.1: Absorption loss in Ocean at 20 °C and 35% salinity.

The absorption loss (α) can be observed from Figure 2.1. In the frequency range of interest, which is from 100 kHz to 300 kHz, the absorption loss can be approximated as a linear line.

0.04 dB/m	@ 100 kHz
0.06 dB/m	@ 200 kHz
0.08 dB/m	@ 300 kHz

Table 2.1: Approximate absorption loss between 100 kHz and 300 kHz

By approximation, the generality is not lost because in the frequency range of interest the absorption loss is approximately linear. After the linearization, the absorption loss is approximated as:

$$\alpha \cong 0.02 + \frac{f}{100x10^3} 0.02 \ dB/m \tag{2.8}$$

In Figure 2.2, frequency and range dependent path loss is illustrated.

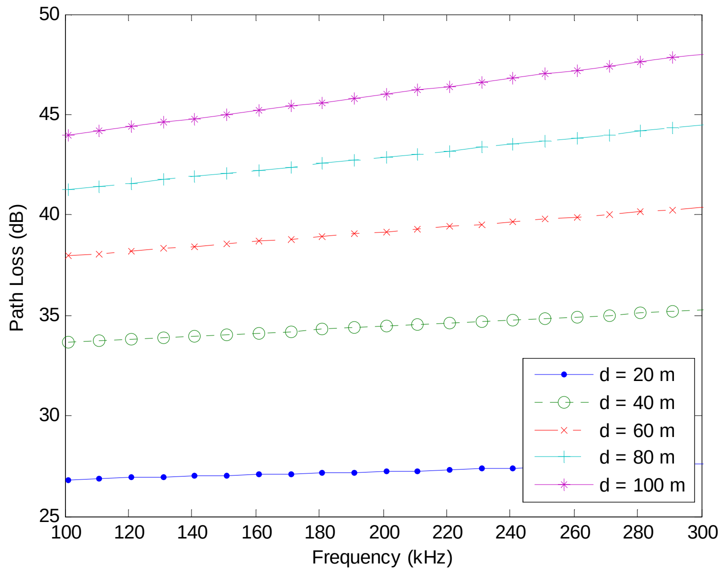


Figure 2.2: Total loss between 100 kHz and 300 kHz for several distances

From the Figure 2.2, it can be concluded that when the acoustic path range is increased the path loss increases, however the increase is not only spherical but also range dependent too. When path loss at 100 m is observed it can be seen that there is almost 4 dBW power difference between the higher and lower frequency components, whereas for shorter ranges the difference is less. This high frequency difference has to be addressed when the communication system is designed.

2.2.3 Acoustic Loss Due to Surface and Bottom Reflections

The underwater acoustic system shall be designed to operate in shallow water and at maximum range of 100 m. In these conditions, there will be multiple reflections from surface and bottom.

If surface and the bottom are considered as flat boundaries, then signal incident on boundaries will be reflected differently, because of the acoustic mismatch between the water-air and water-bottom boundaries. In order to find the acoustic mismatch, acoustic impedance has to be defined. The acoustic impedance is defined as [16, pp.126-156]:

$$\begin{aligned} Z_0 &= \sqrt{\rho B}\,, B = \rho c^2 \\ Z_0 &= \sqrt{\rho\left(\rho c^2\right)} = \rho c \end{aligned} \tag{2.9}$$

In (2.9), ρ is the medium density and c is the speed of acoustic waves in the medium. The unit of acoustic impedance is *Rayl*, which is equal to 1 Pascal-second per meter. From (2.9), the acoustic impedances of the water, air and sea floor are found and approximated as:

$$\begin{aligned} Z_{sea} &= 1.5MRayl \\ Z_{air} &\approx 0 \\ Z_{bottom} &\approx \infty \end{aligned}$$

Table 2.2: Characteristic acoustic impedance of the water, air and the sea floor.

When the acoustic waves are incident on the water-air or water-bottom interface the acoustic waves are subject to reflection through a reflection coefficient. In [20], the reflection coefficient defined as:

$$\Gamma_{12} = \frac{Z_2 \cos\theta_i - Z_2 \cos\theta_t}{Z_2 \cos\theta_i + Z_1 \cos\theta_t} \tag{2.10}$$

In (2.10), Z_1 and Z_2 are the acoustic impedances of the two medium, θ_i and θ_t are the angle of incidence and transmission with respect to normal. From (2.10) the reflection coefficient between air-water and water-bottom boundary is approximated as:

$$\Gamma_{12\,sea-air} \cong -1$$
$$\Gamma_{12\,sea-bottom} \cong 1$$

Table 2.3: Reflection coefficient of the water - air and the water - sea floor boundary

In an ideal case where the boundaries are flat surfaces, the signal will be reflected from the sea surface with a phase shift of 180° whereas from the sea floor without a phase shift. However, due to irregularities and corrugations on the sea floor, and ocean waves on the sea surface due to wind, acoustic waves lose their power per reflection.

In [16, pp.126-156] and [21], the amount of power loss due to scattering from the sea surface and sea floor is given. The scattering loss on the sea surface is dependent on the Sea-State and frequency of transmission. The Sea-State is determined by the wind speed conditions. The scattering loss at the surface is defined as:

$$\alpha_s = -10\log\left[1 - 0.0234(fH)^{3/2}\right] \qquad (2.11)$$

In (2.11), α_s is the surface reflection loss (dB), f is the frequency (kHz) and H is the average trough-to-crest wave height (ft).

In [16, pp.126-156], the scattering loss due to wind at Sea-State at various frequencies and for various Sea-State conditions is given and depicted in Figure 2.3.

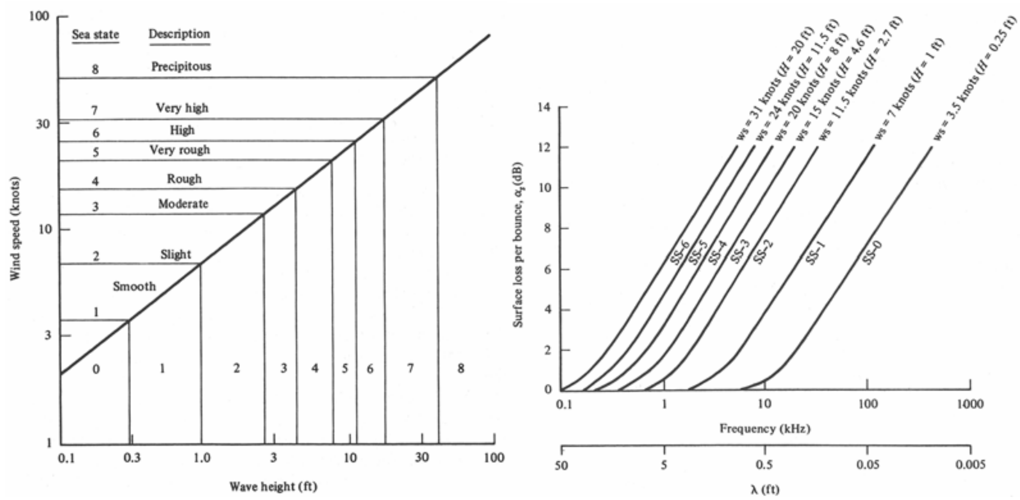


Figure 2.3: (a) Sea-State Conditions (b) Surface reflection loss (Courtesy of W.S. Burdic, Underwater Acoustic System Analysis, pp. 132-133)

From Figure 2.3, it can be concluded that Sea-State (SS) has a great effect on the scattering loss from the surface, along with the frequency. It can be considered that a diving session in most of the occasions would be done in Sea-State-0, where the sea is smooth. In these circumstances, from the Figure 2.3, the scattering loss at 200 kHz is 10 dB and 14 dB at SS-0 and SS-1 respectively. In simulations, the scattering loss is taken at 200 kHz. It can be seen from the figure that from 100 kHz to 300 kHz the loss changes by almost 2 dB however, taking loss at the middle frequency shall provide enough accuracy for our calculations.

The sea floor loss depends on several parameters, namely structure of the sea floor, transmission frequency and angle of incidence [16, pp.126-156], [21]. The structure of the sea floor, which affects the loss parameter, is the porosity of the surface. Porosity is the ratio of volume in sample sediment to the volume of the sediment, which is defined as [21]:

$$n = {}^{V_w}\!/_{V} \tag{2.12}$$

Porosity parameters for some sea floor structures are provided in [21] and is tabulated in Table 2.4.

	n
Coarse Sand	0.4
Fine Sand	0.5
Silt	0.6
Clay	0.8

Table 2.4: Porosity values for sample sea floor structures

Sea floor loss is formatted by Naval Underwater Center (NUC) empirically for several sea floor structures; that is in terms of porosity. The empirical formula for sea floor loss for several sea floor structures are provided in (2.13). The formula provides direct loss in dB where n is the porosity value of the sea floor structure (0 < n <1) and θ is the angle incident measured in degrees, relative to the normal and f is the frequency of transmission in kHz.

$$\text{Sea Floor Loss (dB)} = -(17.5n-1.025)f^{1/3}\left[\tanh((6.55-0.0724\theta)n)^{(1.5/n)}+(0.8-0.296n)(1-0.0117\theta)\right] \quad (2.13)$$

Sea floor loss provided in (2.13) at 200 kHz is illustrated in Figure 2.4, with respect to porosity, frequency and angle of incidence.

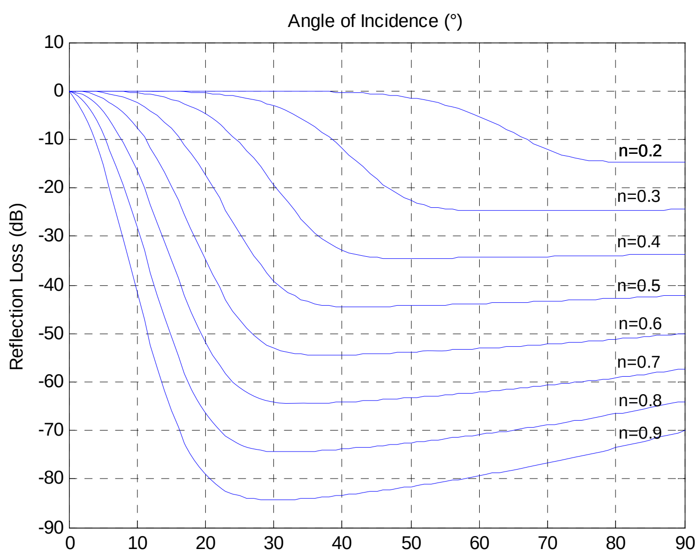


Figure 2.4: Sea floor loss at 200 kHz for several porosity values with respect to angle of incidence

Sea floor loss in our simulations can be taken for incidence angles of 90°. The maximum range of our system is limited to 100 m and reflected rays that shall be arriving the receiver at around 90°. At smaller incidence angles due to high absorption loss and due to high frequency and range, the reflected waves shall be attenuated sufficiently. At 200 kHz and at 90° angle of incidence the sea floor loss is around 15 dB, 35 dB and 70 dB for porosity values of 0.2, 0.4 and 0.9 as depicted in Figure 2.4.

For our simulations, porosity values of 0.2 and 0.4 shall be used with 15 dB and 35 dB loss respectively. The sea floor loss is taken at middle frequency because the empirical formulation given by (2.13) states the mean sea floor losses. The total sea floor loss is more than these values, because the losses do not include the scattering of the acoustic waves, that is only the transmission loss is included.

2.2.4 Doppler Spread and Coherence Time

Due to relative motion between the transmitter and the receiver the transmitted signals are received by the receiver at different frequencies [9, p.179]. This is called Doppler Effect and the amount of change in frequency is represented by [9, p.179]:

$$\begin{aligned} \Delta\phi &= \frac{2\pi v \Delta t}{\lambda}\cos\theta \\ f_d &= \frac{1}{2\pi}\frac{\Delta\phi}{\Delta t} = \frac{v}{\lambda}\cos\theta \end{aligned} \qquad (2.14)$$

The Doppler shift has two components, one is the relative motion between the receiver and the transmitter and the other is the ocean surface motion due to wind [2]. The acoustic waves have a Doppler spread due to wind, that is given by:

$$D_S = \left(\frac{0.0175}{c}\right) f w^{3/2} \cos\theta \qquad (2.15)$$

In (2.15), θ is the incidence angle (°), c is the speed of sound (m/sec), w is the wind speed (m/sec). Due to high absorption loss in the frequency range of interest, the multipath signals that reflect from surfaces with an angle close to 90° with respect to normal, shall be received strongly. Since multipath components that are of interest shall reflect from the surface with an incidence angle close to 90°, the Doppler spread due to wind driven surface shall be very close to 0 Hz. For this reason, the component of Doppler spread due to surface motion is not our interest.

The major component is the relative motion between the transmitter and the receiver. We are assuming that, a diver shall not in most of the cases swim or move with a speed more than 1 m/s and we are not expecting the relative motion between two divers shall exceed 1 m/s. Considering the situation, the maximum Doppler shift at incidence angle 0° due to transmitter and/or receiver motion is calculated using the (2.15), is depicted in Table 2.5.

66.66 Hz	@ 100 kHz
133.33 Hz	@ 200 kHz
199.98 Hz	@ 300 kHz

Table 2.5: Doppler shift due to 1 m/s relative motion (θ=0°)

The dominant Doppler shift is from the relative motion between the transmitter and the receiver and ratio of shift is considerably larger than their counterparts in air when the transmission frequency is concerned.

We expect that we shall have different Doppler shifts however the maximum Doppler shift that we shall observe is 200 Hz (when the incidence angle between is 0°). This way we have a Doppler spread that is expected to have a maximum of 200 Hz. The 200 Hz maximum Doppler shift affects the communication severely because the transmission frequency is 300 kHz and the bandwidth of OFDM pulses (OFDM symbol of length 1 msec) around 2 kHz. The Doppler spread adds spectral broadening caused by the time rate of change of the underwater acoustic channel [9, p.179].

Coherence time is defined from the Doppler spread. Doppler spread and the coherence time describes the time varying nature of the channel [9, pp.197-210]. Coherence time is defined as the time duration over which the channel impulse response remains invariant. If the baseband signal has larger bandwidth than the Doppler spread, then the effect of Doppler shift is negligible; however, in our case the effect might be large according to the bandwidth usage. The Doppler spread and the coherence time are inversely proportional to each other [9, pp.197-210]:

$$T_C \approx \frac{1}{f_m} \tag{2.16}$$

In (2.16), f_m is the doppler shift and T_c is the coherence time. Using the (2.16), the coherence time is found to be 5 msec.

The Doppler spread is the maximum of the Doppler shift over time. Since the relative motion might be changing over time, the Doppler shift has a statistics. The time over which the channel has 0.5 correlation is defined as [9, pp.197-210]:

$$T_C \approx \frac{9}{16\pi f_m} \tag{2.17}$$

For modern communication devices the coherence time is the geometric mean of the (2.16) and (2.17) [9, pp.197-210]:

$$T_C \approx \sqrt{\frac{9}{16\pi f_m^2}} = \frac{0.423}{f_m} \tag{2.18}$$

Using (2.17) as in (2.18), the time over which the channel has 0.5 correlation and practical coherence time is found 8.95 10^{-4} sec and 2 msec respectively.

If the pulse period is much less than the coherence time, then the communication shall not be affected severely from the Doppler shift, therefore complex algorithms and equalizers shall not be required.

2.2.5 Multipath, Delay Spread and Coherence Bandwidth

The underwater acoustic communication system shall be operating in a severe multipath environment especially when the receiver and/or transmitter are very close the surface or sea floor boundaries.

The underwater acoustic channel can be modeled as stratified surfaces as in [1, pp.11-59]. For the multipath propagation environment we consider direct acoustic rays bounced of from the surface and the bottom. The multiple reflections are modeled with image interpretation of the transmitter (*src*) and the receiver (*dst*), however in calculations the boundary reflection losses are taken according to Sea-State level and structure of the sea floor. The surface loss is taken 10 dB and 14 dB for Sea-State-0 and Sea-State-1 respectively and the sea floor loss is taken 35 dB and 15 dB for sea floor porosity of 0.4 and 0.2 respectively. In our simulations 5 ray model is used, including 1 line of sight (LOS) path; 2 single boundary reflections and 2 double boundary reflections. The 5-ray acoustic underwater channel model is depicted in Figure 2.5.

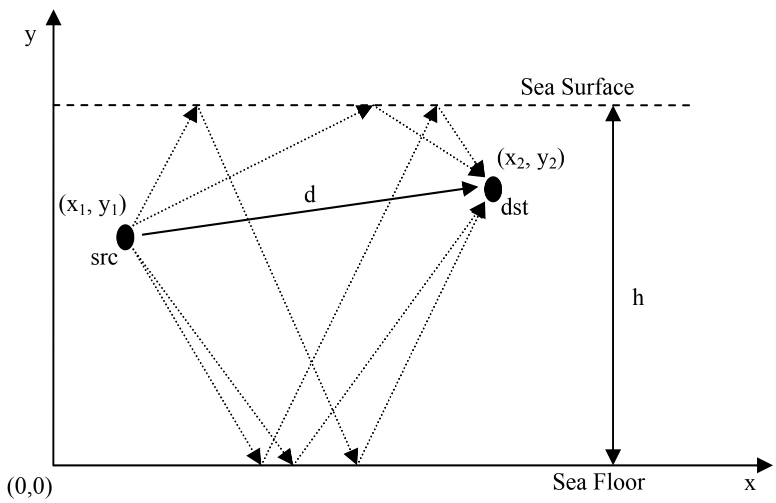


Figure 2.5: 5-Ray Underwater Acoustic Channel Model

In Figure 2.5, the divers are named as *source (src)* and *destination (dst)*; the depth as *h*, the direct distance as *d* and the multiple reflections from the surface and the bottom as depicted as *arrows*, which are found by image reflections of the source and the destination from sea surface and floor.

By using the channel model in Figure 2.5, the path loss model explained in the Section 2.2.2 , the surface and bottom reflection model explained in Section 2.2.3 , the multipath spread of the channel can be found by using (2.19) [9, pp.197-210].

$$\bar{\tau} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)} \qquad \text{(a)}$$

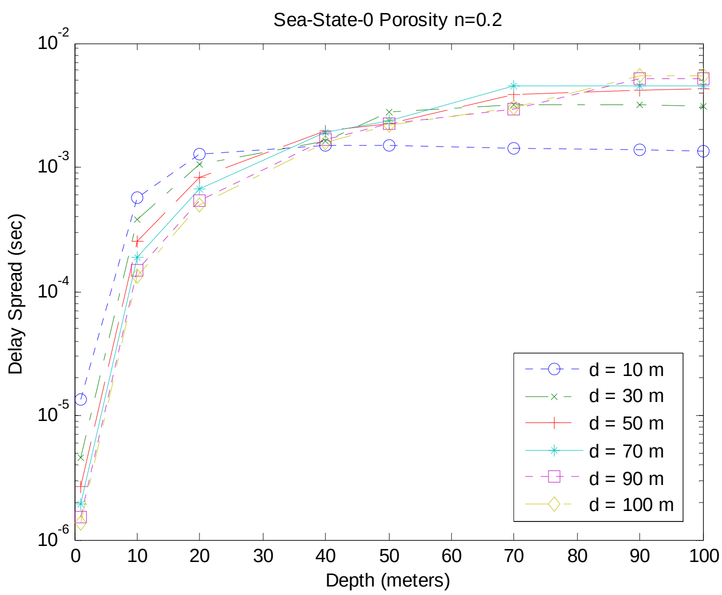
$$\overline{\tau_k^2} = \frac{\sum P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)} \qquad \text{(b)} \qquad (2.19)$$

$$\sigma_\tau = \sqrt{\overline{\tau^2} - \left(\bar{\tau}\right)^2} \qquad \text{(c)}$$

The multipath spread is found by first simulating the underwater channel model to find the distance of the direct and multiple reflections. The arrival time of the reflections is found from the distance and the power level of the reflections is found from the path loss formula in (2.3) and Figure 2.1 along with the scattering power loss from the overall loss. The arrival time and power level of each reflection is then applied to the (2.19a) and (2.19b), which are the mean excess delay and rms delay spread respectively [9, pp.197-210]. The multipath delay spread is found by using the (2.19a) and (2.19b) in (2.19c) [9, pp.197-210].

The depicted multipath spread formulation is for only one scenario, however in underwater there are infinitely many positions where two divers can be; therefore many scenarios have to be simulated.

In order to gain more understanding of the multipath spread, multipath simulation is done. The simulation is done as follows; using the 5-Ray acoustic underwater channel model, depicted in Figure 2.5, the source at first is placed randomly on the vertical line along y axis and then the destination is placed randomly according the depth and the distance between the source and the destination. The path loss between the source and the destination is calculated according to the acoustic path loss formula also applying the scattering loss from the surface and the bottom. The simulation is repeated 5000 times, to find the multipath of different scenarios. This way several multipath spread values are found for several depth and distance values, however since the scenarios are random, the multipath spread histogram for each scenario shows a peak at some specific multipath spread value. This value is taken to be the most probable multipath spread at that specific condition, depth and distance. All the multipath spread values are found by changing the depth and the distance between the source and the destination. The obtained results according to this method for Sea-State-0 and sea floor porosity of 0.2 are illustrated in Figure 2.6. Expected delay spread graphs for the Sea-State-1 and porosity of 0.4 are provided in APPENDIX D.



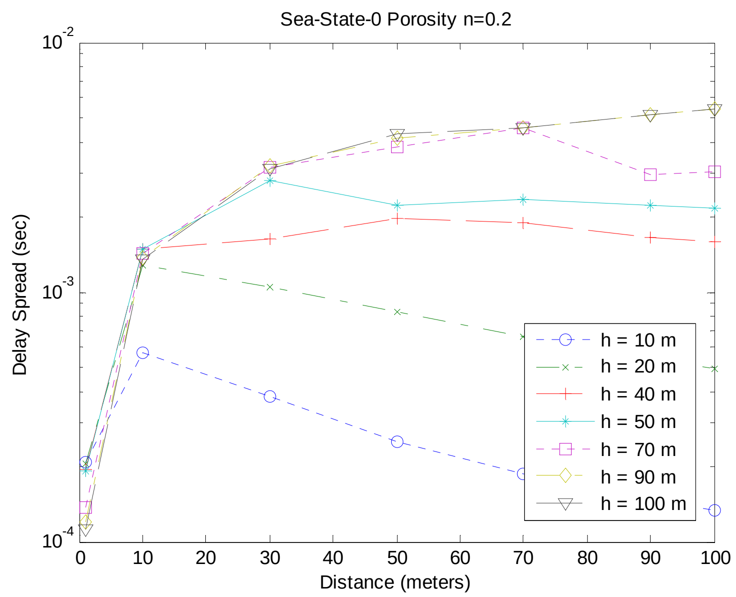


Figure 2.6: Multipath Spread (a) dependence of depth, (b) dependence of distance

Figure 2.6 shows the most probable multipath values of the underwater channel for Sea-State-0 and sea floor porosity of 0.2. The figure also shows the variation of the multipath according to the distance and range. The chosen sea-state condition and the sea floor structure provide the least amount of loss therefore provides the worst delay spread conditions. The worst delay spread conditions are taken as a reference for the expected delay spread because the design for the communication system shall take account of the worst case conditions. The delay spread values for the Sea-State-1 and porosity 0.4 are less than the former case.

It can be concluded from the graph that for shorter ranges, the delay spread is small. Multipath reflections arrive much later than the direct signal, as a matter of fact the received signal power levels of multipath signals are much smaller than the direct path. When the range is increased the delay spread tends to increase however, approaches to 5.4 msec as the range goes to 100 m. The same behavior is observed when the depth goes to 100 m. The delay spread value for the Sea-State condition and the sea floor structure that provide the most expected attenuation (SS-1, porosity n=0.4), is 3.38 msec as given in APPENDIX C and APPENDIX D.

Recreational SCUBA divers are most likely to be in the depth range of at most 60 m and communication range between the divers can be at most 100 m, therefore, the multipath spread can be taken 5.4 msec for the worst case conditions (SS-0, porosity n=0.2) [17], [18].

Reflected and scattered signals from surface and bottom create fading in certain parts of the overall spectrum. Coherence bandwidth is defined from the rms delay spread and it is statistical measure of the range of the frequencies over which the channel can be considered as flat [9, pp.197-210]. In other words, coherence bandwidth is the range of frequencies that have strong amplitude of correlations. The coherence bandwidth is defined in terms of percentage of correlation. If the correlation between the frequency components is higher than 0.9 the coherence bandwidth is approximately given as:

$$B_C = \frac{1}{50\sigma_\tau} \tag{2.20}$$

For 0.5 correlation the coherence bandwidth is:

$$B_C = \frac{1}{5\sigma_\tau} \tag{2.21}$$

In (2.20) and (2.21), σ_τ is the delay spread and B_C is the coherence bandwidth.

For 5.4 msec multipath spread 0.9 and 0.5 correlation coherence bandwidth is 3.70 Hz and 37.03 Hz respectively. The calculated values are the bandwidth over which the frequency response can be considered flat for the underwater communication channel.

The coherence bandwidth, which is related with the delay spread, is a pulse design parameter. If 0.9 correlation is chosen the communication shall be done without inter symbol interference (ISI), while for 0.5 correlation equalizer has to be used [9, pp.197-210].

When the delay spread is higher, the coherence bandwidth is lower. When the signal bandwidth is higher than the coherence bandwidth, signal faces frequency selective fading. Apart from the frequency selective fading multipath signals that arrive at the receiver along with the main path, creates inter symbol interference (ISI). The ISI may be much longer in the underwater acoustic channel especially when the transmission frequency is lower, since attenuation is less, resulting in longer sequences of the bits to be affected [2].

If symbol bandwidth is much less than the coherence bandwidth, then the communication shall not be affected severely from the delay spread, therefore complex algorithms and equalizers shall not be required.

2.2.6 Coherence Time and Bandwidth and Design Criteria

According to the Doppler and multipath spread, the underwater acoustic channel can be categorized. Time dispersion due to multipath causes the transmitted signals to undergo either flat or frequency selective fading while Doppler spread defines the fading properties as either fast or slow fading [9, p.179], [9, pp.197-210].

The channel is said to be flat fading if the transmitted signal has a much smaller bandwidth than the coherence bandwidth of the channel, whereas in frequency selective fading the bandwidth of the signal is much larger than the coherence bandwidth, which is the inverse of the rms delay spread defined in (2.20) [9, pp.197-210].

The channel is called a fast fading channel when the coherence time of the channel is much smaller than the symbol period of the transmitted signal; that is the signal bandwidth is much lower than the inverse of the coherence time. The channel is a slow fading channel if the channel impulse response changes at much slower than the transmitted signal; that is the transmitted signal bandwidth is much larger than the inverse of the coherence time [9, pp.197-210]. A summary of the channel properties can be found in Table 2.6.

Flat Fading	**Frequency Selective Fading**
Coherence BW >> Signal Bandwidth $B_C >> B_S, T_S >> \sigma_\tau$	Coherence BW < Signal Bandwidth $B_C < B_S, T_S < \sigma_\tau$
Fast Fading	**Slow fading**
1/Coherence Time < Signal Bandwidth $B_S < B_D, T_S > T_C$	1/Coherence Time >> Signal Bandwidth $B_S >> B_D, T_S << T_C$

Table 2.6: Summary of channel properties and conditions

In Table 2.6, B_C, B_S are the coherence bandwidth and signal bandwidth and T_S, σ_τ signal period and multipath spread; B_D Doppler spread and T_C coherence time.

According to the coherence time and coherence bandwidth, Figure 2.7 depicts the characteristics of communication channels [9, pp.197-210].

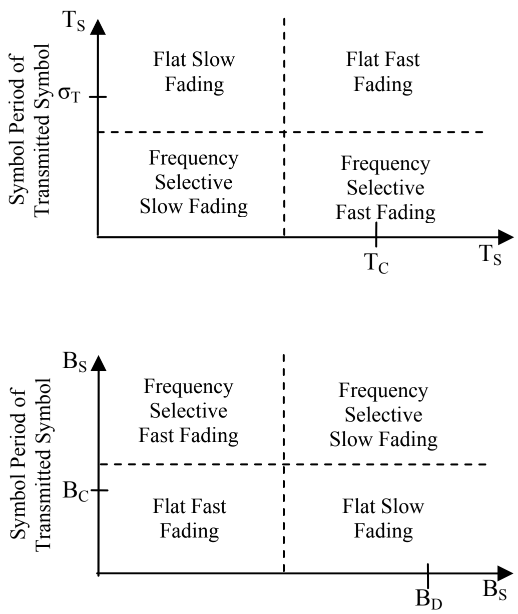


Figure 2.7: Characteristic of communication channel

The fading properties for underwater acoustic communication are much more severe than their counterparts in air. In a good communication channel, which is flat and slow fading, symbol length much larger than the multipath spread and bandwidth much larger than the Doppler spread can be used.

For the underwater communication channel the situation is hard to achieve. The reason is that multipath spread is 5.4 msec, which yields 3.70 Hz coherence bandwidth and the Doppler spread is 200 Hz at 300 kHz, which yields 5 msec coherence time. For a good communication channel the symbol period has to be larger than 5.4 msec and at the same time smaller than 5 msec. The condition is unachievable, therefore the communication system either needs sophisticated equalizers to achieve desirable data rate or a burst and wait communication scheme.

In our work, we chose a non-coherent communication scheme with better bandwidth efficiency. The non-coherent communication scheme is OFDM or COFDM. In OFDM or COFDM, the coherence time limitation, which is caused by Doppler spread is solved by choosing shorter OFDM pulses and the coherence bandwidth limitation, which is caused by multipath spread is solved by insertion of guard intervals. The multipath problem is even further solved with use of cyclic extension [11, pp.33-47], [13].

2.2.7 Noise

The communication reliability is affected by channel impairments as well as by the noise. The signal to noise ratio (SNR), determines the bit error rate (BER) of a digital communication system [15, pp.405-436]. There are two sources of noise in a digital communication system, one is the noise generated at the receiver amplifier, which is due to the input impedance of the receiver and the other is the noise in the channel.

2.2.7.1 Noise Due to Receiver Amplifier

The electrical noise generated at the receiver amplifier is due to the random voltage generated by random motion of electrons in the amplifier [22].

The wideband acoustic transducer has a finite impedance, due to this impedance electrical noise is generated. The noise power generated by acoustic transducer impedance is given in (2.22), where k is the Boltzman constant, T is the temperature in Kelvin, BW is the bandwidth and R is the impedance of the acoustic transducer [22].

$$\sqrt{4kTBWR} \tag{2.22}$$

When the transducer impedance is matched at the receiver amplifier input, the noise power flowing into the system is given (2.23), which is independent of the transducer impedance.

$$kTBW \tag{2.23}$$

The noise flow through the circuitry due to the receiver amplifier for a 1 msec pulse occupying 2 kHz bandwidth at 20 °C is -170.92 dBW.

2.2.7.2 Acoustic Noise

The underwater acoustic noise, within our frequency range of interest is created by the molecular agitation [1, pp.107-112], [16, pp.297-302]. The spectrum level of the noise is provided in [16, pp.297-302]. The N_0 is found as follows:

The noise level is provided in [1, pp.107-112], [16, pp.297-302], [23], [24]. The noise level due to molecular agitation increases with frequency with the rate of 6 dB/octave [16, pp.297-302]. The noise level due to molecular agitation is tabulated in Table 2.7.

@ 100kHz	28 dB re uPa^2/Hz
@ 200kHz	34 dB re uPa^2/Hz
@ 300kHz	40 dB re uPa^2/Hz

Table 2.7: Noise Level due to Molecular Agitation

We have the acoustic noise power; however, we need electrical noise power at the receiver. Electrical noise is found as follows:

$$P_{ElectricalNoise} = (P_{acu} BW)^2 \frac{A}{\rho c} = N_0 \times BW \tag{2.24}$$

(2.24) can be used to calculate the electrical noise power generated by the underwater acoustic noise. In (2.24), P_{acu} is the acoustic noise power at the receiver, BW is bandwidth in Hz, A is water contact area of the transducer in m^2, ρ is the density of water and c is the speed of acoustic waves in water. The contact area of the transducer is taken to be 1 cm^2 and c is taken to be 1500 m/sec.

In our noise calculation, we took P_{acu} of the 300 kHz frequency, because worst case situations shall lead us better understanding of the achievable data rate. From (2.24), N_0 is found to be -171.76 dB. The noise power can be found simply by NoxBW. For a 1 msec pulse, occupying 2 kHz bandwidth the acoustic noise power is -138.75 dBW.

2.2.7.3 The Total Noise

The two sources of noise are available to the circuitry flowing through the receiver. Even though they are both available, relatively the effect of acoustic noise power dominates over the receiver noise, therefore the receiver noise power can be ignored. The noise source in our simulations is only the acoustic noise, which is dominated in our frequency range interest by molecular agitation.

2.2.8 Overall Design Criteria Due to All Channel Properties

The underwater acoustic communication system design shall be based on several parameters. The design requirements are data rate, bit error rate (BER), frame error rate (FER), battery life and multi-user capability.

In order to achieve the requirements, OFDM/COFDM parameters has to be chosen such that desirable data with certain reliability and sufficient battery life is achieved.

Chapter 3

Underwater Acoustic System Needs and Architecture

The underwater acoustic communication system shall be designed for SCUBA diving purposes at first approach; however in later work the system shall be designed for other underwater applications, such as underwater acoustic networks, remote control operations, environment monitoring.

Since the first approach for the system design is for SCUBA divers, the system shall be designed to operate in shallow water, which does not exceed more than 100 m and short range, which shall not exceed more than 100 m. The system shall be a multi-user system, that is more than one user can occupy the channel at the same time.

The system shall be a spread spectrum system, operating between 100 kHz and 300 kHz. The spread spectrum technique shall be OFDM/COFDM.

3.1 Underwater Acoustic System Layered Architecture

The underwater communication shall have a layer based architecture. The system shall have application layer, which provides the information data, network layer, which shall route the packets from the source to the destination, link layer, which shall do error control and medium access coordination, physical layer, which shall prepare the digital data for transmission and a wide band acoustic transducer, which shall convert the electrical signals to acoustical signals [5], [14, pp.49-57]. The basic underwater communication system architecture is depicted in Figure 1.1.

In this work, we mainly focused on the physical layer to obtain the desirable data rate. While studying the physical layer, since the system shall have multi-user capability, application layer and data-link layer is taken into account. The application layer is studied in order to gain insight about the capacity of the system, while the data link layer is studied to have the end to end link reliability by having error coding and medium access control (MAC).

The underwater communication system in our work shall be discussed in a top-down design approach, starting from the acoustic transducer and continuing with the physical layer, data-link layer and application layer. The network layer is omitted because no research was done for this layer. However for the overall system design a suitable network protocol should be chosen to complete the communication protocol architecture.

3.1.1 Acoustic Transducer

The underwater communication is made possible by acoustic wave emitting and receiving acoustic transducers. The acoustic transducers are devices that convert electrical waves to acoustic waves [1, pp.137-172], [16, pp.59-84].

The underwater acoustic system shall use an omni directional wideband acoustic transducer, in order for the system to be spread spectrum. The acoustic transducer shall have 200 kHz bandwidth around 200 kHz, for transmission and reception. The transducers are made of ceramic material. The extra wide bandwidth of the transducer was achievable after the developments in ceramic materials. The wide bandwidth of the transducer is studied by a still continuing work and additional information can be found in [25].

3.1.2 Physical Layer

In our work, we propose that the underwater communication system shall be a spread spectrum system, having 200 kHz bandwidth around 200 kHz. For the spread spectrum communication technique, we chose orthogonal frequency division multiplexing (OFDM) or Coded Orthogonal Frequency Division Multiplexing (COFDM). We propose to obtain as much data rate as possible with suitable modulation and error coding schemes.

OFDM is a spread spectrum system that has great possibility of usage in the near future. The system has already been deployed and developed in Wi-Fi family 802.11a, digital video broadcasting (DVB), digital audio broadcasting (DAB), various digital subscriber lines (xDSL) [11, pp.20-24], [26], [27], [28], [29].

3.1.2.1 OFDM / COFDM

OFDM and COFDM is a special case of multi-carrier transmission in which instead of transmitting the entire data over a single carrier, the data is split up to lower-rate data and the lower-rate data is transmitted simultaneously over a number of narrowband sub-carriers using the entire spectrum at the same time. Since the transmission is done in parallel, the symbol duration can be relaxed and it can be longer than single carrier transmission system, this in turn provides less time dispersion due to multipath. The main reason OFDM is used is for its robustness to frequency selective fading, due to multipath propagation. In single carrier narrowband transmission system, frequency fading affects the entire narrow band, however in OFDM only some part of the spectrum is affected from fading. The frequency selective fading is overcome with coding and equalization. For a single carrier narrowband system complex time domain equalizers are need however, for OFDM simple frequency domain equalizers are sufficient. The fade affected OFDM symbols are recovered by using suitable error coding techniques [11, pp.20-24], [26], [30], [31], [32], [33], [34].

Usually OFDM systems rely on the error correcting codes and interleaving to overcome frequency selective fading. OFDM, which is used in conjunction with channel coding, is known as Coded OFDM (COFDM) [26], [27].

OFDM can be seen as a special case of frequency division multiplexing (FDM), where the transmission is done over non-overlapping bands, whereas in OFDM the transmission is done over overlapping bands. By using overlapping channels in OFDM the bandwidth efficiency is increased, because the need for guard bands in FDM is avoided [11, pp.20-24], [26]. In Figure 3.1, the difference of OFDM and FDM and the bandwidth efficiency of OFDM is depicted.

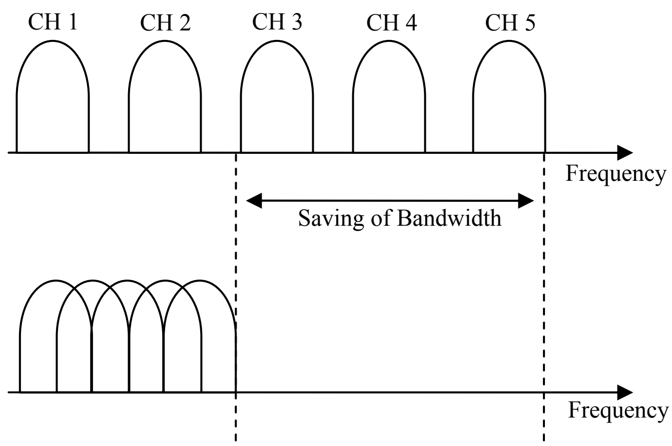


Figure 3.1: Comparison of FDM and OFDM.

OFDM technique was made feasible after the developments in very large-scale integrated circuit (VLSI) technology. The generation and degeneration of OFDM signal relies on the Fast Fourier Transform (FFT) and inverse FFT (IFFT) algorithms. The orthogonal sub-carriers are generated using IFFT algorithms, which eliminates the use of bank of filters and modulators. Likewise, for demodulation of the OFDM signal, the FFT algorithms are used.

Therefore, usually one IC is sufficient for the modulator and the demodulator of the OFDM communication systems [11, pp.33-47], [26].

The serial data stream is transmitted in parallel within overlapping channels in a single OFDM pulse. The overlapping channels are distinguished between each other by selecting the overlapping channels orthogonal to each other. The orthogonality is achieved in frequency domain, by separating each carrier 1/T (inverse of OFDM symbol duration) apart from each other [11, pp.33-47], [26], [32], [35]. The orthogonality is depicted in Figure 3.2.

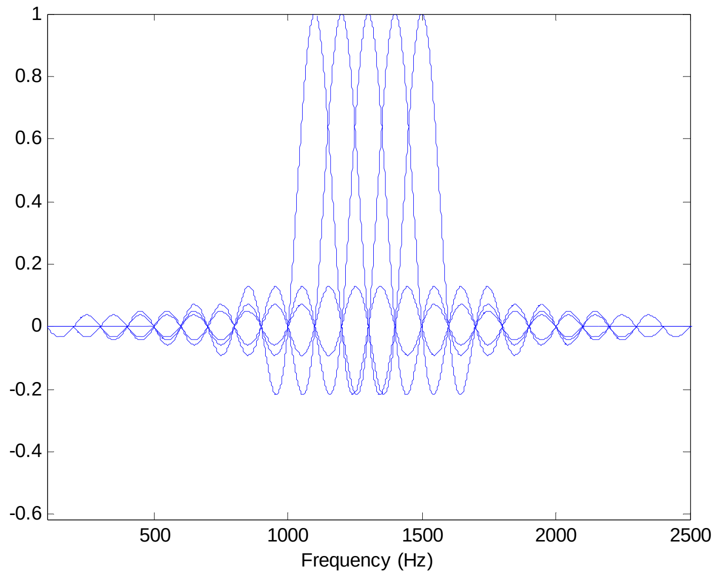


Figure 3.2: Spectra of carriers in OFDM symbol

The key advantages of OFDM are as follows [11, pp.20-24]:

- Robustness to multipath fading: The OFDM need less complexity to deal with multipath signals than a single carrier system with an equalizer. Using simple frequency domain equalizers and suitable error coding techniques, resistance to fading is achieved.

- Narrowband interference rejection: Since the system is a spread spectrum system, narrowband interference only affects certain part of the spectrum. The sub-carriers in the jammed spectrum are lost, however error coding techniques enable the lost sub-carriers to be recovered.

- Bandwidth efficiency: OFDM uses overlapping channels as compared to single frequency systems. The overlapping provides bandwidth efficiency as compared to FDM systems.

Some disadvantages and tackling problems of OFDM are:

- Sensitivity to frequency off-set and phase noise.
- Large peak to average power ratio, which creates problems for the high power amplifiers linearity.

The spread spectrum OFDM system can be analyzed through block diagrams. In an OFDM system the necessary blocks not only contain the physical layer, but also some part of the data link layer [11, pp.33-47]. Without the data link layer the performance and advantages of OFDM is decreased. The overall system diagram is depicted in the Figure 3.3.

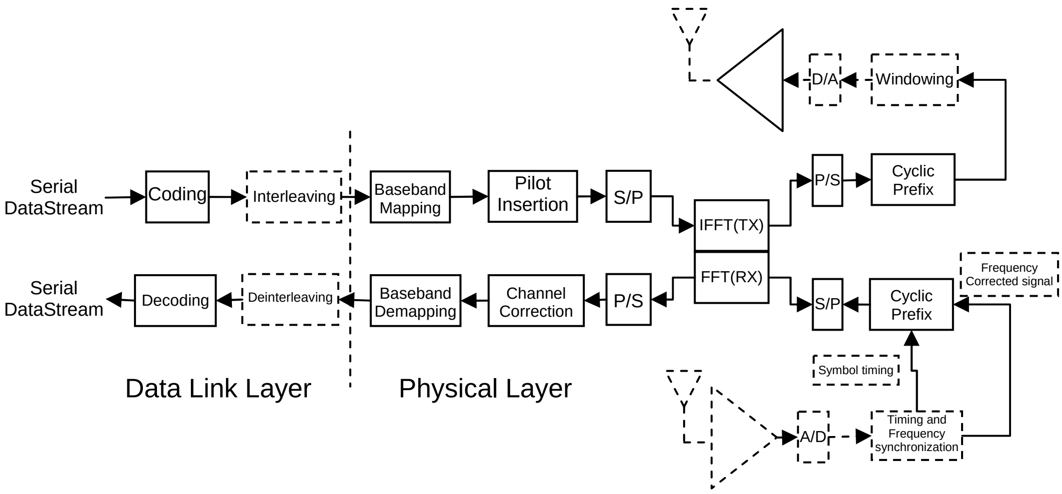


Figure 3.3: Block diagram of OFDM transceiver

Within our work we studied on solid covered blocks in order to find the suitable transmission parameters for underwater communication. The dashed blocks are assumed to be operating perfectly in our system.

3.1.2.1.1 OFDM System Architecture

Physical layer part of the OFDM system requires several blocks namely; generation and degeneration of sub-carriers; pilot tone insertion and equalization; cyclic prefix addition and removal; windowing and synchronization.

Generation and degeneration of Sub-carriers: An OFDM signal consists of several sub-carriers that are modulated orthogonally to each other. The OFDM symbol is mathematically constructed in time and frequency domain according to (3.1) and (3.2) [11, pp.33-47].

$$s(t) = \mathrm{Re}\left\{ \sum_{i=-\frac{N_S}{2}}^{\frac{N_S}{2}-1} d_{i+N_S/2} \exp\left(j2\pi \left(f_c - \frac{i+0.5}{T} \right)(t - t_s) \right) \right\}, t_s \le t \le t_s + T \tag{3.1}$$

$$s(t) = 0 \text{ ,t < t}_\text{s} \text{ and t > t}_\text{s} + \text{T}$$

$$s(t) = \sum_{i=-\frac{N_S}{2}}^{\frac{N_S}{2}-1} d_{i+N_S/2} \exp\left(j2\pi \frac{i}{T}(t - t_s) \right), t_s \le t \le t_s + T \tag{3.2}$$

$$s(t) = 0 \text{ ,t < t}_\text{s} \text{ and t > t}_\text{s} + \text{T}$$

In (3.1) and (3.2), T is the OFDM symbol duration, N_s is the total number of sub-carriers, d_i is mapped symbols of the data stream according to complex baseband modulation techniques and f_c is the center frequency.

The orthogonality can be seen either in frequency domain or in time domain. In time domain, it can be seen from the (3.1) that the sub-carriers are generated such that for each sub-carrier exactly an integer number of cycles is occupied within interval T. At the demodulator, in order to extract one sub-carrier the OFDM symbol is correlated with the intended sub-carrier, since there are integer multiple of cycles, the integration is zero for all sub-carriers other than the intended one [11, pp.33-47]. The orthogonality of the sub-carriers is depicted in (3.3) [11, pp.33-47].

$$\int_{t_s}^{t_s+T} \exp\left(-j2\pi\frac{j}{T}(t-t_s)\right)\sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s/2}\exp\left(j2\pi\frac{i}{T}(t-t_s)\right)dt$$
$$=\sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s/2}\int_{t_s}^{t_s+T}\exp\left(j2\pi\frac{i-j}{T}(t-t_s)\right)dt = d_{j+N_s/2}T \tag{3.3}$$

The other method to see the orthogonality is in frequency domain. The OFDM symbol has length of T seconds, each sub-carrier is separated from each other in frequency domain by the inverse of the symbol period (1/T). The frequency domain representation can be seen as dirac pulses at the sub-carriers frequencies and since the symbol is transmitted within rectangular pulses, the sinc(πfT) are located at each sub-carriers' frequency. By 1/T separation, each sub-carrier is positioned in frequency domain orthogonally such that at the maximum of each carriers other sub-carriers contribution is zero; that is at the maximum of sub-carrier other sub-carriers sinc(πfT)s cross zero [11, pp.33-47], [31]. The orthogonality is depicted in Figure 3.2. The orthogonality means that there is no ISI. The criterion for zero ISI is formulated in Nyquist Theorem as [15, pp.492-496]:

$$\sum_{m=-\infty}^{\infty} X\left(f+\frac{m}{T}\right)=T \tag{3.4}$$

(3.4) is the condition for zero ISI. In (3.4), X is the Fourier transform of each carrier and T is the pulse period.

Figure 3.2 depicts each orthogonal sub-carrier of OFDM pulse. When sub-carriers are applied to (3.4), it can be seen that the OFDM symbol fulfils the Nyquist Theorem; therefore the OFDM symbol is ISI free.

If complex baseband OFDM symbol in (3.2) is analyzed, the representation is nothing more than the inverse Fourier transform of N_S symbols. The time discrete equivalent is the inverse discrete Fourier transform as given in [11, pp.33-47], [36].

$$s(n) = \sum_{i=0}^{N_S - 1} d_i \exp\left(j2\pi \frac{in}{N} \right) \tag{3.5}$$

The OFDM symbol can be generated simply by using Inverse Discrete Fourier Transform (IDFT). Likewise the detection of OFDM symbol is done with DFT. In practice the generation and degeneration can be done with FFT and IFFT ICs, instead of using several filter banks, modulators and demodulators [11, pp.33-47].

Guard time and cyclic extension: The high rate data-stream is divided to lower rate data stream and the lower rate data is transmitted in parallel in a single OFDM symbol. In an OFDM symbol there are a total of N_s carriers. Since in OFDM, N_S symbols are transmitted in parallel at the same time, the OFDM symbol might be N_S times longer to achieve the same data rate.

The multipath propagation affects the sub-carriers severely because it destroys the orthogonality of the sub-carriers. In order to avoid the intercarrier interference (ICI); guard interval is introduced after the OFDM symbol, so that the multipath propagation fades out before the new OFDM symbol is transmitted. The guard interval might be left blank, however when the multipath signal interferes the main OFDM symbol, ICI can not be avoided. The ICI in the presence of multipath can not be avoided because, the multipath signal does not have integer multiple of cycles within the integration interval. In order to avoid ICI completely, in the guard time, the OFDM symbol is cyclically extended [11, pp.33-47], [26], [32], [35]. The cyclic extension is basically, adding the first part of the OFDM symbol at the end of the symbol. The cyclic extension is depicted in Figure 3.4.

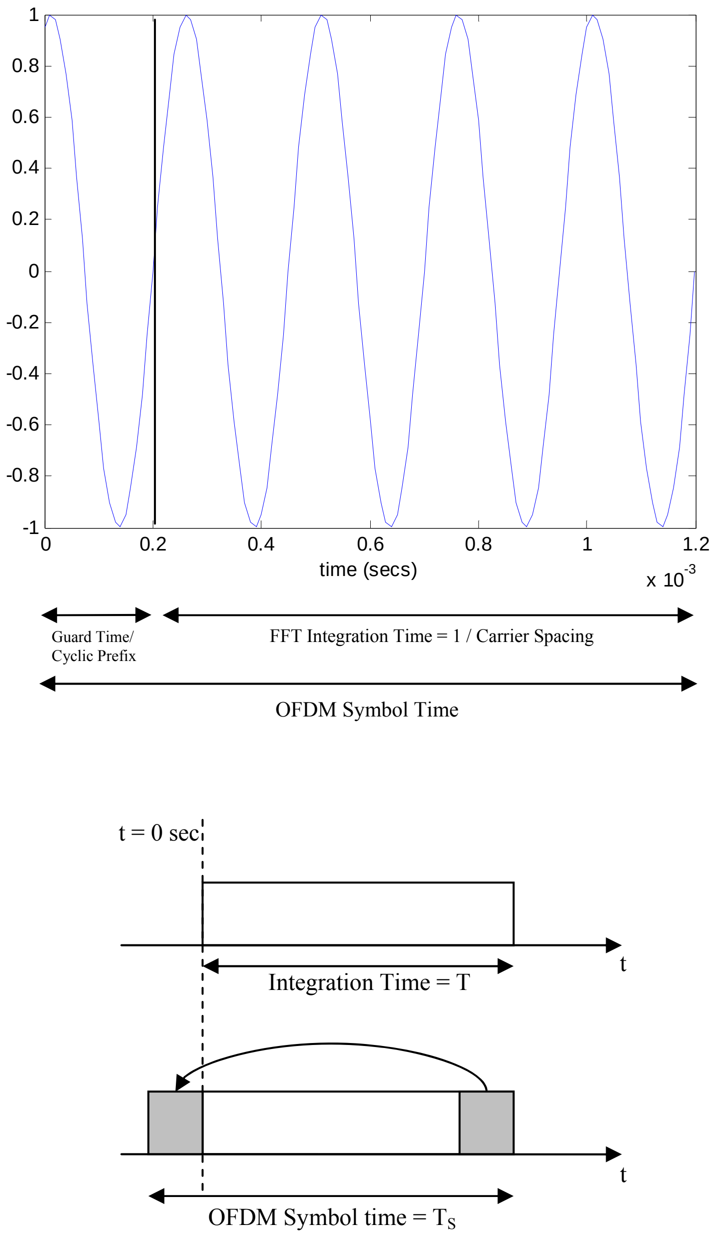


Figure 3.4 (a) Cyclically extended OFDM pulse (b) Cyclic Extension

The guard time and the cyclic extension should be selected such that within the guard time all the multipath propagation signals are attenuated sufficiently, in other words the guard time should be related to the maximum delay spread of the channel.

Pilot Tone Insertion and Equalization: The channel impairments, frequency selective fading due to multipath propagation and Doppler shift affects the OFDM symbols severely causing ICI. The Doppler shift affects the OFDM symbol detection because like multipath propagation, when Doppler shift happens within the integration period, the sub-carriers do not have integer multiple of cycles [11, pp.33-47] . The reason for non integer multiple of cycles is that the low and high end of the frequency spectrum faces different doppler shifts.

The channel impairments affects the communication, therefore in order to overcome the channel impairments, equalizers are employed. There are various kinds of equalization schemes, namely time domain and frequency domain. Time domain equalizers are more complex than frequency domain equalizers [33], [34]. For OFDM systems, frequency domain equalizers are preferred due to their less complexity and easier implementation than time domain equalizers [33], [34]. The equalizer parameters are obtained by insertion of pilot symbols in the OFDM frame. The pilot symbols can be either inserted using the whole OFDM frame or part of the OFDM frame. When pilots are inserted in part of the OFDM frame, the insertion has to be done carefully, in order to provide the channel frequency domain characteristics [33], [34].

In our work, equalization is done at the start of data exchange. We chose a less frequent equalization update scheme because it is assumed that diver position and speed shall not change frequently enough.

In this respect, at the start of the data exchange an OFDM symbol is transmitted with a known sequence with a known complex baseband representation. After demodulation of the OFDM symbol, we obtain the transmitted complex baseband sequence that is affected from multipath, Doppler and noise. The ratio of the received complex baseband sequence to the transmitted complex baseband sequence can be considered as the frequency response of the channel. This ratio provides the frequency domain equalizer parameters. The frequency response of the underwater acoustic communication channel is given in (3.6).

$$s_{rx,dop}(t) = \mathrm{Re}\left\{ \sum_{i=-\frac{N_S}{2}}^{\frac{N_S}{2}-1} d_{i+N_S/2} \exp\left(j2\pi \left(f_c \mp \Delta f - \frac{i+0.5}{T} \right)(t - t_s) \right) \right\}, t_s \le t \le t_s + T$$

$$H_{tx} = \sum_{i=-\frac{N_S}{2}}^{\frac{N_S}{2}-1} d(TX)_{i+N_s/2}$$

$$H_{rx} = \sum_{i=-\frac{N_S}{2}}^{\frac{N_S}{2}-1} d(RX)_i = H_t H_{prop} H_{multi} + AWGN \tag{3.6}$$

$$H_{chan} = \frac{H_{rx}}{H_{tx}}$$

In (3.6), Δf is the Doppler shift that is a function of the transmission frequency. $s_{rx,dop}$ contains the effect of Doppler effect to each carrier, H_{tx} is the transmitted complex baseband sequence H_{rx} is the received complex baseband sequence and H_{chan} is the approximated mean frequency response equalizer parameters.

After the equalizer parameters are obtained, the received complex baseband sequences are divided to channel frequency response to obtain the equalized received complex baseband sequences.

Using the equalizer, the channel effects are equalized in order to obtain the corrected transmitted sequence. This statement is completely true in situation where there is no Doppler shift. The multipath propagation and the Doppler shift causes ICI. The ICI, due to frequency selective fading is overcome by the cyclic extension; however the ICI due to Doppler shift can not be corrected. The multipath propagation causes each sub-carrier to shift only its phase and amplitude, however since cyclic extension is used the orthogonality is still maintained. The multipath effect is depicted in (3.7) for a single sub-carrier.

$$s_{1,1} = d_1 \exp\left(j\frac{2\pi}{T}t \right),\ s_{1,2} = d_1 \exp\left(j\frac{2\pi}{T}(t+\tau) \right)a$$

$$s_1 = s_{1,1} + s_{1,2} = d_1 \exp\left(j\frac{2\pi}{T}t \right) + d_1 \exp\left(j\frac{2\pi}{T}(t+\tau) \right)a \qquad (3.7)$$

$$s_1 = d_1 \exp\left(j\frac{2\pi}{T}t \right)\left(1 + \exp\left(j\frac{2\pi}{T}\tau \right)a \right)$$

In (3.7), multipath propagation for a single carrier is given. For the example, cyclic prefix maintains the orthogonality and there is no Doppler shift affecting the signal. It can be understood from the (3.7), that the effect of the multipath is to add phase shift and change amplitude. For instance for a=1 and for $\tau = \pi + k2\pi$, where k=0,1,2,3…the output is 0 that is the sub-carrier is completely in deep fade and for $\tau = k2\pi$ where k=1,2,3… the output is $2d_1$ that is the sub-carriers amplitude is doubled. The former case is known as *destructive interference* and the latter case is known as *constructive interference*.

For the Doppler shift, the orthogonality of the sub-carriers are lost, due to non integer multiple of cycles occurring within the integration period.

Since Doppler shift destroys the orthogonality and creates ICI, the obtained frequency response by (3.6), can not equalize the channel precisely, leaving certain level of error.

Windowing: In our work, spectral occupancy is not taken into account however, transmitting rectangular pulses occupies unnecessary frequency spectrum. Therefore, time domain windowing is done in order to limit the used spectrum. The pulse is shaped within the windowing block. While the pulse is shaped, the Nyquist theorem should be taken into account because otherwise ICI shall affect the OFDM symbol detection. In order to fulfill the Nyquist criterion, several pulse shaping methods are being used; one of these methods is raised cosine filtering. Using a suitable raised cosine filtering the occupied frequency spectrum is limited.

3.1.2.1.2 Modulation, IQ mapping, Link Budget, Gray Coding

The prospected Underwater Communication system is a digital system. The digital data is subject to multipath propagation, Doppler shift, frequency and range dependent attenuation and AWGN in the underwater acoustic channel. The received bits have to have certain signal to noise ratio (SNR) in order to obtain desired bit error rate (BER). The required SNR at the receiver sets the transmitter output power parameters. The selection of parameters include range, frequency of transmission and modulation scheme.

In communication with OFDM method, the Link Budget (LB) is calculated such that required SNR is achieved for each sub-carrier. Since each sub-carrier is orthogonal to each other, the required SNR is the SNR of each sub-carrier.

Modulation and IQ mapping: For digital communication systems several baseband modulation schemes are available, namely, M-PSK, FSK, QAM. The baseband modulation scheme has to be selected such that the channel impairments' effect to the communication reliability is at minimum.

The data is mapped either to the phase or the amplitude or both. In underwater communication the suitable baseband modulation scheme is M-PSK. The reason PSK is chosen for the modulation but not any other amplitude mapping schemes is that the underwater communication channel has a frequency and range dependent frequency response as given in (2.3), Table 2.1 and depicted in Figure 2.2; therefore mapping on the amplitude might lead to high errors in the receiver. For this reason the baseband modulation is selected to be M-PSK.

In M-PSK modulation, the bits are grouped as symbols and the symbols are mapped on the in-phase and quadrature phase (IQ) components [9, pp.294-328]. The baseband mapping is represented by:

$$x_c(n) = \exp\left(j \frac{x(n)}{M/2} \pi \right) \tag{3.8}$$

In (3.8), x(n) is symbols calculated from the bit stream that is grouped according to the level of modulation, ie. 00, 01, 10, 11 as 0, 1, 2, 3 respectively. $x_c(n)$ is the baseband modulated stream and M is the level of modulation.

The symbols contain various numbers of bits according to the level of modulation. If the symbol is 1 or 0 then modulation is BPSK, if the symbol contains two bits then the modulation is QPSK, if the symbol contains 3 bits then the modulation is 8-PSK. The modulation level of M-PSK is given in M, where the number is either 2, 3, 4 for our simulations.

The mapping of the grouped bits are either placed regularly or coded to have better error rate. This mapping coding is called Gray coding. In Gray coding, the symbols are placed on the IQ plane such that each symbol that crosses the neighbor symbol region in IQ plane creates one bit error. Using Gray Coding better error rate is achieved. In our work, the source data is first Gray coded, then IQ mapped and modulated. The regular coding and gray coding is depicted in Figure 3.5.

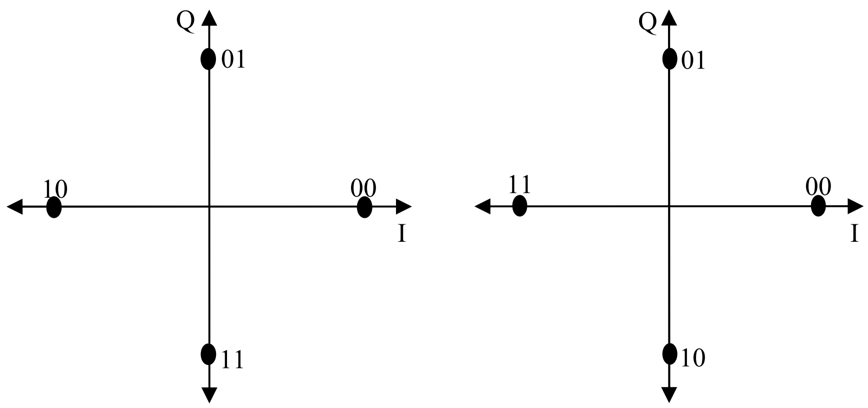


Figure 3.5: Regular and Gray Coding

The baseband signal is then transmitted after modulating to higher frequency. The passband and baseband conversion represented by [9, pp.294-328]:

$$s(t) = \mathrm{Re}\{Am(t)\exp(j2\pi f_c t)\}$$
$$s(t) = A[m_R(t)\cos(2\pi f_c t) - m_I(t)\sin(2\pi f_c t)] \tag{3.9}$$

In (3.9), s(t) is the transmitted signal, A is the amplitude, f_c is the center frequency and $m(t) = m_R(t) + jm_I(t)$ is the complex envelope representation of the modulated signal which is represented in general complex form [9, pp.294-328].

Link Budget: The link budget (LB) defines the required transmission power in order to achieve the desired SNR at the receiver at certain distance for required BER. The LB is a combination of parameters, such as required SNR for certain BER, path loss (PL), and noise power (NP).

$$LB = SNR_{required} - PL(@300kHz@dist.d) + NP \tag{3.10}$$

The SNR to achieve the required bit error rate (BER) is provided in formulas in [9, pp.294-328], [15, pp.405-436]. The required SNR is dependent on the modulation scheme. In our work, the modulation scheme is PSK and we design our system to achieve 1 10^{-3} BER. The required SNR is obtained from [9, pp.294-328], [15, pp.405-436] and is provided in Table 3.1 and Figure 3.6 for several modulation levels (M) and BER values.

$P_{e,\,BPSK}$	$Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$
$P_{e,\,QPSK}$	$Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$
$P_{e,\,M\text{-ary PSK}}$	$\approx 2Q\left(\sqrt{\frac{4E_s}{N_0}}\sin\left(\frac{\pi}{2M}\right)\right)$

Table 3.1: BER for BPSK, QPSK and M-PSK

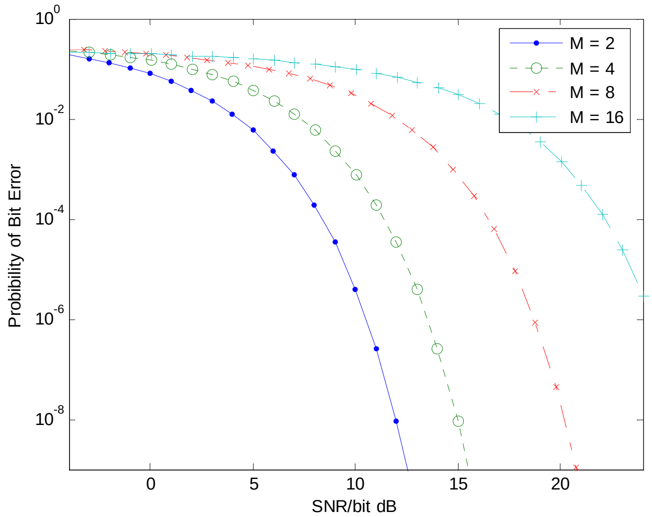


Figure 3.6: BER for M-PSK

The path loss is defined in Section 2.2.2 and given in (2.3) and Table 2.1. The PL is a function of both range and frequency. The required SNR has to be designed for the most attenuated part of the spectrum. In our work, the most attenuated part of the spectrum is 300 kHz, therefore the PL that is used for LB calculation has to be calculated at 300 kHz.

NP is the noise power available at the front end of the receiver. The NP as discussed in Section 2.2.7 is due to the acoustic noise in the frequency range of interest is generated by the molecular agitation. The NP in (3.10) is formulated as in (3.11), where BW is the bandwidth of each sub-carrier and T is the OFDM symbol period.

$$NP = N_0 + 10\log(BW)$$
$$\text{Where } BW = 2/T \tag{3.11}$$

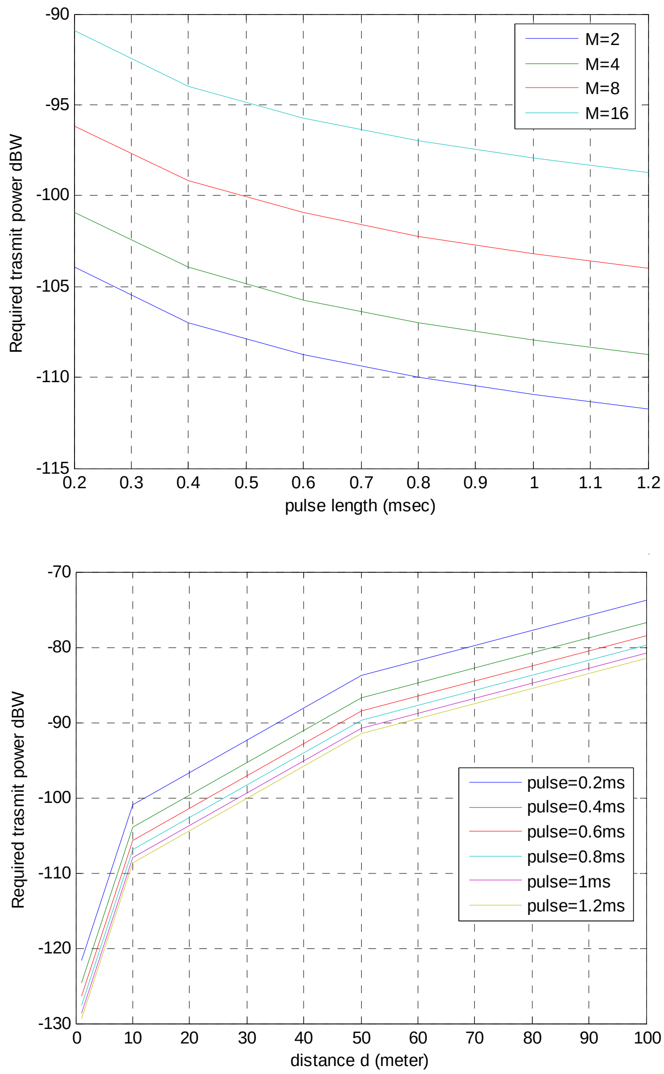


Figure 3.7: Required transmit power level to achieve the desired $1x10^{-3}$ BER for 300 kHzth symbol in OFDM pulse (a) with respect to pulse length at a distance of 10 m (b) with respect to distance for QPSK modulation.

Figure 3.7a shows how much transmission power has to be used for a symbol to obtain BER of $1x10^{-3}$ for the highest frequency component symbol at 10m range and Figure 3.7b shows the required transmit power for BER of $1x10^{-3}$ for symbol alphabet length of 4 (QPSK) at various distances and pulse lengths.

The parameters of LB are the sub-carrier BW, distance and SNR. All the parameters but distance is fixed prior to transmission. The distance parameter that affects the PL has to be gathered prior to transmission. The distance is obtained by the link layer MAC protocol, with the RTS/CTS packet exchange [4], [5].

The RTS, CTS packets are transmitted with a certain power level, and from the received power level the distance between the transmitter and the receiver is gathered. From the distance information, the PL is obtained and the LB is adjusted accordingly.

3.1.2.1.3 OFDM Design Parameters for Underwater Acoustic Communication System

The OFDM system parameters have to be designed such that desired performance and required data rate is achieved. There is a trade-off between the parameters. The choice starts with available bandwidth, bit rate, delay spread and Doppler spread. The delay spread and Doppler, which corresponds to coherence bandwidth and coherence time respectively creates limits on the symbol duration and level of modulation therefore achievable bit rate.

The channel impairment creates trade-off for the OFDM parameters. The delay spread and Doppler as stated in Section 2.2.4 and Section 2.2.5 set a limit on the pulse duration. In Section 2.2.6 it is stated that for an ISI free communication the pulse length has to be larger than the multipath spread and at the same time the bandwidth of the pulse has to be larger than the Doppler spread. The two conditions are conflicting conditions to be met for underwater communications. The multipath spread is our environment is found to be 5.4 msec, while the maximum Doppler shift is expected to be 200 Hz. For the stated condition the pulse length has to be larger 5.4 msec and bandwidth has to be greater than 200 Hz that is pulse length has to be smaller than 5 msec. This condition can not be met in underwater communication therefore special attention has to be given to the design of pulse length.

In our work, the condition on the delay spread is solved with the addition of the cyclic prefix and the condition on the Doppler spread is solved with the OFDM symbol duration.

While selecting the pulse duration, including the guard interval, the parameter has to depend on the delay spread. If the pulse duration is longer than the delay spread the narrowband sub-carriers experience independent flat fades. The delay spread creates limit on the guard time [13], [37]. In [11, pp.33-47] and [30], it is stated that the guard time should be about two to four times the delay spread. However, the condition is mostly suitable for air EM communication. For underwater communication, especially in our frequency range of interest the delayed signals are attenuated heavily, therefore in our work we design our OFDM systems' guard interval to be equal to the most expected delay spread. Multipath signal arriving later than 5.4 msec multipath arrival will vanish or attenuated sufficiently not to interfere with the next OFDM symbol.

After the guard time is set according to the delay spread of the channel the OFDM pulse length and therefore the total number of sub-carriers has to be fixed. In [11, pp.33-47] and [30], it is stated that the OFDM pulse length has to much larger than the guard time to minimize the SNR loss due to guard time and to have more bit rate. However the OFDM pulse duration cannot be arbitrarily large because larger the OFDM pulse length, the greater the implementation complexity and more sensitivity to phase noise and frequency offset. On the other hand, if the OFDM pulse length is larger than the inverse of the Doppler spread (larger than coherence time) the system is more sensitive to the Doppler shift. When coherence time is taken into account, the OFDM pulse length has to be smaller than 5 msec [11, pp.33-47] and [30].

In [13], a representative OFDM underwater communication system is presented. The presented system operates at 12 kHz having 8 kHz bandwidth. The multipath spread is taken to be 50 msec and the Doppler spread at 16 kHz is 0.64 Hz. This system can be said to be a highly reverberant, however the Doppler shift does not have considerable effect as our underwater communication system. For the delay spread and Doppler spread the system parameters are selected. The guard interval is taken to be equal to the delay spread of the channel. The OFDM pulse is taken to be 5 times the guard interval, 256 msec. The represented system uses QPSK modulation and manages 11.8 kbps. The rule stated in [11, pp.33-47] and [30] that symbol pulse should be 5 times the guard interval could be applied here due to low Doppler shifts. However, in our system environment the rule cannot be applied.

After the OFDM pulse length is set according to the Doppler spread the total number of sub-carriers and therefore baud rate can be calculated. The total number of sub-carriers in the allocated spectrum is found as in (3.12). In (3.12), BW is the total allocated bandwidth for the communication and T is the OFDM pulse length.

$$\#\text{ of sub-carriers} = N_s = \frac{BW}{1/T} = BWxT \tag{3.12}$$

(3.12) provides the total number of sub-carriers that can be transmitted within an OFDM pulse. The design of the pulse length must be done according to the Doppler spread. (3.12) is the baud rate that is symbol rate per OFDM pulse. The data is modulated according to several modulation schemes. The level of modulation that is the number of bits encoded within a symbol provides the number of bits that can be transmitted within an OFDM symbol. (3.13) provides the amount of bits contained in an OFDM symbol. In (3.13), M is the level of modulation that is the total number of symbols.

$$\text{Bits/OFDM symbol} = \frac{BW}{1/T}\log_2 M = BWxTx\log_2 M \tag{3.13}$$

In (3.13), the effect of level of modulation can be observed. The bits/OFDM symbol can be larger with increasing level of modulation. However, the level of modulation cannot be arbitrarily large, due to transmit power and ICI considerations. For the transmit power condition, the SNR has to be larger with larger level of modulation. For the ICI considerations, the concern is the effect of orthogonality loss with the Doppler spread. It is stated in Section 3.1.2.1.1 that when Doppler affects the communication the effect cannot be compensated completely using an frequency domain equalizer. For this reason, when the level of modulation is higher the level of ICI is much higher and the equalizer cannot compensate for the Doppler shift.

The achievable data is the combination design parameters over the guard interval, OFDM pulse length and the level of modulation. The raw data rate is calculated over the total bits contained in an OFDM symbol divided by the pulse length and guard interval as represented by (3.14):

$$\text{Raw data rate} = \frac{\frac{BW}{1/T}\log_2 M}{T+T_g} = \frac{BWT\log_2 M}{T+T_g} \tag{3.14}$$

In (3.14), T is the OFDM pulse length, T_g is the guard interval.

The raw data shall have payload along with data link layer headers and the error correcting codes that will be discussed in Section 3.1.3 .

3.1.2.1.4 Multi-user OFDM

The underwater acoustic communication system in our work is intended to be designed for multi-user systems, such as for a group of SCUBA divers. For SCUBA diving activities, more than one diver is present in underwater and the communication system should allow many users to communicate with each other at the same time.

In communication using OFDM method, the transmission is done using the entire spectrum. However, the available data rate is more than one user need for the communication. As it will be discussed in Section 3.1.5 , a diver shall require on the average 5 kbps data rate for voice communication. Using the entire allocated spectrum, excessive data rate can be achieved; therefore the overall data rate should be distributed between users, to have a multi-user system.

The multi-user communication in OFDM is discussed in [38]. In an OFDM symbol, there are N_s number of sub-carriers. When all N_s sub-carrier is used at the same time, excessive data is achieved. However, if N_s sub-carriers are distributed to users such that each user shall use certain number of sub-carriers for transmission then multi-user communication is achieved. The multi-user communication obtained by this method creates multiple access to the shared medium. The multiple access technique obtained from OFDM is called Orthogonal Frequency Division Multiple Access (OFDMA) [33], [38].

The distribution of sub-carriers are done in several ways, one of these ways is grouping as discussed in [38]. By grouping the sub-carriers to each user, each user can independently transmit data from the other users. However, due to multipath fading the grouping must be done over the entire spectrum. By grouping using the whole spectrum, possible faded carriers are distributed over the entire spectrum.

The grouped carriers might also be overlapping, so that there is a certain probability of some sub-carriers to collide with each other. However, since the OFDM system uses FEC, the collided carriers are corrected.

The use of multi-user OFDM, demands MAC. The MAC protocol for the multi-user OFDM has the duty of assigning sub-carriers to users and commanding the transmit and receive of the grouped carriers.

3.1.3 Data Link Layer

The major function of the data link layer is to packetize the data. Also in the link layer, error coding is done to achieve desired reliability and MAC is done to coordinate the access of each user to the shared medium [4], [5], [14, pp.419-447].

3.1.3.1 Forward Error Correction (FEC)

The error correction codes are used to correct the corrupted data due to channel impairments. Upon all error correcting codes, namely; block codes, convolutional codes, turbo codes, we chose block codes, specifically Reed-Solomon (RS) block codes for error correction in our system.

Block codes are Forward Error Correction (FEC) codes that enable the detection and correction of corrupted data without requiring any retransmission [9, pp.394-412]. In block codes, parity bits are added to the end of the packet to make *codewords* or *code blocks.* In a block encoder, k information bits are encoded into n code bits. A total of n–k redundant bits are added to k information bits in order to correct certain amount of bits in error. The reed-solomon block code is referred as RS(n,k) code [9, pp.394-412], [39], [40, pp.102-103].

In OFDM spread spectrum modulation system, due to multipath propagation, the sub-carriers are affected in bursts. In our work, we chose reed-solomon (RS) codes because of the codes ability to correct burst of errors [9, p.400], [39], [40, pp.103-106], [41], [42].

Reed-Solomon codes are non-binary codes, which can be capable of correcting errors appearing in bursts. The block length of these codes is $n=2^m-1$, which can be extended to 2^m or 2^m+1, where m is the symbol length that is most commonly 8, which is 1 byte. The number of parity symbols that must be used to correct e symbol errors is $n-k=2e$ [9, p.400], [39], [40, pp.103-106], [41]. For instance, in computer-based systems 1 byte, 8 bits can be taken as symbol length. The code length is in this case $n=2^8-1=255$ and in order to correct 16 symbols (16 bytes) 32 of 255 symbols (bytes) have to be parity symbols. In this case, within the code only 255–32 =223 symbols (bytes) contain payload. The code is denoted as RS(255,223).

The underwater communication system requires FEC because the data to be sent is compressed, coded. Since the data is coded with certain voice coding algorithms, any bit error in the packet would require the packets to be retransmitted or dropped. Retransmission, as will be discussed in the following section reduces the data rate because the propagation times underwater are high. Dropping a packet means that the communication cannot be done without interruption.

The FEC rate should be chosen such that neither any excessive redundancy is added nor packets are lost due to excessive errors in the packets. The criterion taken for the FEC rate is the frame error rate (FER); that is the rate of frames (OFDM pulses) that are dropped due to error detection in the frames. When errors are detected in the frames the frame is dropped. The rate is chosen to be 1% over the all transmitted frames. The percent is also the FER for GSM, mobile telephone networking system [43]. Dropping 1% of the transmitted frames due to error shall not create any considerable interruption in the communication.

In order to determine the required redundancy for the FEC, excessive simulations are performed. Over the simulation interval, numbers of packets containing error are collected, along with the number of errors in the packets. The collected data is then examined in a histogram according to how many errors are detected in the packets. Over the histogram 1% of the packets is left to have packet dropping, the others are corrected by using the FEC algorithm. The amount of redundancy is chosen to have the 1% of the packets to the dropped.

3.1.3.2 Medium Access Control (MAC)

MAC coordinates the access of users' transmission to the shared medium, in order to avoid collisions and avoid waste of available bandwidth [4], [5], [14, pp.419-447], [44].

In underwater communication system, the access to the shared medium is coordinated by the MAC layer protocol that is located in the link layer. In our work, the underwater communication system took its roots from the already developed and deployed air wireless Ethernet protocol, Wi-Fi family. However, the air protocol has to be modified to accommodate the high propagation times.

In [4] and [5], collision sense multiple access/collusion avoidance (CSMA/CA) based multiple access with collision avoidance (MACA) and MACAW are discussed for underwater acoustic communication and proven to provide reliable, collision free communication. The protocol also solves the *hidden* and *exposed* node problem [4], [5]. By using the RTS/CTS signaling channel properties can be acquired, distance between the transmitter and the receiver can be gathered, power control can be done and channel parameters can be adjusted [4], [5]. The operational SEAWEB acoustic network uses MACA protocol, RTS/CTS signaling for the MAC layer [45]. The details of MACA protocol, RTS/CTS signaling and *hidden* and *exposed* node problem and its solution are given in APPENDIX B.

MACA protocol is far from an efficient MAC protocol for underwater communication in terms achievable data rate due to long propagation times. In [46], it is stated that for certain level of throughput MACA protocol is not suitable for underwater communications, due to long waiting times between the RTS/CTS exchange. CSMA media access control is highly specialized to produce high throughput when packet transmission time is 100 times bigger than the propagation time [46]. In [12], it is stated that propagation delay in underwater acoustic communications is a critical problem. The discussion of the long propagation times and the suitability of MACA protocol can be done over defined rations, namely packet duration and flight time.

$$\text{Packet Duration} = \text{Packet Length / Data rate} \tag{3.15}$$

$$\text{Flight Time} = \text{Distance / Speed of Waves} \tag{3.16}$$

The packet duration, given in (3.15), is defined as the time it takes for a packet to transmit when the propagation delay is neglected; that may also be seen as the time it takes between departures the first bit of the packet and the last bit of the packet. The flight time given in (3.16) is the time it takes for the packet it to reach the destination; that is the time it takes for the first bit of the packet to reach the destination.

A comparison of the packet duration and the flight time in underwater and air shall reveal the suitability of MACA protocol for air communications inconveniency for high-speed underwater communications. For the discussion, the packet length and flight time is done with the following parameters for several distances: packet length 1 kbits, bit rate 50 kbps, the speed of acoustic waves underwater 1500 m/s, the speed of electromagnetic waves 3 10^8 m/s.

Flight Time			
Distance	10 m	50 m	100 m
Air (EM)	3.3 10^{-8} sec	1.66 10^{-7} sec	3.33 10^{-7} sec
Underwater (Acoustic)	6.7 10^{-3} sec	33.3 10^{-3} sec	66.7 10^{-3} sec

Packet Duration	
Air (EM)	20 10^{-3} sec
Underwater (Acoustic)	

Packet Duration / Flight Time			
Distance	10 m	50 m	100 m
Air (EM)	1.65 10^{-6}	8.3 10^{-6}	1.66 10^{-5}
Underwater (Acoustic)	**0.33**	**1.66**	**3.33**

Table 3.2: Ratio of packet duration to flight time

In Table 3.2, the ratio of packet duration to flight time is calculated for distances of 10 m, 50 m and 100 m. It can be stated that the higher the ratio the less suitability of MACA protocol for the communication channel to achieve high data rate.

The MACA protocol as used in Wi-Fi wireless Ethernet technology is a powerful MAC algorithm that overcomes the *hidden* and *exposed* node problem, provides collision free communication, however for the underwater acoustic communication channel the protocol is inconvenient to achieve high data rates due to long waiting periods, even though it provides reliable, collision free communication.

The MACA would restrict the available data bandwidth; however modification of the protocol would bring good advantages. In [4], [5] and [45] it is stated that RTS/CTS packet exchange solves the *hidden* and *exposed* node problem, within the exchange, the channel properties, the distance between the transmitter and the receiver can be gathered, the required power level are obtained and adjustments to the equalizer parameters can be done. For this reason, instead of RTS/CTS exchange for every other message, the protocol shall be modified to exchange RST/CTS packets during the link establishment and prior message transmission. During the link establishment the channel and equalizer parameter would be adjusted and the adjusted parameters would stay fixed for certain period of time. This way MACA protocol is used partially for equalizer and power adjustment, while still providing high data rate. The communication parameters shall be adjusted less frequency using RTS/CTS exchange such that the communication link and reliable communication is maintained.

3.1.4 Network Layer

In our work, we did not have detailed study over the network layer; however, we gained some information about the major underwater specific properties.

The underwater communication system shall be deployed in network based architecture. Since the underwater communication system shall be deployed freely, without any preparation, the network shall have a multi-hop peer-to-peer topology. By deploying a multi-hop network, the communication range is increased. The multi-hop, peer-to-peer networks are called *ad-hoc* networks. The routing in ad-hoc networking is done using specific network optimization criteria. The optimization criterion is based on several points, namely; minimum distance, minimum delay, minimum energy consumption, least congestion. The routing algorithm shall be considered according to the needs of the underwater communication system and underwater acoustic communication properties [4], [5], [14, pp.293-317].

Another advantage of deploying ad-hoc networks besides the range increase is that the network lifetime is longer than single hop networks. A discussion of the advantages and disadvantages of the ad-hoc networking is discussed in APPENDIX B.

3.1.5 Application Layer

In the application layer, the information data is multiplexed for transmission and for reception the received data is demultiplexed. The multiplexing/demultiplexing is done because there are various types of data to be transmitted along with voice data. The information data can be classified into two, as low bit rate and high bit rate. The low bit rate data contains messaging, quick messaging, environmental information, diver information, vital diver information, whereas the high bit rate data contains voice. A basic diagram of the function of the application layer is depicted in Figure 3.8.

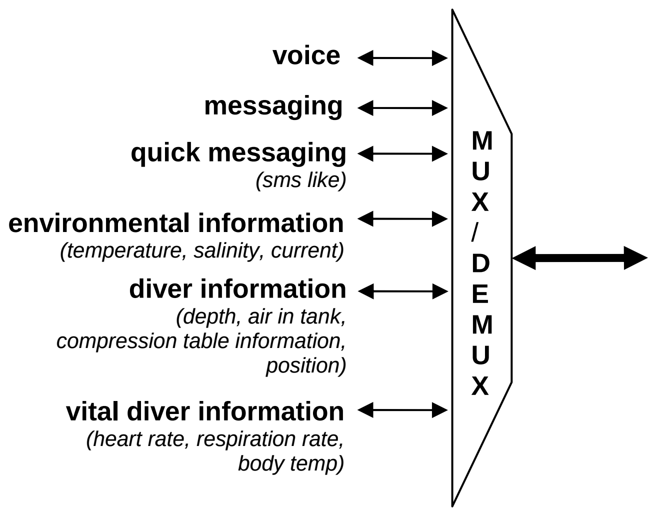


Figure 3.8: Architecture of the application layer

3.1.5.1 Low Bit Rate Data

The low bit rate data can be classified as the data that does not have excessive information and does not have to be exchanged frequently. The low bit rate information data contains *quick messages*, which are sent with only a push button like *"I'm running out of air"* or *"I'm cold"*; *messages*, which is *SMS* type messaging done between the divers, *environmental information*, which is the water temperature, salinity, water current information exchanged either between the divers or the surface station, *diver information*, which is the diver depth, left air in the tank, compression table information, position information exchanged between either with the divers or the surface station and also within the *diver information*, *vital diver information*, which is the diver heart rate, respiration rate and body temperature information exchanged between either divers or the surface station.

The low data rate information as compared to high data rate voice is not frequent and the information is not as complex or large either, therefore the required data rate for this information data is not high. The environmental monitoring does not have to be done frequently because the environment does not change a lot. The diver information does not have to be done frequently however, the vital information, left air in tank and compression table monitoring might have to be done more frequently due to safety reasons.

The required data rate for the low data rate information can be found simply by the sampling frequency, data length and bit resolution as in (3.17).

$$\text{Data rate (bps)} = \text{Sampling Frequency} \times \text{Data Length} \times \text{Bit Resolution} \tag{3.17}$$

The prospected data rate for the low data rate information, considering the safest diving conditions, is depicted in Table 3.3.

Information Type	Sampling Frequency	Bit Resolution	Data Length	Required Data Rate
Temp, Salinity, Water Current	30 sec	8 bit	3 bytes	48 bps
Depth, Air in tank, compression table info	10 sec	8 bit	4 bytes	192 bps
Position	10 sec	8 bit	3 bytes	144 bps
Heart rate, respiration rate, body temp	10 sec	8 bit	3 bytes	144 bps
Quick message	15 sec	8 bit	1 byte	32 bps
SMS message (160 characters)	60 sec	8 bit	160 bytes	1.25 kbps
Total				**1.75 kbps**

Table 3.3: The required data rate for low data rate information

The prospected data rate for the low data rate communication is no more than a few kbps.

3.1.5.2 High Data Rate Data, Voice Data

The high data rate can be classified by mainly voice data. The voice data rate is larger than the low data rate information, however since the available bandwidth underwater is limited, it cannot be excessively large. Since the available bandwidth underwater is limited, instead of transmitting the voice directly, the data is compressed with certain voice coding algorithm, in order to require less data rate. Even though voice coding results in less data rate requirement, the cost of coding is the reduction in voice quality.

In [2], it is given that the required data rate is on the order of several kbps using Linear Predictive Coding (LPC). Representative underwater acoustic phone systems studied in the literature are given in [47] and [48]. In [47], voice data is coded with LPC algorithm reducing the transmission rate to 2.4 kbps with error coding included. In [48], the speech signal is compressed to 5.45 kbps using Code Excited Linear Prediction (CELP) algorithm. The required data rate after source and channel coding is 8 kbps.

In our work, we shall take already deployed and successfully proven algorithms used in GSM and CDMA, mobile telephone network systems, as voice coding algorithms.

In GSM, mobile telephone network system, the voice is coded and compressed to around 13 kbps, using Residual Excited Linear Predictive coder (RELP), which is enhanced by including a LONG-term Predictor (LTP). The coder provides constant bit rate and provides 260 bits for each 20 msec blocks of speed [9, p.563][40, p.94].

In CDMA digital cellular standard (IS-95), unlike GSM the data rate changes depending on the voice activity and requirements in the network. The speech coder in IS-95 is the Qualcomm 9600 bps Code Excited Linear Predictive (QCELP) coder. The QCELP coder in IS-95 detects the voice activity and reduces the data rate to 1200 bps during the silent periods. The coder supports intermediate data rates of 2400, 4800 and 9600 bps [9, p. 567]. The IS-

95 also supports higher data rate services for Personal Communication System (PCS). In higher data rate services in IS-95, a variable rate speech coder, QCELP13 is used. QCELP13 is a modified version of QCLEP and the coder provides 14.4 kbps [9, p. 580].

The CDMA, IS-95 is an already established and developed mobile cellular network technology. The technology bring greater abilities to users over GSM. Since CDMA IS-95 technology is an already developed and proven system, using the already developed voice coder of IS-95 shall bring us promising results in terms of voice quality along with reduced data rate. In IS-95, the voice coder is a variable rata rate coder that has data rates from 1.2 kbps to 9.6 kbps, according to the voice activity, therefore the bit rate requirement in our underwater communication system that uses IS-95, QCELP voice coder, shall require at most 9.6 kbps data rate and on the average around 5 kbps data rate.

Chapter 4

Methods and Simulations

In order to choose the suitable OFDM parameters, computer aided simulation were performed. Even if there are communication tools devoted to digital communication and OFDM, a dedicated simulation tool to be used for underwater could not be found in the literature. The difficulty is that the underwater communication channel is more troublesome than air, having longer multipath delay spread, frequency and range dependent frequency response and relatively greater Doppler spread.

In order to simulate the OFDM communication technique and to choose the communication parameters for underwater acoustic channel, a dedicated and underwater specific simulation program is written in MATLAB. The simulation details, which will be explained below is for 1 msec OFDM pulse length, however the simulation program can incorporate with changes of variables other pulse lengths as well, providing greater simulation details.

The simulation incorporates 5 rays, line of sight, 2 one reflection from the surface or the sea floor and 2 double reflections. The simulation first simulates the direct path, taking account of the frequency and range dependent frequency response along with Doppler shift and then the multipath signals are simulated similarly way as direct path. The total signal received by the receiver is then demodulated to obtain the transmitted data stream. According to the received signal and the data stream, OFDM parameters are selected. A block diagram of the OFDM simulation and OFDM parameter selection procedure is depicted in Figure 4.1.

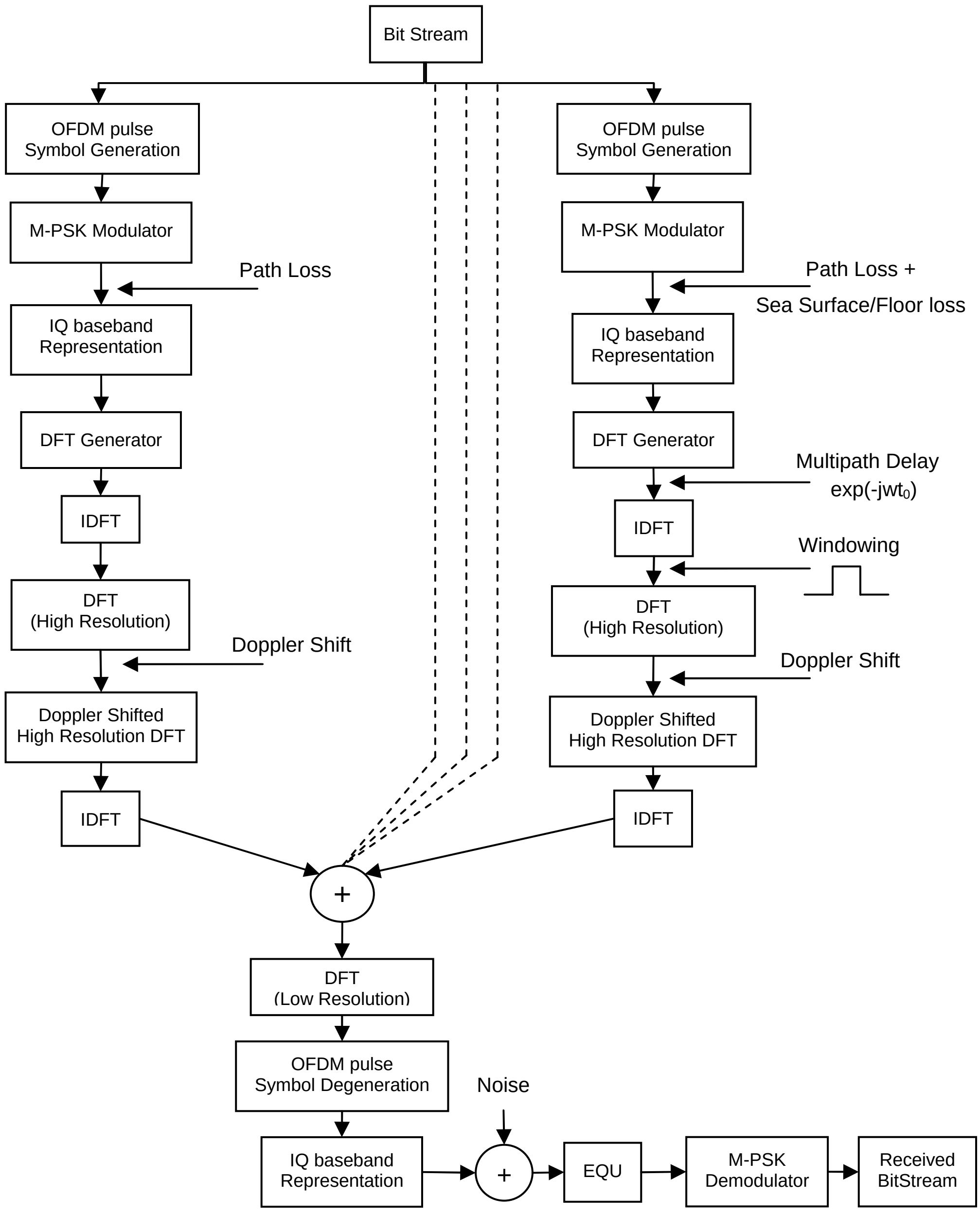


Figure 4.1: OFDM simulation procedure

4.1 Simulation of Direct path OFDM Signal

Some user application of the underwater communication system such as voice or telemetry data generates the data, bit stream. The bit stream shall consist either symbols or bits. The bit stream is grouped into OFDM pulse symbols, that is a function of the OFDM pulse length and the total frequency spectrum as given in (3.12). The grouped bitstream is either 1's and 0's or integers, designated by symbols, which carry more than one bit per symbol; that is an alphabet of symbols are used to assign bits.

The grouped bitstream is converted into complex baseband representation having in-phase and quadrature-phase (IQ) components to have points in the constellation plane. The modulation technique that is used to create the IQ components is M_{ary}-PSK where M is the number of symbols to be used.

As discussed in Section 3.1.2.1.1, baseband representation of the grouped bitstream provides the DFT of the OFDM pulse. This way the frequency domain representation of the OFDM pulse is obtained.

While generating the complex baseband representation of the OFDM symbol, channel attenuation, provided in Section 2.2.2 , is added, according to the frequency and the path the waves travel underwater. The pulse length is chosen 1 msec, leading to frequency difference between the carriers 1 kHz in the spectrum, therefore THE DFT length and sampling time, T_s is chosen such that frequency resolution is 1 kHz, so that each carrier is separated by 1 kHz. Since each carrier is separated by 1 kHz there a total of 200 symbols that can be transmitted in 1 msec period and within 200 kHz bandwidth.

In underwater channel, the Doppler shift is prospected to be as high as 200 Hz, therefore in order to simulate the Doppler shift we need much smaller resolution than 1 kHz. After the frequency domain representation of the OFDM symbol is created, inverse DFT is taken to obtain the time domain signal. The time domain signal is zero padded with 64 times the time signal length, providing a high resolution DFT of the time domain signals has 1/64 times more resolution than before, which is 15.642 Hz. With this resolution Doppler shift can be integrated to the simulation in a quantized manner.

The frequency domain representation of the time domain signal with higher frequency resolution is Doppler shifted to according to how much each frequency component should face Doppler shift. The measure of how much Doppler shift each frequency component should face is found by (2.14).

The frequency domain resolution after taking DFT of zero padded signal is 15.64 Hz, therefore the Doppler shift can not be integrated exactly, because we have a quantized frequency domain. Even if we have a quantized frequency domain, this resolution and application of Doppler shift provides us sufficient insight about how much the Doppler shift affects the communication.

In order to maintain the orthogonality in the multipath environment, as stated in Section 3.1.2.1.1, cyclic prefix is added at the end of the OFDM symbol. The addition of cyclic prefix in our simulations is not physical rather conceptional. For the direct path signal no addition is made, however the addition of the cyclic prefix is more apparent for the multipath signals. The cyclic prefix addition shall be explained more detailed for the multipath signals.

After the Doppler shift is applied to the frequency domain, another inverse DFT is taken to obtain time domain signal. In order to obtain the IQ components back, this time a low resolution DFT is taken to obtain a 1 kHz resolution frequency domain representation of the Doppler shifted signal. This obtained frequency domain representation of the signal gives the complex baseband representation of the bit stream that is transmitted, attenuated in the channel and affected by Doppler shift.

After the IQ components at the receiver are obtained, underwater acoustic noise is added as AWGN. The spectral density of the noise is provided in Section 2.2.7.2. The addition of AWGN noise does not only include the noise, but also the required transmission power to achieve required BER at the specific distance as well. The distance between the transmitter and the receiver can be obtained by using RTS/CTS packet exchange. Using the distance between the transmitter and the receiver required transmission power can be found. The required transmission power and the acoustic noise at the receiver dictates the signal to noise ratio (SNR). SNR is added in the noise addition function as provided in (3.10). The addition of AWGN underwater acoustic noise degrades the communication. After this stage, PSK demodulation is done to recover the transmitted symbols.

4.2 Simulation of Multipath OFDM Signals

It was stated earlier that multiple echoes reach the receiver. Multipath signals combining at the receiver destroys the orthogonality in OFDM symbol, however use of cyclic extension preserves the orthogonality. With the use of cyclic extension the effect of multipath signals creates only frequency selective fading, which is easily overcame by use of simple frequency domain equalizers.

In order to simulate the multipath effect on the system, the same procedure with the direct OFDM pulse is followed however this time; the path loss is altered with extra distance the waves have to travel and also with the scattering loss from the surface or sea floor. The reflection from the surface also adds a phase shift of 180 degrees.

Late arrival of the OFDM pulse and the cyclic extension can easily be added by including phase shift to the frequency domain representation of the OFDM pulse according to the guard interval, which is determined by most likely delay spread values of the underwater environment as discussed in Section 2.2.5 . Like direct path signal, path loss and surface or sea floor loss is included in the complex baseband representation of the bit stream. After the frequency domain representation of the OFDM symbol is obtained the cyclic prefix is applied by adding phase to each frequency component in the frequency domain. After phase is added, inverse DFT is taken to obtain the time domain signal. The time signal is then, multiplied with a time window according to the arriving multipath. The time window multiplication is applied because there might be multipath signals arriving after the guard interval. The rest of the procedure is the same with the direct path signals.

The addition of multipath signals is done at the high resolution time domain part. After the time domain addition of the direct and multipath signals, the low resolution frequency domain IQ conversion is done and then the AWGN noise is added. After the noise is added, the PSK demodulation takes place to recover the transmitted symbols.

4.3 Gray Coding

In order to achieve better BER, Gray coding is done in communication systems, as discussed in Section 3.1.2.1.2. In our underwater acoustic communication system simulation, gray coding is applied. The block diagram of gray coding application to our simulation is depicted in Figure 4.2.

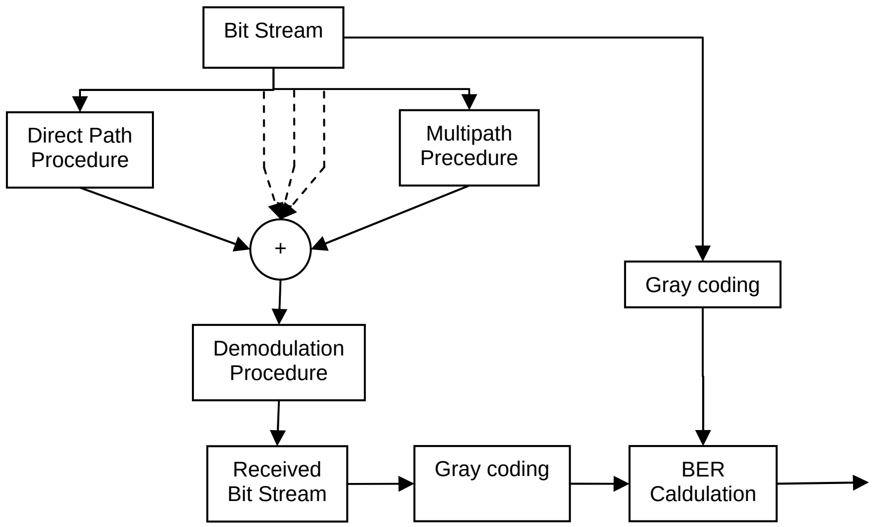


Figure 4.2: Gray coding and BER calculation simulation procedure

The application of gray coding is done not physically by conceptionally. The uncoded transmitted and uncoded received bitstreams are gray coded and compared with each other to obtain the gray coded BER. This way the gray coded BER and data rate is achieved.

4.4 Equalization Parameter Selection

The equalization procedure is discussed in Section 3.1.2.1.1. In our simulations, the equalization is done by dividing received complex baseband data to the frequency domain equalizer parameters. The block diagram of obtaining the frequency domain equalizer parameters is depicted in Figure 4.3.

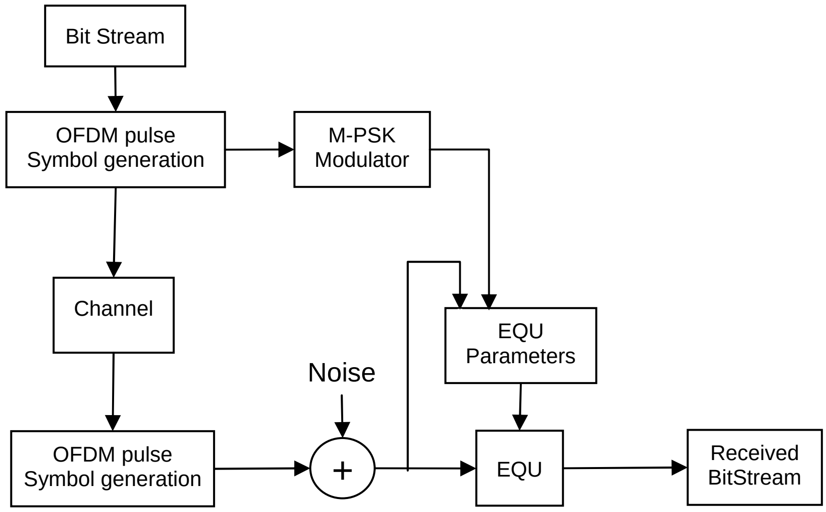


Figure 4.3: Equalization parameter selection and Equalization procedure

The frequency domain equalizer parameters are obtained by RTS/CTS packet exchange. Before transmission of the bitstream a known bit sequence is transmitted with higher transmission power. At the receiver the received complex baseband data is divided by the known complex baseband data. This way the frequency domain equalizer parameters are obtained. After the equalizer parameters are obtained, the latter received data is equalized with parameters until the next RTS/CTS packet exchange.

4.5 Reed-Solomon Coding Parameter Selection

Reed-Solomon coding is applied to the underwater acoustic communication simulation. As discussed in Section 3.1.3.1, the RS parameters have to be selected in order to obtain the required FER. The addition of RS coding is not physical but conceptional. The block diagram of RS coding parameter selection is depicted in Figure 4.4.

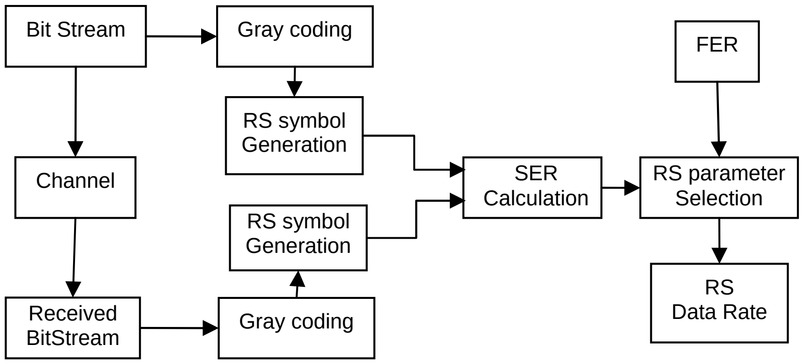


Figure 4.4: RS code parameter selection and RS coded data rate calculation procedure

The RS coding parameters are selected such that required FER is achieved. As discussed in Section 3.1.3.1, RS coding recovers symbols of length 8, therefore after the transmitted bitstream is passed over the channel and demodulated, the demodulated bitstream is grouped into 8 bits of symbols. For example for modulation level of 4 (M=4), 4 symbols are grouped into an 8 bit symbol. After this grouping, symbol error rate (SER) of each OFDM pulse is calculated. The SER shows a histogram and by using the required FER the number of symbols to be recovered is found. The total redundancy to add in order to obtain the required FER is found from the histogram as depicted in Figure 4.5.

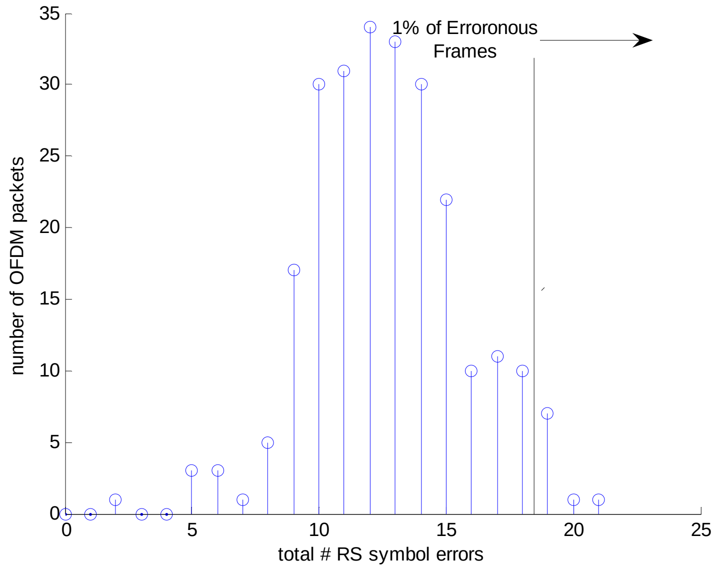


Figure 4.5: RS code parameter selection procedure

In Figure 4.5, an example of an histogram of number of RS symbol errors to number of OFDM symbols is given. For the example, 100.000 bits are used, for M=16 there are total of 25.000 symbols and for pulse period of 0.5 msec there are a total of 250 OFDM packets. Each OFDM packet contains 50 RS symbols. The FER is 1 % of packets, therefore 2.5 packets are assumed to be lossed or dropped due to corruption. For 1% FER, 19 RS symbols has to be recovered and RS code length has to be designed according to the total redundancy. In this particular example, the RS code is RS(50,12).

Chapter 5

Results and Discussions

In order to find the suitable OFDM communication parameters for the underwater acoustic communication system, simulations were performed; however investigation special cases shall provide how the communication performance is affected from the challenging underwater impairments, namely multipath, Doppler shift, frequency and range dependent frequency response and acoustic noise.

5.1 Special Cases Study of OFDM Simulation

The performance of the underwater communication system shall be investigated over how the complex baseband representation of the transmitted bit stream is affected from the channel impairments, how the equalizer recovers the impairments and how the FEC provide suitable correction of corrupted bits or symbols.

Before the performances are investigated, the performance metrics have to be defined:

- *Baseband complex representation:* The transmitted bits or more generally symbols are modulated with certain modulation scheme. In our simulations PSK modulation is done. As discussed in Section 3.1.2.1.2, the symbols are modulated into phase of the carrier. The baseband complex representation can be viewed in In-phase quadrature-phase (IQ) diagram. From the IQ diagram, the effect of channel impairments, multipath and Doppler shift can be observed.

- *Data rate and BER:* The data rate and BER is calculated from data bits or symbols that are correctly detected in the receiver.
- *Gray coded data rate and BER:* The data is gray coded. With gray coding the BER performance of the system is improved. The gray coded data rate and BER is calculated from data bits or symbols that are correctly detected in the receiver.
- *Gray coded trueput:* The underwater communication system as discussed in Section 3.1.3.1, does not tolerate errors in OFDM packets when there is no FEC; therefore the gray coded trueput is the data rate that includes only the OFDM packets are received without any bit or symbol error.
- *RS coded data rate:* The data bit stream has to be forward error coded (FEC) in order to tolerate corrupted bits and symbols. The calculation of RS coded data is discussed in Section 3.1.3.1.
- *Data / packet in RS coding:* With RS coding some part of the OFDM packets are used as a redundancy in order to recover the corrupted bits or symbols. The data / packet is the data part of the OFDM packet, leaving the redundancy.
- *Confidence Interval:* The BER rate and the data rate have certain statistics that in real life the same performance shall be observed. The confidence interval (CI) is an interval between two numbers, where there is a certain specified level of confidence that a population parameter lies. With the confidence interval, the BER and data rate shall have statistical confidence. In our simulations 95% confidence is taken for BER and data rate data.

The special cases shall depict the effect of multipath, Doppler spread and the underwater acoustic channel properties. The effect of multipath, Doppler spread and underwater acoustic channel properties shall easily be seen with noiseless case simulations, whereas noisy case simulation shall reveal the real communication performances.

5.1.1 Noiseless Simulations

For the noiseless simulations, underwater diver scenario of both diver being 1 m below the surface, being 1 m and 100 m apart; OFDM pulse length of 0.4 msec and 1 msec and modulation level of M=4 is used. For the noiseless case scenarios, sea surface and sea floor losses are chosen for the Sea-State-0 and porosity 0.2 to have 10dB and 15dB losses respectively. The chosen scenario has the least reflection attenuation from surface and floor, which would affect the communication most. For the simulations 100.000 bits/simulation is used to observe the effects of channel impairments. For the simulations the cyclic extension is used to help frequency domain equalizer, the length of the cyclic extension is 5.4 msec, which is the maximum expected delay spread as discussed in Section 2.2.5 .

- *Multipath Effect*

The effect of multipath as depicted in Section 3.1.2.1.1 is to change the phase and the amplitude of the carriers and create frequency selective fading. The underwater communication scenario and approximate frequency response are depicted in Figure 5.1. For the scenario, the delay spread is 0.13556 msec.

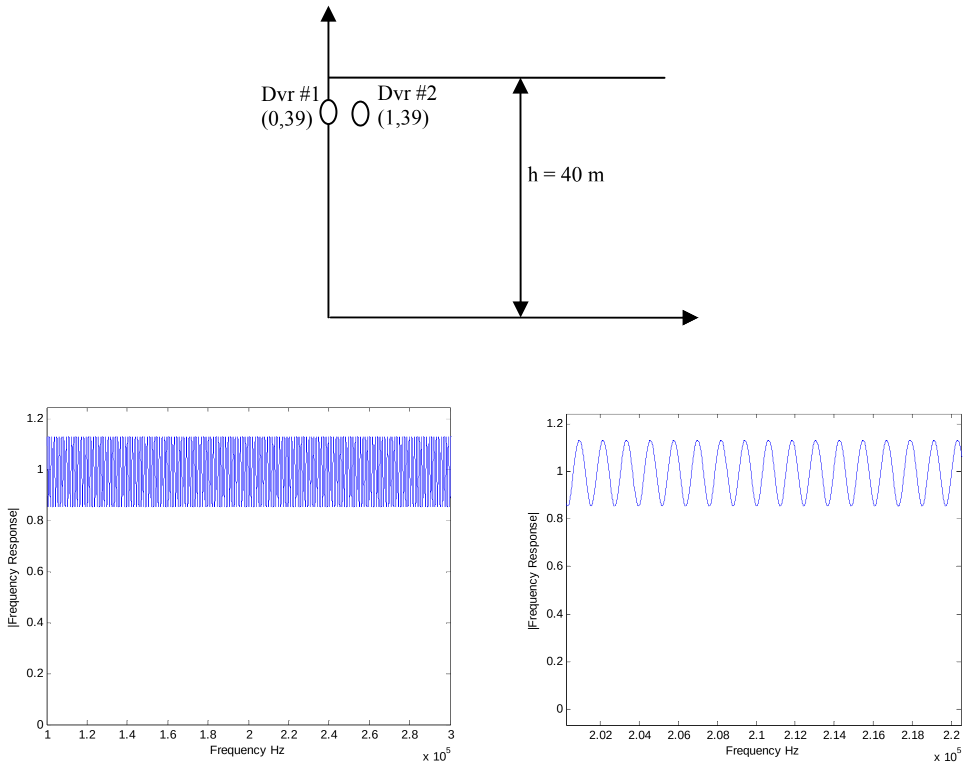


Figure 5.1: Diver scenario, approximate frequency response and zoomed frequency response

For the scenario, only surface reflection shall be received strongly with 10 dB power loss along with the LOS path.

The baseband complex representation of the received sequence is shown in Figure 5.2.

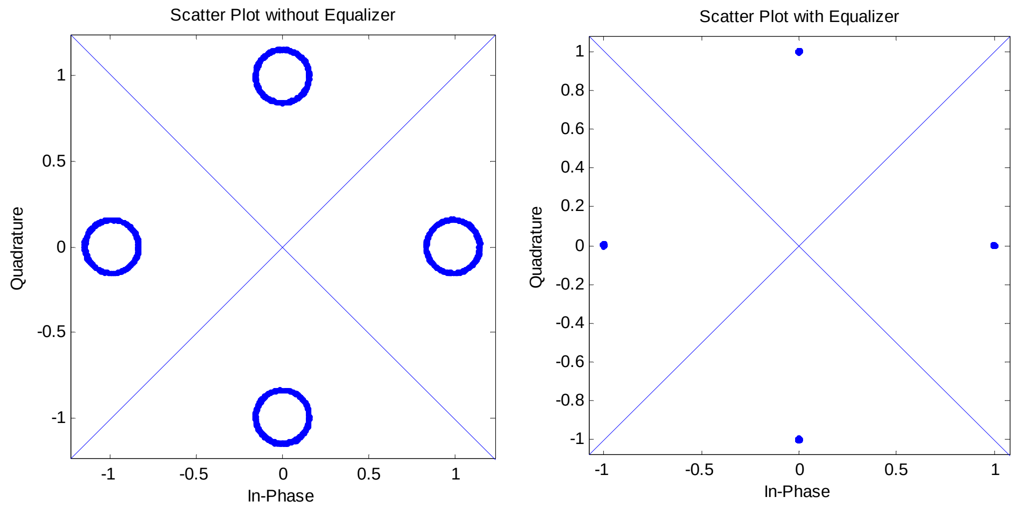


Figure 5.2: Received baseband complex representation with and without equalizer for underwater scenario of Diver#1@(0,39), Diver#2@(1,39), depth=40 m SS=0, porosity=0.2 Noiseless and motionless case, OFDM symbol length 1 msec, cyclic extension 5.4 msec

From Figure 5.2, the frequency selective fading is observed. The complex baseband representation of the transmitted sequence shows a circle around the transmitted complex point. The received signal is equalized perfectly because the orthogonality is maintained by addition of cyclic prefix.

For the scenario, the communication performances are depicted in Table 5.1.

	CI_{min}		CI_{max}	CI_{min}		CI_{max}
	Without Equalizer			With Equalizer		
Gray coded BER	0	0	36.8 10^{-6}	0	0	36.8 10^{-6}
Gray Coded Data Rate	62.49 10^{3}	62.5 10^{3}	62.5 10^{3}	62.49 10^{3}	62.5 10^{3}	62.5 10^{3}
Trueput	62.5 10^{3}			62.5 10^{3}		
RS coded Data Rate	-			62.5 10^{3}		
RS Code	-			No coding		

Table 5.1: Communication performance of the depicted scenario

From Table 5.1, it can be concluded that for the depicted scenario, in which only frequency selective fading affects the communication, the equalizer perfectly equalizes the affected signal with the use of cyclic extension. For this scenario, data rate as high as 62.5 Kbps can be achieved with equalizer.

A second case shall depict the frequency and range dependent frequency response of the underwater acoustic channel as well as the frequency selective fading due to multipath propagation. The underwater communication scenario and approximate frequency response are depicted in Figure 5.3. In this scenario, the divers are 100 m apart from each other and the delay spread is 2.2 msec.

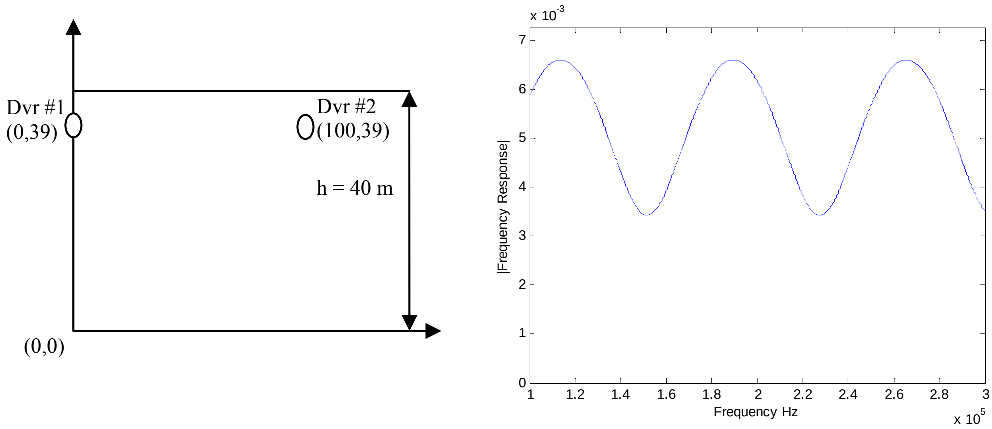


Figure 5.3: Diver scenario and the approximate frequency response

For the scenario, only surface reflection shall be received strongly with 10 dB power loss along with the LOS path.

The baseband complex representation of the received sequence is shown in Figure 5.4.

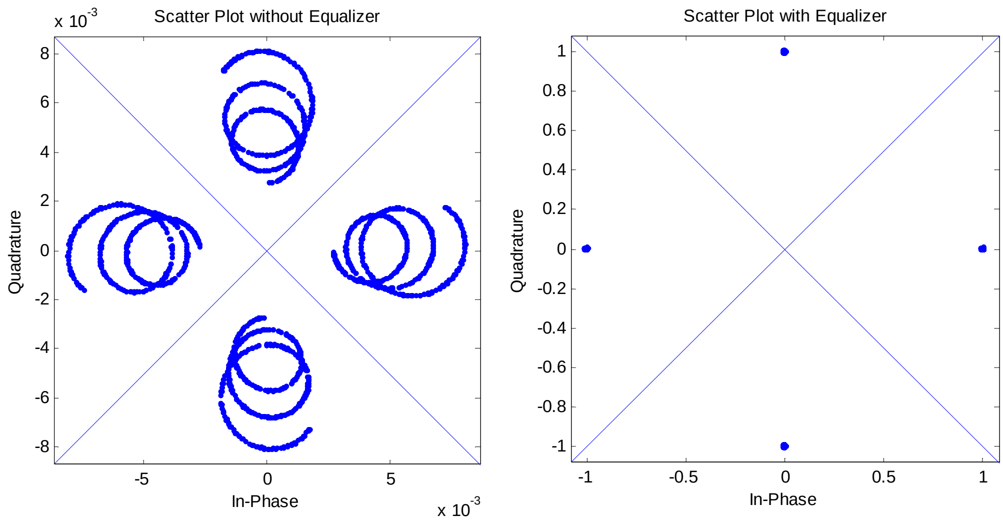


Figure 5.4: Received baseband complex representation with and without equalizer for underwater scenario of Diver#1@(0,39), Diver#2@(100,39) depth=40 m SS=0, porosity=0.2 Noiseless and motionless case, OFDM pulse length 1 msec, cyclic extension 5.4 msec

From Figure 5.4, the frequency and range dependent frequency response and frequency selective fading is observed. The complex baseband representation of the transmitted sequence shows a spiral like shape around the transmitted complex point narrowing to the origin. The reason for the spiral is due to frequency and range dependent frequency response. In this scenario the distance between the divers is 100 m and as discussed in Section 2.2.2 , there is 4 dB power difference between 100 kHz and 300 kHz. This frequency difference is observed in this scenario. In this scenario, the received signal is equalized perfectly because the orthogonality is maintained by addition of cyclic prefix.

For the scenario the communication performances are depicted in Table 5.2.

	CI_{min}		CI_{max}	CI_{min}		CI_{max}
	Without Equalizer			With Equalizer		
Gray coded BER	0	0	36.8 10^{-6}	0	0	36.8 10^{-6}
Gray Coded Data Rate	62.4 10^{3}	62.5 10^{3}	62.5 10^{3}	62.4 10^{3}	62.5 10^{3}	62.5 10^{3}
Trueput	62.5 10^{3}			62.5 10^{3}		
RS coded Data Rate	-			62.5 10^{3}		
RS Code	-			No coding		

Table 5.2: Communication performance of the depicted scenario

From Table 5.2, it can be concluded that for the depicted scenario, in which frequency selective fading and frequency and range dependent frequency response affects the system, the equalizer perfectly equalizes the affected signal. For this scenario, data rate as high as 62.5 Kbps can be achieved with equalizer.

For the two depicted scenarios, the communication performances are the same. The effect of multipath is completely equalized with the use of frequency domain equalizer. The frequency domain equalizer with the cyclic extension provides perfect reconstruction of the transmitted sequence in the absence of noise, as long as the multipath OFDM signals are within the cyclic extension period.

- *Doppler Effect*

Doppler shift in an OFDM communication system as discussed in Section 3.1.2.1.1, destroys the orthogonality of the carriers. The loss in orthogonality, avoids equalizers to equalize the affected signal perfectly. The effect of Doppler shift is depicted in the following scenario, in which no significant multipath signals exists within the OFDM pulse. Diver #1 and diver #2 are positioned at (0,50) and (1,50) respectively where the depth is 100 m. This way only Doppler effect is observed. Since there is no significant multipath, the frequency response of the channel is flat. The relative velocity between the divers is 1 m/s. The OFDM pulse is selected 1 msec for this case. The underwater communication scenario is depicted in Figure 5.5.

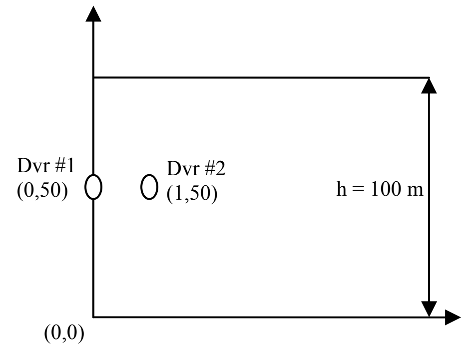


Figure 5.5: Diver scenario

The baseband complex representation of the received sequence is shown in Figure 5.6.

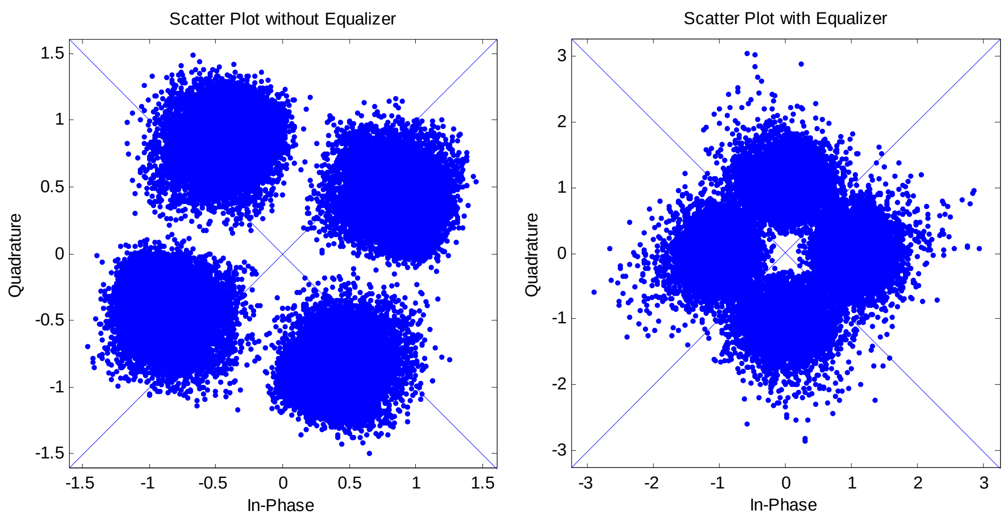


Figure 5.6: Received baseband complex representation with and without equalizer for underwater scenario of Diver#1@(0,50), Diver#2@(1,50) depth=100 m SS=0, porosity=0.2 Noiseless and relative velocity *v*=1 m/sec , OFDM pulse length 1 msec, cyclic extension 5.4 msec

From Figure 5.6, the effect of Doppler shift is observed. Doppler shift destroys the orthogonality, creating a noise like behavior as well as shifting the phase of the signal. Since the orthogonality is lost, frequency domain equalizers cannot equalize the affected signal perfectly, leaving considerable amount of error.

For the scenario, the communication performances are depicted in Table 5.3.

	CI_{min}		CI_{max}	CI_{min}		CI_{max}
	Without Equalizer			With Equalizer		
Gray coded BER	32.2 10^{-3}	33.3 10^{-3}	34.4 10^{-3}	2.5 10^{-3}	2.8 10^{-3}	3.2 10^{-3}
Gray Coded Data Rate	60.34 10^{3}	60.41 10^{3}	60.48 10^{3}	62.30 10^{3}	62.32 10^{3}	62.34 10^{3}
Trueput	0			18 10^{3}		
RS coded Data Rate	-			51.97 10^{3}		
RS Code	-			RS (50,42)		

Table 5.3: Communication performance of the depicted scenario

From Table 5.3, it can be concluded that for the depicted scenario, in which only Doppler shift affects the communication, low communication performance is achieved without equalization or FEC. The equalizer cannot equalize the effect of Doppler shift, because the orthogonality is lost. For this scenario in the absence of noise and with relative velocity between the divers, no trueput is achieved without the use of equalizer, using the equalizer 18 kbps is achieved and using the FEC around 52 kbps is achieved.

A second case shall depict effect of OFDM pulse length on the Doppler effect. The OFDM pulse length for this scenario is 0.4 msec. The divers are in the same positions. The underwater communication scenario is depicted in Figure 5.7.

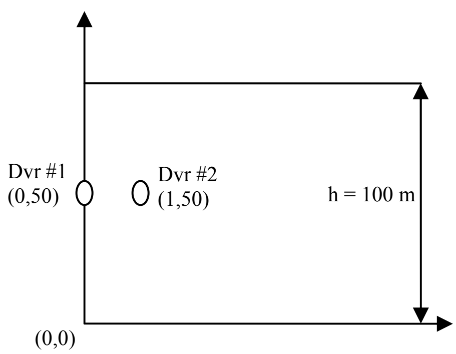


Figure 5.7: Diver scenario

The baseband complex representation of the received sequence is shown in Figure 5.8.

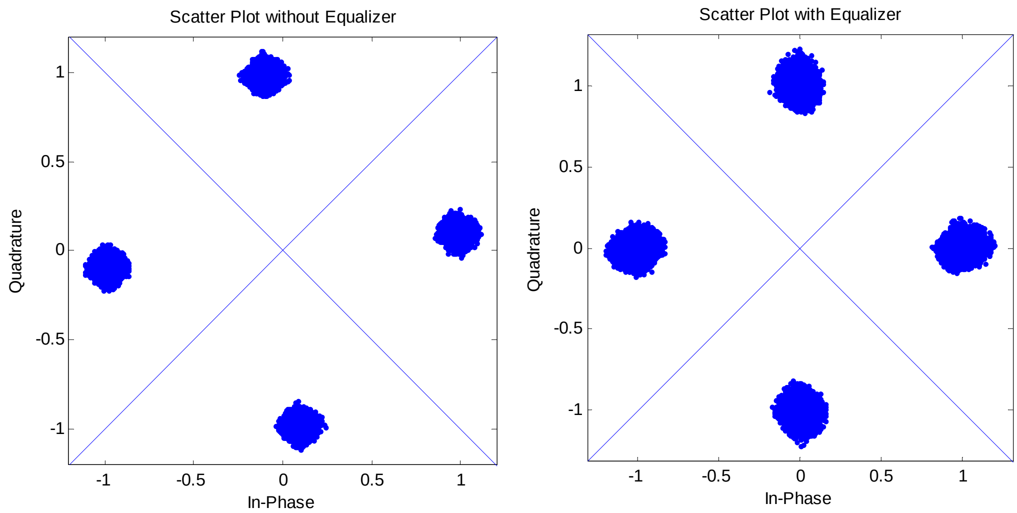


Figure 5.8: Received baseband complex representation with and without equalizer for underwater scenario of Diver#1@(0,50), Diver#2@(1,50) depth=100 m SS=0, porosity=0.2 Noiseless and relative velocity v=1 m/sec case, OFDM pulse length 0.4 msec, cyclic extension 5.4 msec

From Figure 5.8, when compared with Figure 5.6, the effect of OFDM pulse length on Doppler Effect is observed. When the OFDM pulse length is shorter, the bandwidth of each carrier is wider; therefore, the effect of Doppler shift is less. It can also be observed from the figures that the phase shift is less as compared to 1 msec OFDM pulse case. The noise like behavior is less as compared to 1 msec case, leaving less error.

For the scenario the communication performances are depicted in Table 5.4.

	CI_{min}		CI_{max}	CI_{min}		CI_{max}
	Without Equalizer			With Equalizer		
Gray coded BER	0	0	$36.8\ 10^{-6}$	0	0	$36.8\ 10^{-6}$
Gray Coded Data Rate	$14.28\ 10^{3}$	$14.28\ 10^{3}$	$14.28\ 10^{3}$	$14.28\ 10^{3}$	$14.28\ 10^{3}$	$14.28\ 10^{3}$
Trueput	$14.28\ 10^{3}$			$14.28\ 10^{3}$		
RS coded Data Rate	-			$14.28\ 10^{3}$		
RS Code	-			No coding		

Table 5.4 Communication performance of the depicted scenario

From Table 5.4, it can be concluded that for the depicted scenario, in which only Doppler shift affects the communication, the Doppler shift destroys the orthogonality. The equalizer closely equalizes the affected signal; however due to loss in orthogonality, not perfectly. For this scenario, data rate as high as 14.2 Kbps can be achieved. Even though, having shorter OFDM pulses provide resistance to Doppler shift, the trade off is that the data rate is smaller. The data rate is decreased because shorter OFDM pulses have fewer carriers; therefore less data rate. Having smaller OFDM pulses provide good BER, however lack data rate.

From the two Doppler shift case scenarios, the effect of OFDM pulse length is observed. As discussed in Section 2.2.4 , the OFDM pulse length has to be much smaller than the inverse of the maximum Doppler shift. The OFDM pulse length of 0.4 msec provides much better error performance, however the problem is that the data rate reduces with the OFDM pulse length decrease.

- *Multipath and Doppler Shift Effect*

In normal communication scenarios, both multipath and Doppler shift affects the communication. The effect of multipath can be equalized; however the effect of Doppler shift can not, because Doppler shift destroys the orthogonality. The combination of multipath and Doppler shift shall leave worse data and error rate performances than the previous scenarios. The combined effect of multipath and Doppler shift is depicted in the following scenario. Diver #1 and diver #2 are positioned at (0, 39) and (100, 39) respectively, where the depth is 40 m. The relative velocity between the divers is 1 m/s. The OFDM pulse is selected 1 msec for this case. The underwater communication scenario is depicted in Figure 5.9. For the scenario the delay spread is 2.2 msec.

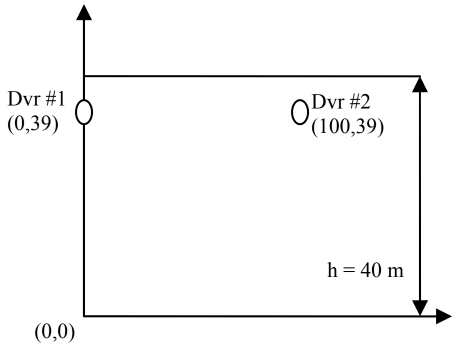


Figure 5.9: Diver scenario

The baseband complex representation of the received sequence is shown in Figure 5.10.

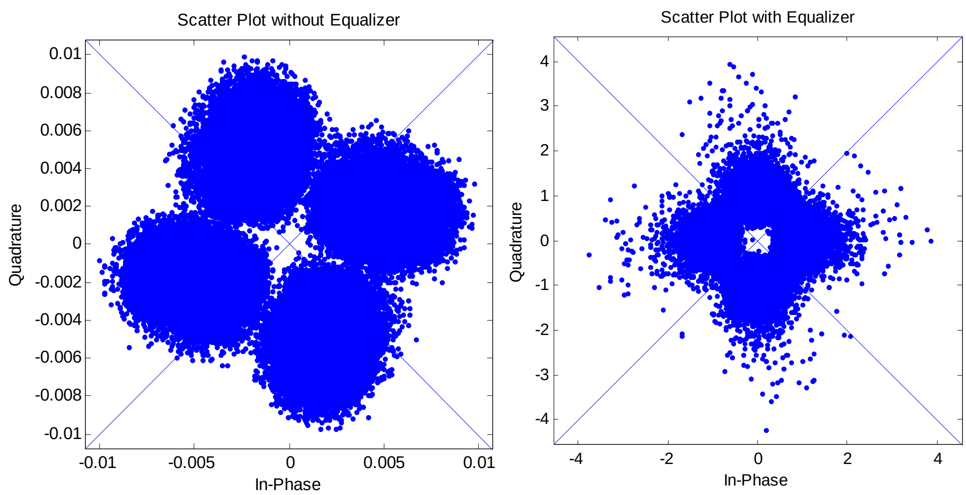


Figure 5.10: Received baseband complex representation with and without equalizer for underwater scenario of Diver#1@(0,39), Diver#2@(100,39) depth=40 m SS=0, porosity=0.2Noiseless and relative velocity *v*=1 m/sec, OFDM pulse length 1 msec, cyclic extension 5.4 msec

From Figure 5.10, the combined effect of multipath Doppler shift is observed. From the complex baseband representation, it is observed that orthogonality is destroyed due to Doppler shift. Even though multipath path effect can be equalized individually, the combined effect cannot be equalized perfectly. As before, the Doppler shift, shifts the phase of the signal. Since the orthogonality is lost, frequency domain equalizer cannot equalize the signal perfectly, leaving considerable amount of error.

For the scenario the communication performances are depicted in Table 5.5.

	CI_{min}		CI_{max}	CI_{min}		CI_{max}
	Without Equalizer			With Equalizer		
Gray coded BER	51.5 10^{-3}	52.9 10^{-3}	54.3 10^{-3}	2.8 10^{-3}	3.1 10^{-3}	3.5 10^{-3}
Gray Coded Data Rate	59.10 10^{3}	59.19 10^{3}	59.28 10^{3}	62.28 10^{3}	62.30 10^{3}	62.32 10^{3}
Trueput	0			18.5 10^{3}		
RS coded Data Rate	-			51.97 10^{3}		
RS Code	-			RS (50,42)		

Table 5.5: Communication performance of the depicted scenario

From Table 5.5, it can be concluded that for the depicted scenario, in which both multipath and Doppler shift affects the communication, low communication performance is achieved without equalization and FEC. The equalizer cannot equalize the combined effect of multipath and Doppler shift, because the orthogonality is lost. For this scenario in the absence of noise and with 1 m/sec relative velocity between the divers, no trueput is achieved without the use of equalizer. Using the equalizer 18.5 kbps and using the FEC around 52 kbps is achieved.

A second case shall depict effect of OFDM pulse length on the Doppler effect. The OFDM pulse length for this scenario is 0.4 msec. The divers are in the same positions. The underwater communication scenario is depicted in Figure 5.11.

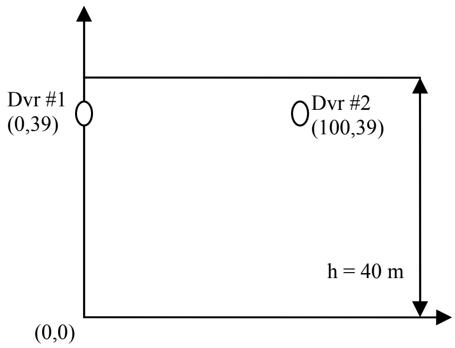


Figure 5.11: Diver scenario

The baseband complex representation of the received sequence is shown in Figure 5.12.

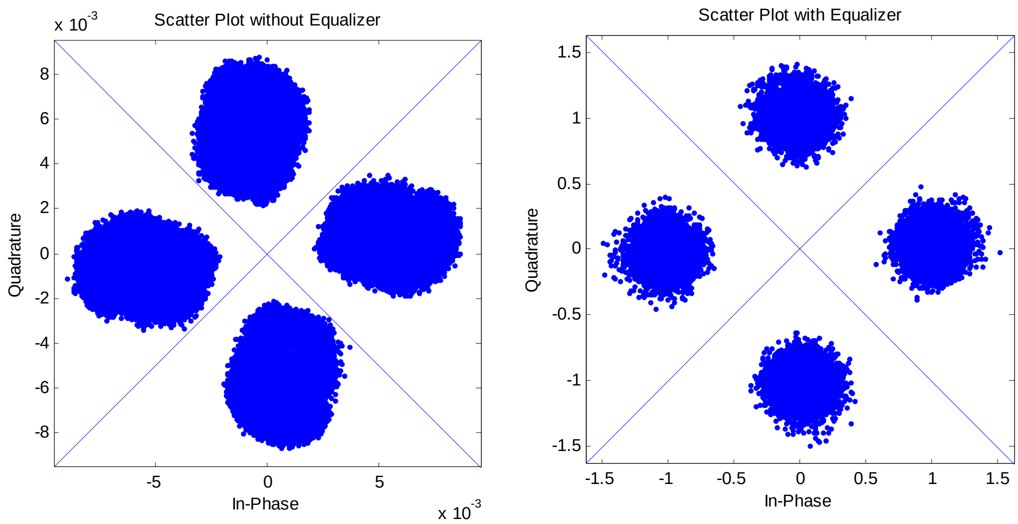


Figure 5.12: Received baseband complex representation with and without equalizer for underwater scenario of Diver#1@(0,39), Diver#2@(100,39) depth=40 m SS=0, porosity=0.2 Noiseless and relative velocity *v*=1 m/sec case, OFDM pulse length 0.4 msec, cyclic extension 5.4 msec

From Figure 5.12, when compared with Figure 5.10, the effect of OFDM pulse length on multipath and Doppler effect is observed. When the OFDM pulse length is shorter, the bandwidth of each carrier is wider; therefore, the effect of Doppler shift is less. It can also be observed from the figures that the phase is shift is less as compared to 1 msec OFDM pulse case. The noise like behavior is less, leaving less error.

For the scenario the communication performances are depicted in Table 5.6.

	CI_{min}		CI_{max}	CI_{min}		CI_{max}
	Without Equalizer			With Equalizer		
Gray coded BER	0	0	$36.88\ 10^{-6}$	0	0	$36.88\ 10^{-6}$
Gray Coded Data Rate	$27.58\ 10^3$	$27.58\ 10^3$	$27.58\ 10^3$	$27.58\ 10^3$	$27.58\ 10^3$	$27.58\ 10^3$
Trueput	$27.58\ 10^3$			$27.58\ 10^3$		
RS coded Data Rate	-			$27.58\ 10^3$		
RS Code	-			No coding		

Table 5.6: Communication performance of the depicted scenario

From Table 5.6, it can be concluded that for the depicted scenario, in which both multipath Doppler shift affects the communication, the Doppler shift destroys the orthogonality. The equalizer closely equalizes the affected signal. For this scenario, in the absence of noise, data rate as high as 27.5 Kbps without the need of FEC is achieved.

The effect of OFDM pulse length is observed when complex baseband representations in Figure 5.12 and Figure 5.10 are observed. When the OFDM pulse length is smaller, the bandwidth of each carrier is wider, providing resistance to Doppler shift. For shorter OFDM pulses the complex baseband representation is less cloudy and the phase shift is less. This, in turn leads to better error performance. Even though, having shorter OFDM pulses provide resistance to Doppler shift, the trade off is that the data rate is smaller, because for shorter OFDM pulses there are fewer carriers. Having smaller OFDM pulses provide good BER, however lack data rate.

5.1.2 Noisy Simulations

For the simulations in the presence of noisy, the same scenarios and same OFDM parameters are used. The only difference is that in these cases the acoustic noise is present at the front end of the receiver of the system. The system is designed such that 1 10^{-3} BER is achieved for the LOS, ideal communication channel, without taking account of any channel impairments. The transmission power is calculated in order to achieve the desired BER. The transmission power is calculated from the modulation type, distance between the divers, using the RTS/CTS packet exchange as discussed in Section 3.1.2.1.2. The noise shall decrease the performance of equalizers because the equalization parameters now include the noise. The same scenarios, as simulated in noiseless cases shall be simulated in order to find the real life communication performances.

- *Multipath Effect*

The simulation scenario is that divers are 1 m below the surface and the distance between is 1 m. The Sea-State and porosity are 0 and 0.2 respectively. The OFDM pulse length is 1 msec.

The baseband complex representation of the received sequence is shown in Figure 5.13.

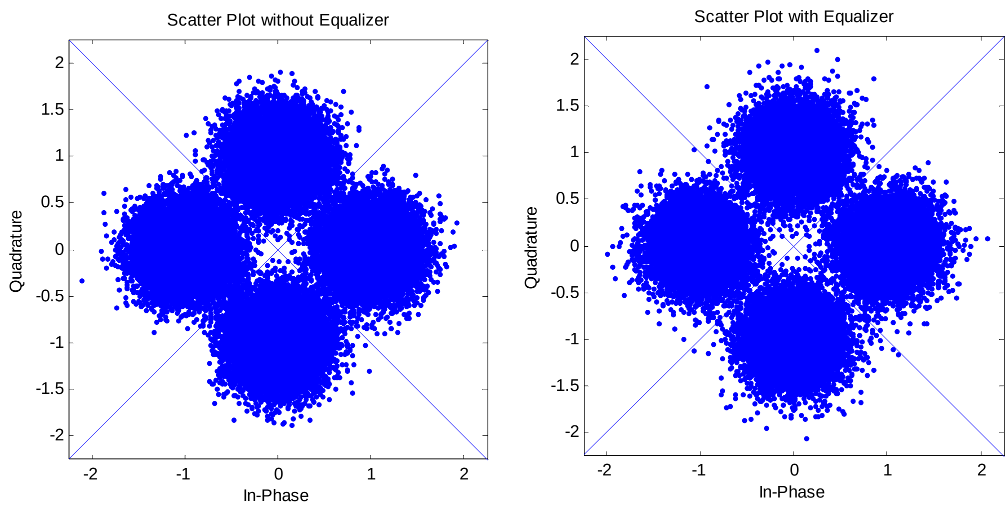


Figure 5.13: Received baseband complex representation with and without equalizer for underwater scenario of Diver#1@(0,39), Diver#2@(1,39) depth=40 m SS=0, porosity=0.2 Noisy and motionless case, OFDM pulse length 1 msec, cyclic extension 5.4 msec

From Figure 5.13 the effect of multipath and noise is observed when compared with Figure 5.2. The equalizer in the noisy case cannot equalize the received signal perfectly, leaving some error.

For the scenario the communication performances are depicted in Table 5.7.

	CI_{min}		CI_{max}	CI_{min}		CI_{max}
	Without Equalizer			With Equalizer		
Gray coded BER	$2.2\ 10^{-3}$	$2.5\ 10^{-3}$	$2.8\ 10^{-3}$	$1.6\ 10^{-3}$	$1.9\ 10^{-3}$	$2.2\ 10^{-3}$
Gray Coded Data Rate	$62.32\ 10^{3}$	$62.34\ 10^{3}$	$62.36\ 10^{3}$	$62.36\ 10^{3}$	$62.38\ 10^{3}$	$62.39\ 10^{3}$
Trueput	$23.75\ 10^{3}$			$30.25\ 10^{3}$		
RS coded Data Rate	-			$54.45\ 10^{3}$		
RS Code	-			RS(50, 44)		

Table 5.7: Communication performance of the depicted scenario

From Table 5.7, it can be concluded that the BER and data rate performances decreased. In the absence of noise, data rate of 62.5 Kbps is achieved. The achievable data rate in the presence of noise after FEC is 54.4 Kbps. The equalized simulation has BER close to expected however due to noise the expected BER cannot be achieved, because the noise affects the equalizer parameters.

The second scenario is the case when the divers are 100 m distant from each other. In this scenario, the frequency and range dependent frequency response affects the channel along with the multipath propagation and noise.

The baseband complex representation of the received sequence is shown in Figure 5.14.

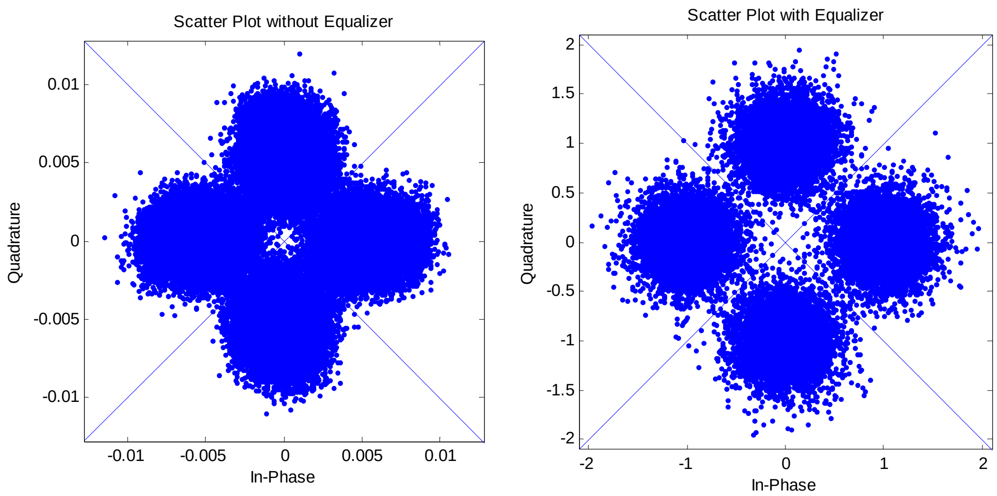


Figure 5.14: Received baseband complex representation with and without equalizer for underwater scenario of Diver#1@(0,39), Diver#2@(100,39) depth=40 m SS=0, porosity=0.2 Noisy and motionless case, OFDM pulse length 1 msec, cyclic extension 5.4 msec

In this scenario, similar complex baseband representations are obtained as with the previous case. The un-equalized complex baseband representation is now wider than the previous case due to spiral shape as explained for the noiseless case. However, the received signal is equalized closely, leaving some error.

For the scenario the communication performances are depicted in Table 5.8.

	CI_{min}		CI_{max}	CI_{min}		CI_{max}
	Without Equalizer			With Equalizer		
Gray coded BER	$3.5\ 10^{-3}$	$3.9\ 10^{-3}$	$4.3\ 10^{-3}$	$1.1\ 10^{-3}$	$1.3\ 10^{-3}$	$1.5\ 10^{-3}$
Gray Coded Data Rate	$62.23\ 10^{3}$	$62.25\ 10^{3}$	$62.28\ 10^{3}$	$62.40\ 10^{3}$	$62.41\ 10^{3}$	$62.43\ 10^{3}$
Trueput	$14.25\ 10^{3}$			$36.50\ 10^{3}$		
RS coded Data Rate	-			$54.45\ 10^{3}$		
RS Code	-			RS(50, 44)		

Table 5.8: Communication performance of the depicted scenario

From Table 5.8, it can be concluded that the BER and data rate performance are decreased. Data rate in the absence of noise is 62.5 kbps. The achievable data rate after FEC is 54.4 Kbps. The BER is close to expected however is not, due to noise and noise affected equalizer parameters.

For the two scenarios, the BER performances are close to expected and the data rate performances decreased due to noise. The received signal is equalized; however, due to noise the equalizer parameters contain some error. This in turn causes the equalization to leave certain amount of error. The FEC recovers the corrupted data and provides for the two scenarios 54.4 Kbps data rate.

- *Doppler Effect*

The Doppler effect for the noiseless case is observed in the previous section. In this section the effect of noise and Doppler shift be observed. The scenario to observe only the Doppler shift, without the multipath effect is that divers are at (0, 50) and (1, 50) where the depth is 100 m. For this scenario the OFDM pulse length is 1 msec and the relative velocity between the divers is 1 m/sec.

The baseband complex representation of the received sequence is shown in Figure 5.15.

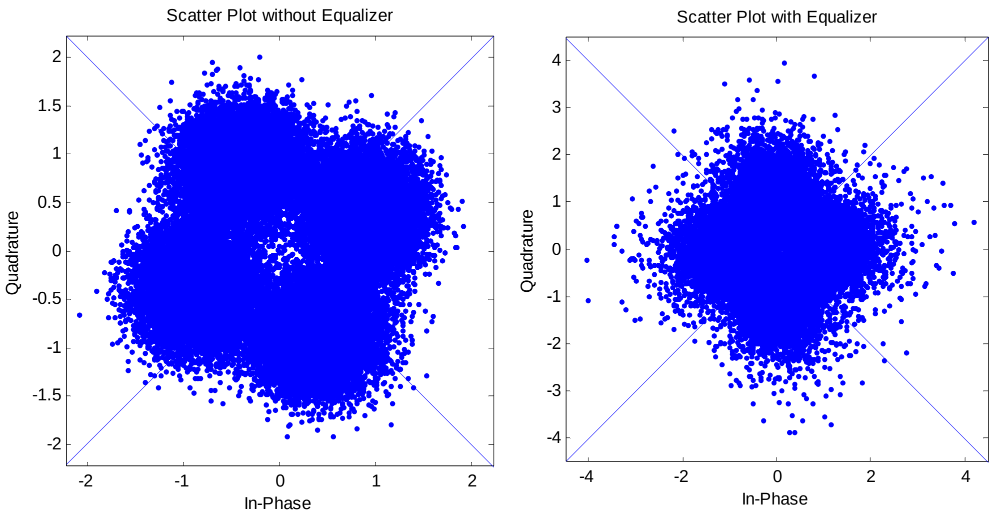


Figure 5.15: Received baseband complex representation with and without equalizer for underwater scenario of Diver#1@(0,50), Diver#2@(1,50) depth=100 m SS=0, porosity=0.2 Noisy and relative velocity *v*=1 m/sec, OFDM pulse length 1 msec, cyclic extension 5.4 msec

The effect of Doppler shift and noise is observed in Figure 5.15. Since Doppler shift destroys the orthogonality, the complex baseband representation of the received signal has a noise like behavior. As explained for the noiseless case, equalizer cannot perfectly equalize the received signal. In the presence of noise, the equalizer parameters are corrupted with noise; therefore, the equalization leaves certain amount of error.

For the scenario the communication performances are depicted in Table 5.3.

	CI_{min}		CI_{max}	CI_{min}		CI_{max}
	Without Equalizer			With Equalizer		
Gray coded BER	$66.2\ 10^{-3}$	$67.7\ 10^{-3}$	$69.3\ 10^{-3}$	$17.9\ 10^{-3}$	$18.7\ 10^{-3}$	$19.6\ 10^{-3}$
Gray Coded Data Rate	58.16 10	$58.26\ 10^{3}$	$58.36\ 10^{3}$	$61.27\ 10^{3}$	$61.32\ 10^{3}$	$61.38\ 10^{3}$
Trueput	0			0		
RS coded Data Rate	-			$29.7\ 10^{3}$		
RS Code	-			RS (50,24)		

Table 5.9: Communication performance of the depicted scenario

From Table 5.9, it can be concluded that for the depicted scenario, in which both Doppler shift and noise affects the communication, low communication performance is achieved without equalization and FEC. The equalizer cannot equalize the effect of Doppler shift, because the orthogonality is lost. For this scenario, in the presence of noise and with relative velocity between the divers, no trueput is achieved with the use of equalizer. Data rate of 29.7 Kbps can be achieved with the use of RS codes. Without FEC, no communication is possible. As compared to noiseless case, the BER and data rate performance degrades from 51.9 Kbps to 29.7 Kbps.,

A second case shall simulate the effect of shorter OFDM pulse length in the presence of noise and Doppler shift. The OFDM pulse length is 0.4 msec. The diver scenario is the same as the previous case.

The baseband complex representation of the received sequence is shown in Figure 5.16.

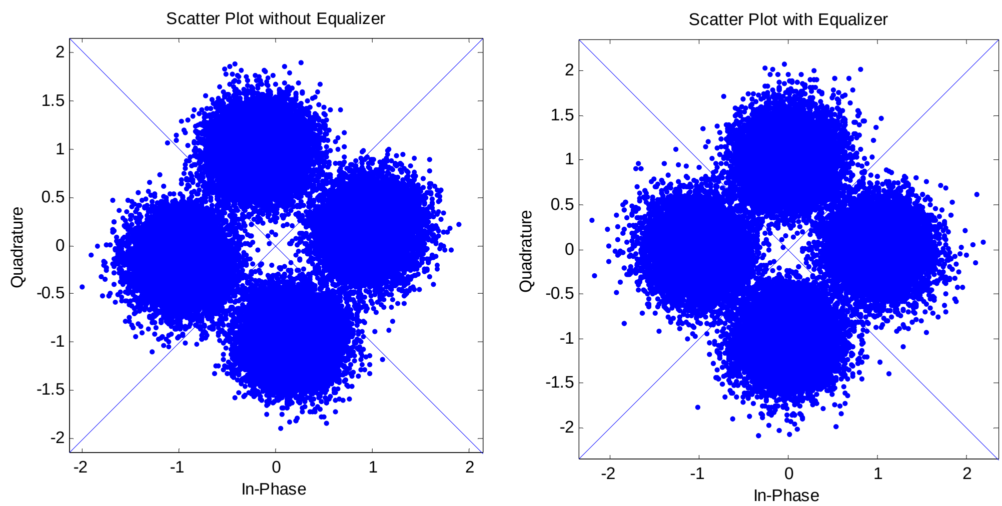


Figure 5.16: Received baseband complex representation with and without equalizer for underwater scenario of Diver#1@(0,50), Diver#2@(1,50) depth=100 m SS=0, porosity=0.2 Noisy and relative velocity *v*=1 m/sec case, OFDM pulse length 0.4 msec, cyclic extension 5.4 msec

When Figure 5.16 is compared with Figure 5.15, the effect of shorter OFDM pulse length is observed. When the OFDM pulse length is shorter, the effect is that the complex baseband representation is narrower; leaving less error and better performance and the phase shift is less as compared to longer OFDM pulse.

For the scenario the communication performances are depicted in Table 5.10.

	CI_{min}		CI_{max}	CI_{min}		CI_{max}
	Without Equalizer			With Equalizer		
Gray coded BER	$4.4\ 10^{-3}$	$4.8\ 10^{-3}$	$5.3\ 10^{-3}$	$2.0\ 10^{-3}$	$2.3\ 10^{-3}$	$2.6\ 10^{-3}$
Gray Coded Data Rate	$27.44\ 10^{3}$	$27.45\ 10^{3}$	$27.46\ 10^{3}$	$27.51\ 10^{3}$	$27.52\ 10^{3}$	$27.53\ 10^{3}$
Trueput	$12.93\ 10^{3}$			$18.84\ 10^{3}$		
RS coded Data Rate	-			$21.84\ 10^{3}$		
RS Code	-			RS(20,16)		

Table 5.10: Communication performance of the depicted scenario

From Table 5.10 when compared with Table 5.9, it is observed that the BER performance increased from $18.7\ 10^{-3}$ to $2.3\ 10^{-3}$, this is due to fact that shorter OFDM pulse results in resistance to Doppler shift. In this case, since the BER is low, trueput without the use of FEC and even equalizer is achieved. However, the data rate performance with FEC decreased from 29.7 kbps to 21.8 kbps. The decrease in data rate, despite better BER is that shorter OFDM pulse has fewer carriers; therefore, the achievable data rate is less than the longer OFDM pulse case. There is a trade of between the OFDM pulse length, data rate and BER performance.

- *Multipath and Doppler Shift Effect*

In this scenario, multipath and Doppler shift shall be simulated along with noise. The noise shall degrade the performance of equalizer and the communication. The scenario is that diver #1 is at (0,39) and diver #2 (100,30) where the depth is 40 m. The OFDM symbol length is be 1 msec. The relative velocity between the divers shall be 1 m/sec.

The baseband complex representation of the received sequence is shown in Figure 5.17.

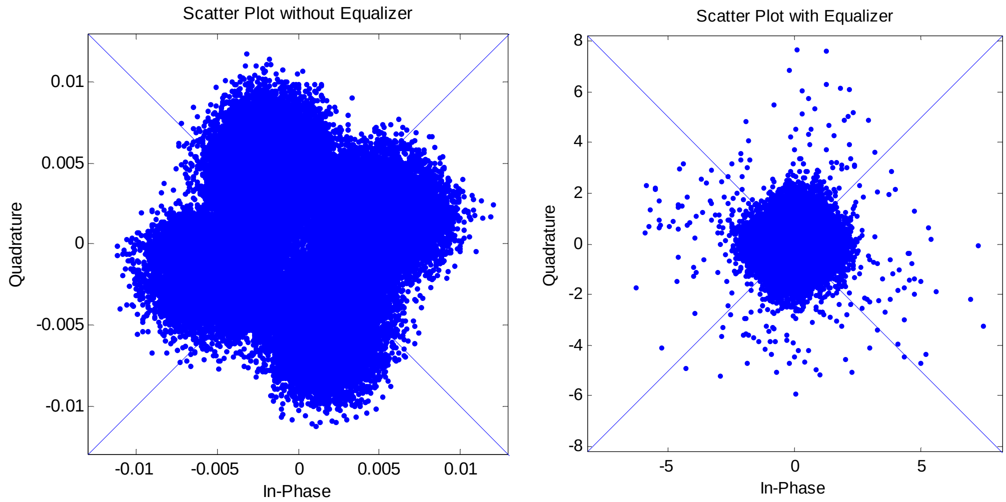


Figure 5.17: Received baseband complex representation with and without equalizer for underwater scenario of Diver#1@(0,39), Diver#2@(100,39) depth=40 m SS=0, porosity=0.2 Noisy and relative velocity *v*=1 m/sec, OFDM pulse length 1 msec, cyclic extension 5.4 msec

In Figure 5.17, the effect of multipath, Doppler shift and noise is observed. As stated before, the equalizer cannot perfectly equalize the corrupted signal, because the Doppler shift destroys the orthogonality. Along with the loss of orthogonality, the noise corrupts the signal and the equalizer parameters; therefore, this leaves considerable amount of error at the output.

For the scenario the communication performances are depicted in Table 5.11.

	CI_{min}		CI_{max}	CI_{min}		CI_{max}
	Without Equalizer			With Equalizer		
Gray coded BER	70.6 10^{-3}	72.2 10^{-3}	73.8 10^{-3}	16.4 10^{-3}	17.2 10^{-3}	18.1 10^{-3}
Gray Coded Data Rate	57.88 10^{3}	57.98 10^{3}	58.08 10^{3}	61.37 10^{3}	61.42 10^{3}	61.47 10^{3}
Trueput	0			0		
RS coded Data Rate	-			34.65 10^{3}		
RS Code	-			RS (50,28)		

Table 5.11: Communication performance of the depicted scenario

From Table 5.11, it can be concluded that in this scenario, no communication is possible without the use of FEC. For this scenario, the

Doppler shift destroys the orthogonality also the noise affects the equalizer parameters; therefore perfect equalization is not possible. In this scenario, data rate of 34.6 Kbps is achieved with the use of FEC.

Second case shall depict the effect of OFDM symbol length on the communication performance. For the scenario, Doppler shift, multipath and noise affect the communication. For this case, the OFDM symbol length is 0.4 msec. All the other parameters are the same.

The baseband complex representation of the received sequence is shown in Figure 5.18.

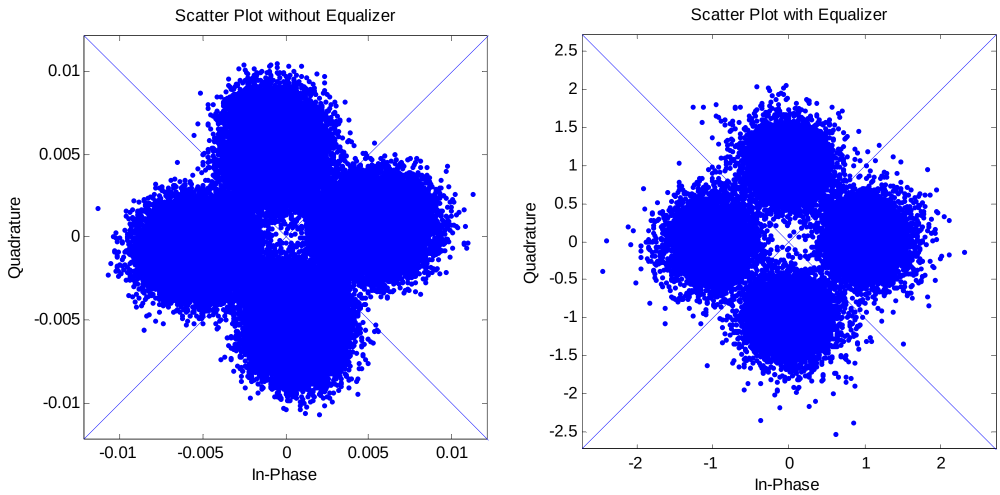


Figure 5.18: Received baseband complex representation with and without equalizer for underwater scenario of Diver#1@(0,39), Diver#2@(100,39) depth=40 m SS=0, porosity=0.2 Noisy and relative velocity *v*=1 m/sec case, OFDM pulse length 0.4 msec, cyclic extension 5.4 msec

From Figure 5.18, when compared with Figure 5.17, the complex baseband representation is narrower, so that there is less error. The carrier orthogonality is lost due to Doppler shift; however the loss is not as much as the previous case. Shorter OFDM pulse has the property of having resistance to Doppler shift, leaving less error.

For the scenario, the communication performances are depicted in Table 5.12.

	CI_{min}		CI_{max}	CI_{min}		CI_{max}
	Without Equalizer			With Equalizer		
Gray coded BER	$8.7\ 10^{-3}$	$9.3\ 10^{-3}$	$9.9\ 10^{-3}$	$1.6\ 10^{-3}$	$1.8\ 10^{-3}$	$2.1\ 10^{-3}$
Gray Coded Data Rate	$27.31\ 10^{3}$	$27.32\ 10^{3}$	$27.34\ 10^{3}$	$27.52\ 10^{3}$	$27.53\ 10^{3}$	$27.54\ 10^{3}$
Trueput	$60.46\ 10^{3}$			$20.65\ 10^{3}$		
RS coded Data Rate	-			$21.84\ 10^{3}$		
RS Code	-			RS(20, 16)		

Table 5.12: Communication performance of the depicted scenario

From Table 5.12, it can be concluded that for the depicted scenario, in which multipath, Doppler shift and noise affect the system, the Doppler shift destroys the orthogonality. Since the orthogonality is lost due to Doppler shift and noise, the equalizer parameters cannot be set properly; leaving certain amount of error at the output. In this scenario, data rate of 21.84 Kbps is achieved with the use of FEC.

When Table 5.12 and Table 5.11 are compared, it is observed that the BER improves with shorter OFDM pulse lengths. For the scenarios, the BER decreased from $17.2\ 10^{-3}$ to $1.8\ 10^{-3}$, this performance provides 0 and 27.53 Kbps trueput respectively with equalizer. Using FEC, data rate of 34.6 Kbps and 21.8 Kbps is achieved for 1 msec and 0.4 msec OFDM pulse length respectively. It is concluded that even if the BER performance improves for shorter OFDM pulse lengths, the data rate performance decreases. The decrease in data rate is because of the fact that there are fewer OFDM carriers for shorter OFDM pulses. In this respect, there is a trade of between the OFDM pulse length and data rate.

5.1.3 Comparison and Discussion of Special Case Simulations

The underwater OFDM communication system performances, namely BER and data rate depends on the channel conditions. The Doppler shift and multipath are main concerns that an underwater communication system faces. Investigation of the noisy scenarios shall reveal the trade of between the OFDM parameters and how the channel impairments and OFDM parameters affect the system.

- *Multipath Effect:* Cyclic extension preserves the orthogonality of carriers in multipath environment. The performance figures for the equalized, multipath and noise affected scenarios are shown in Table 5.13.

Scenario: Diver #1 (0, 39) Diver #2 (***x***, 39) h = 40 m OFDM pulse length 1 msec, cyclic extension 5.4 msec		
x = 1 m	BER	$1.9\ 10^{-3}$
	Gray coded Data Rate	62.38 Kbps
	Trueput	30.25 Kbps
	RS Coded Data Rate	54.45 Kbps RS(50,44)
x = 100 m	BER	$1.3\ 10^{-3}$
	Gray coded Data Rate	62.41 Kbps
	Trueput	36.50 Kbps
	RS Coded Data Rate	54.45 Kbps RS(50,44)

Table 5.13: Performances comparison of multipath affected scenarios

The performance of the systems are close to the expected BER, which is $1\ 10^{-3}$. This is achieved with the use of cyclic extension and preservation of the orthogonality. The BER and data rate performances of the two scenarios are close, however not the same. The reason for this kind of behavior is because of the noise affected equalizer parameters and transmission power characteristics. The equalizer parameters are affected from noise while setting the equalizer parameters. Since the parameters are not ideal, the equalization leaves some error at the output. The other reason is; as discussed in Section 2.2.2 , the frequency response of the acoustic channel is both frequency and range dependent. When the distance is 100 m, the frequency response varies 4 dB between 100 kHz and 300 kHz. Since the transmission power is adjusted according to the most affected frequency carrier, lower frequency carriers have better BER; therefore, the 100 m scenario performs better than the 1 m scenario.

- *Doppler Effect:* As discussed in Section 2.2.4 , the Doppler shift affects the OFDM pulses irreversibly, because Doppler shift destroys the orthogonality. The performance figures for the equalized, Doppler and noise affected scenarios are in Table 5.14.

Scenario: Diver #1 (0, 50) Diver #2 (1, 50) h = 100 m OFDM pulse length ***T*** msec, cyclic extension 5.4 msec		
T = 1 msec	BER	18.7 10^{-3}
	Gray coded Data Rate	61.32 Kbps
	Trueput	0
	RS Coded Data Rate	29.7 Kbps RS (50, 24)
T = 0.4 msec	BER	2.3 10^{-3}
	Gray coded Data Rate	27.52 Kbps
	Trueput	18.84 Kbps
	RS Coded Data Rate	21.84 Kbps RS(20, 16)

Table 5.14: Performances comparison of Doppler affected Scenarios

The performance of the systems are low because of the effect of Doppler shift. The Doppler shift destroys the orthogonality of the carriers. The BER and data rate performances of the two scenarios are very different. The reason for this kind of behavior is because of system's different resistivity to Doppler shift. Shorter OFDM pulses have wider carriers in the frequency domain therefore, more resistance to Doppler shift. Therefore, the BER performance of the shorter pulse length system is better. However, the data rate performance of the longer pulse length system is better. The reason is that longer OFDM pulse system has more carriers; therefore have more data carrying capability. With the use of FEC longer OFDM pulse system provides more data rate. This way, it is observed that there is a trade of between the pulse length and data rate.

- *Multipath and Doppler Effect:* The multipath, Doppler and noise affected scenarios are simulated and performance figures compared in Table 5.15.

Scenario: Diver #1 (0, 39) Diver #2 (100, 39) h = 40 m OFDM pulse length ***T*** msec, cyclic extension 5.4 msec		
T = 1 msec	BER	17.2 10^{-3}
	Gray coded Data Rate	61.42 Kbps
	Trueput	0
	RS Coded Data Rate	34.65 Kbps RS(50, 28)
T = 0.4 msec	BER	1.8 10^{-3}
	Gray coded Data Rate	27.53 Kbps
	Trueput	20.65 Kbps
	RS Coded Data Rate	21.84 Kbps RS(20, 16)

Table 5.15: Performances comparison of Doppler and multipath affected scenarios

The performance of the systems is low because of the combined effect of multipath and Doppler shift. The effect of multipath is compensated with the use of cyclic extension and frequency domain equalizer; however, the effect of Doppler shift cannot because Doppler shift destroys the orthogonality of the carriers. The BER and data rate performances of the two scenarios are very different. The reason for this kind of behavior is like the previous scenarios, systems, different resistivity to Doppler shift. Shorter OFDM pulses have wider carriers in the frequency domain therefore more resistance to Doppler shift. Therefore, the BER performance of the shorter pulse length system is better. However, the data rate performance of the longer pulse length system is better. The reason is discussed for the previous scenarios. With the use of FEC the longer data rate system provides more data rate.

When Table 5.14 and Table 5.15 are observed, the BER performance of the latter scenario is better. Even tough, in the second scenario, there is both multipath and Doppler shift, the BER performances are better. The reason behind this point is explained for the first scenario. The multipath effect is closely compensated with the use of cyclic extension and frequency domain equalizer. However, since for the last scenario, the lower and higher frequency component carriers are affected differently and the transmission power is adjusted for the higher frequency components, the BER of the second scenario, which is multipath and Doppler shift affected, has better BER performance despite having both multipath and Doppler shift effects.

5.2 Discussion of Simulation Results

In order to find the compromise between the OFDM communication system parameters, simulations were performed using MATLAB. The simulations were done with several scenarios and several communication system parameters. The information data is random sequence of bits, consisting of 100.000 bits. Several levels of modulation were performed, namely M=2, 4, 8 and 16. The underwater acoustic loss is taken into account along with sea surface and sea floor losses. The sea surface and sea floor losses are taken as worst and better case; that is worst case scenario is the one that has the least attenuation; whereas better case is the most expected attenuation. The worst case scenario is Sea-State-0 and sea floor porosity 0.2 having 10 dB loss from surface and 14 dB loss from sea floor respectively and better case scenario is Sea-State-1 and porosity 0.4 having 15 dB loss from surface and 35 dB loss from sea floor respectively. The boundary state scenarios are summarized in Table 5.16.

	Sea-State (SS)	Porosity (n)
Boundary state scenario #**1**	SS : 0 10 dB loss	n : 0.2 14 dB loss
Boundary state scenario #**2**	SS : 1 15 dB loss	n : 0.4 35 dB loss

Table 5.16: Boundary state scenarios

For the underwater communication system, the transmission power is adjusted according to the line of sight (LOS) acoustic loss, by using the distance between the divers. The distance between the divers is acquired using RTS/CTS packet exchange. The transmission power guarantees 1 10^{-3} BER for the most attenuated OFDM carrier, which is 300^{th} kHz carrier.

For the simulations, the maximum expected delay spread is taken as 5.4 msec, resulting in OFDM cyclic extension length of 5.4 msec.

The diver scenarios are selected such that *worst* and *better* case conditions are achieved. The scenarios are categorized *worse* for the larger delay spread cases, and *better* for less. The diver scenarios are selected for the most probable diver positions. Distance between the divers is selected to span the maximum expected distance between the divers; namely 1 m, 5 m, 10 m, 50 m and 100 m. Figure 2.5 depicts the 5-Ray paropagation model. Table 5.17 shows the simulated diver scenarios.

	Depth h (m)	**x_1 (m)**	**y_1 (m)**	**x_2 (m)**	**y_2 (m)**
Diver Scenario #**1**	40	0	39	**x**	39
Diver Scenario #**2**	40	0	20	**x**	20
Diver Scenario #**3**	40	0	39	**x**	2
Diver Scenario #**4**	40	0	1	**x**	1
Diver Scenario #**5**	100	0	20	**x**	20
Diver Scenario #**6**	100	0	80	**x**	80

Table 5.17: Underwater communication simulation scenarios

The Doppler shift is added in the simulations with relative velocity between the divers 1 m/sec. 1 m/sec relative velocity is the most expected motion between the divers.

The underwater communication system parameters should be selected according to the worst case performance; that is worst BER and least data rate performance. Choosing the parameters this way, we provide guaranteed performance of the system in good and bad sea conditions and scenarios.

The simulation results are graphed with respect to distance between divers with fixed OFDM pulse length and with respect to OFDM pulse length with fixed distance between the divers. The former graphs explain the effect of distance between the diver on the performance of the system in motionless cases and the latter graphs explain the effect of OFDM pulse length on the system in cases in motion.

The simulation results in graphs contain the following information:

- *Bit Error Rate (BER):* Provides the bit error rate information of the communication system in certain diver, boundary scenarios and conditions.
- *Bit Rate:* Provides the data bit rate over the total transmitted information bits. The bit rate is calculated over correctly received bits.
- *Trueput:* Provides the data rate of the communication system. The rate is calculated over correctly received transmitted OFDM symbols. This measure is essential because the system shall be digital and compressed data; therefore, successful reception of each packet is essential.
- *RS Coded Data Rate:* Provides the Reed-Solomon (RS) error coded data rate of the communication system. The Reed-Solomon code parameters are set using the Frame error rate (FER) of 1%. The RS coded data rate is the achievable data rate of the communication system using RS forward error correction.
- *Confidence Interval (CI):* The certainty of the BER and data rate results is depicted within the confidence interval of 95 %. The CI is graphed in the figures by dashed lines around the main solid lines. Using CI we provide certainty of the result.

Simulation findings are explained below:

- *Effect of frequency domain equalizer on communication performance:*

For diver scenario #1 and boundary state scenario #1, the delay spread profile with respect to distance between the divers is at most 2.2 msec, as depicted in Figure 5.19.

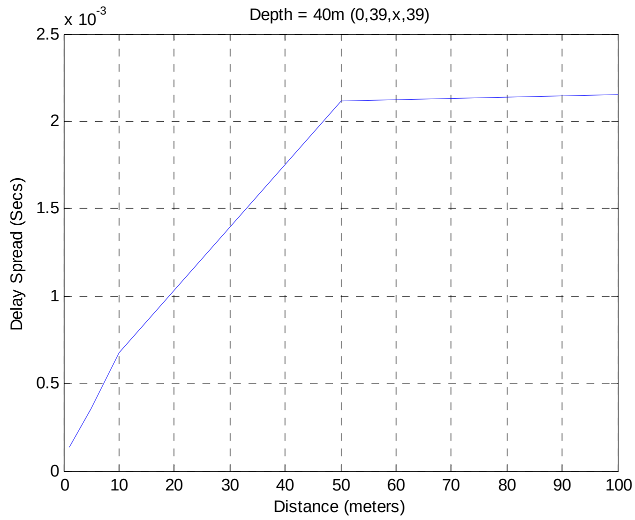


Figure 5.19: Delay Spread profile for diver scenario#1 and boundary state scenario#1

The BER performance for the OFDM communication system having pulse length 1 msec in motionless case is depicted in Figure 5.20.

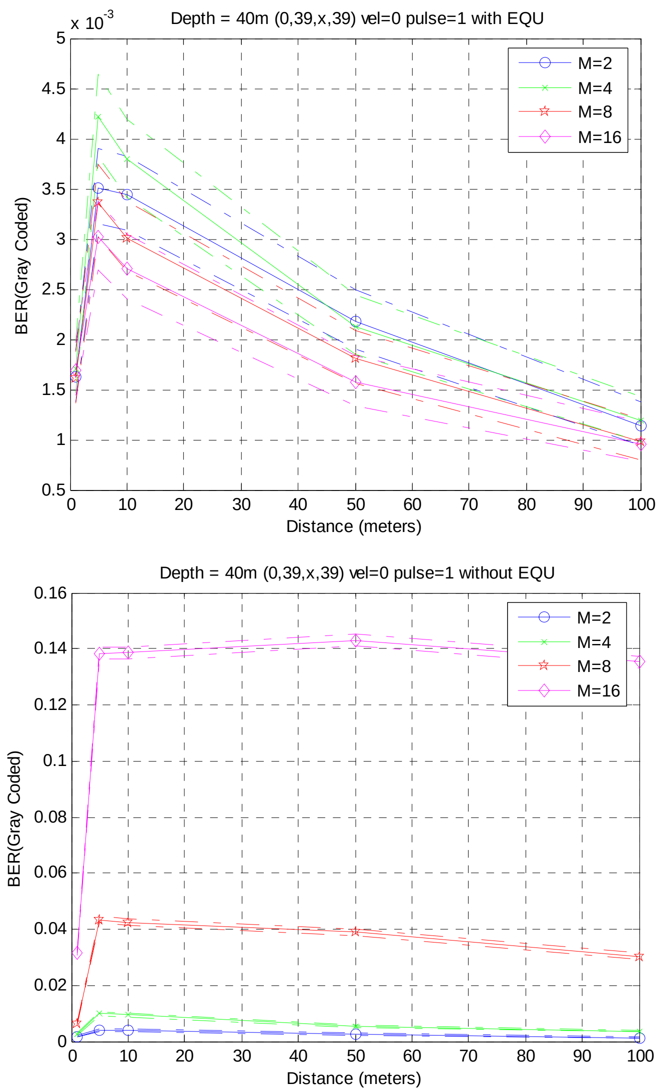


Figure 5.20: BER performance of frequency domain equalized and non-equalized system

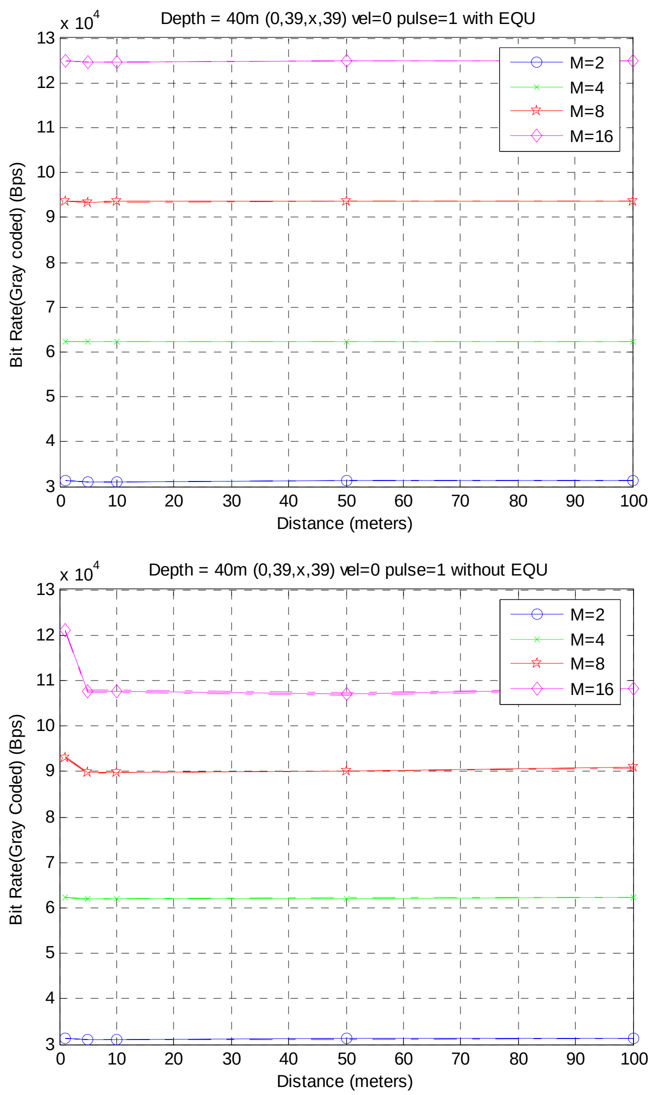


Figure 5.21: Bit rate performance of frequency domain equalized and non-equalized system

From Figure 5.20 and Figure 5.21, the BER and bit rate performance of equalized and non equalized system is observed. The BER performance improves as distance between divers increase because the transmission power is adjusted according to the most affected carrier and less affected part of the spectrum performs better. This way, as the distance increases the performance increases. For modulation level of M=16 the BER of equalized system is below $4\ 10^{-3}$ providing around 125 kbps bit rate whereas for non equalized system the BER is around $140\ 10^{-3}$ providing around 118 kbps bit rate.

In the presence of Doppler shift, where the relative velocity is 1 m/sec, for diver scenario #1 with boundary state scenario #1, the need for equalizer is even more crucial. In APPENDIX E.1, the BER and data rate performance of the Doppler shift affected communication is depicted. For 1 msec OFDM pulse length the BER with equalizer is 180 10^{-3} and without equalizer 260 $10^{-3}$for modulation level of M=16.

It can be concluded that the OFDM system in the presence of multipath propagation within the OFDM pulse period need either low level of modulation or a frequency domain equalizer, whose parameters are set using a known bit sequence. Lower level of modulations lead to low data rate, therefore simple frequency domain equalizer is needed for underwater communication systems that use OFDM.

- *Effect of diver scenarios on the communication performance:*

Diver positions underwater define the multipath signals arrival and frequency selective fading. It is found that scenarios having divers just beneath the sea surface or just above the sea floor provides the worst performance, namely diver scenarios #1 and #3, due to strong multipath reflections from the boundaries. Scenarios that have divers towards the middle of depth of the sea; namely diver scenario #2 provide better performance because the multipath reflections are received with considerable power attenuation as compared to the direct OFDM pulse and the multipath signals are received outside of the main OFDM pulse.

For diver scenario #1 and diver scenario #2 with boundary state scenario #1, the delay spread profile with respect to distance between the divers is at most 2.2 msec and 1.8 msec respectively, as depicted in Figure 5.19 and Figure 5.22.

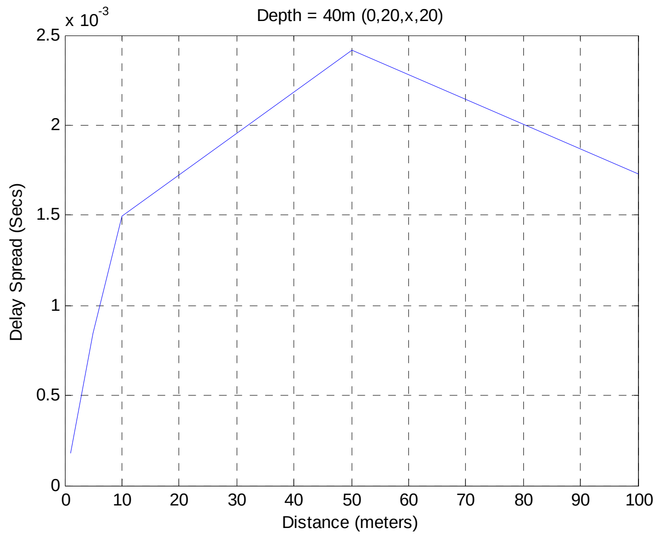


Figure 5.22: Delay spread profile of diver scenario#1 and #2 with boundary state scenario#1

The BER performance for the diver scenario #1 and # 2 of OFDM communication system having pulse length 1 msec using equalizer in motionless case is depicted in Figure 5.23.

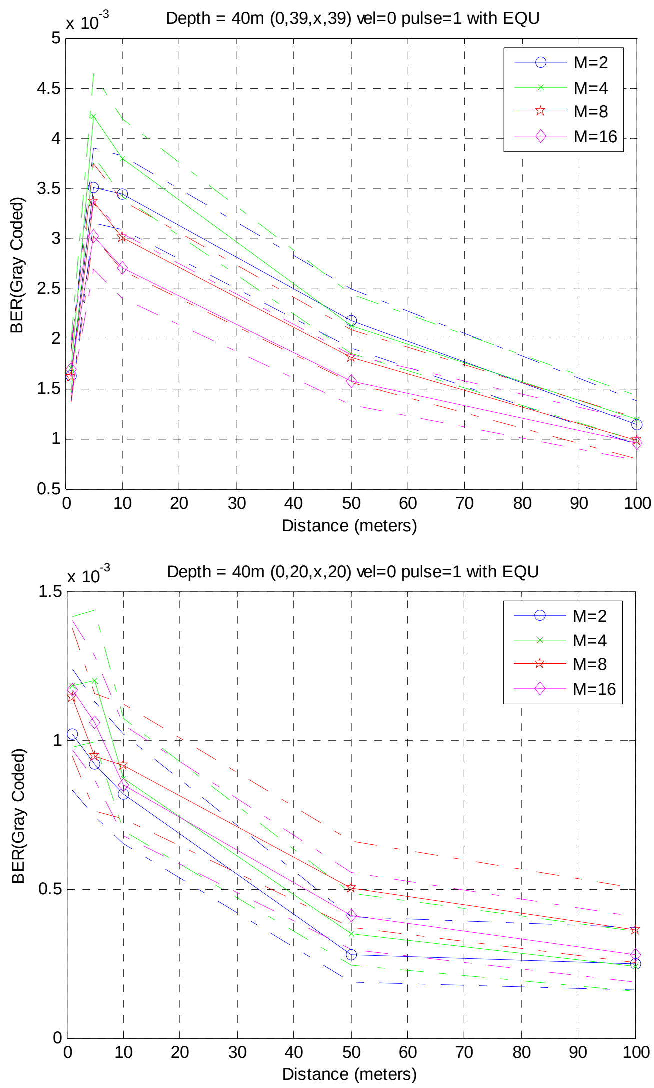


Figure 5.23: BER performance of the diver scenario#1 and #2

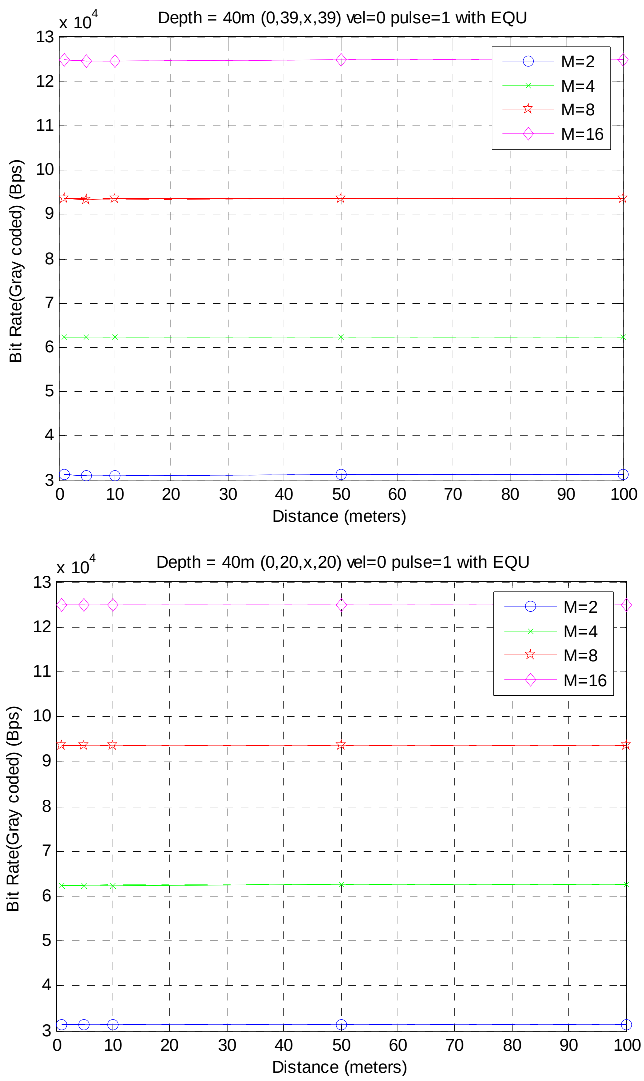


Figure 5.24: Bit rate performance of the diver scenario#1 and #2

From Figure 5.23 and Figure 5.24, the effect of diver scenarios on the communication system is observed. The BER performance of the communication system for diver scenario #1 and diver scenario #2 are less than 4.5 10^{-3} and 1.5 10^{-3} providing around 125 kbps bit rate for modulation level of M=16 respectively.

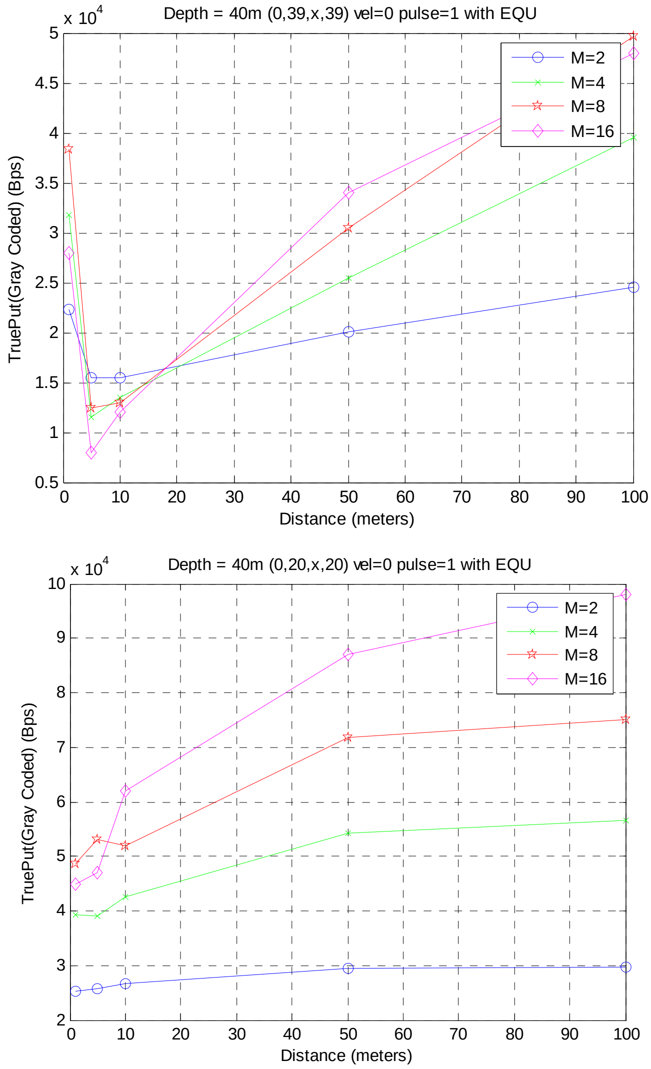


Figure 5.25: Trueput performance of the diver scenario#1 and #2

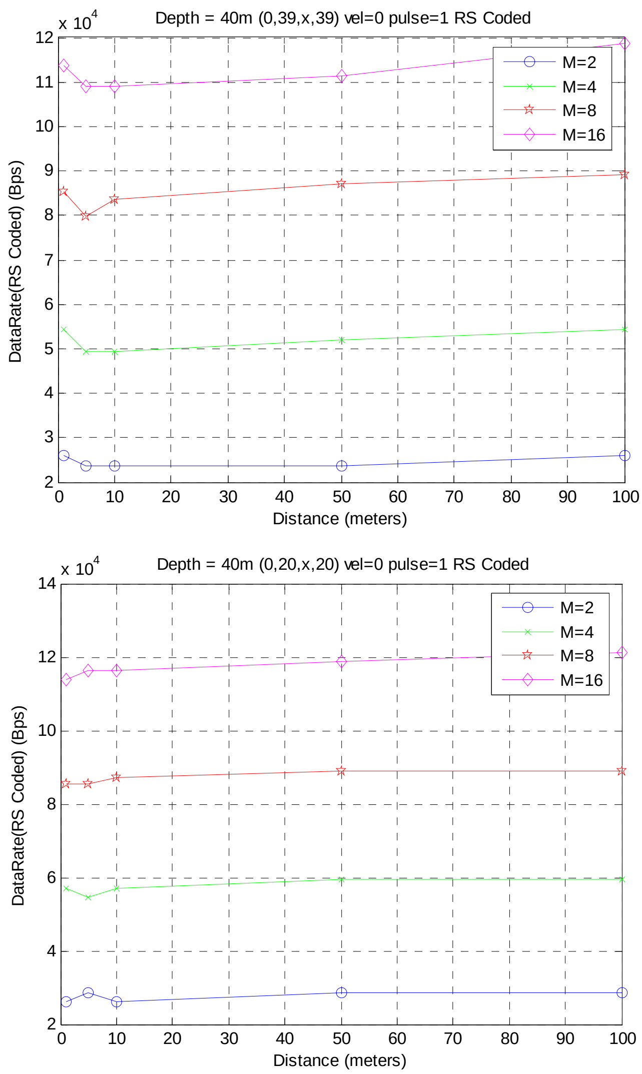


Figure 5.26: RS Coded data rate performance of the diver scenario#1 and #2

From Figure 5.25 and Figure 5.26 the trueput and RS coded data rate performance of the two scenarios is observed. The trueput performance results are low, therefore error coding is necessary. With suitable RS error coding parameter, better data rate performance is achieved. For diver scenario #1 around 110 Kbps data rate using RS(100,90) and for diver scenario #2 around 120 Kbps data rate is achieved using RS(100,96) error coding for modulation level of M=16.

For diver scenario #3 with boundary state scenario #1 in motionless case, the communication system performance is depicted in APPENDIX E.2. The system with 1 msec OFDM pulse length modulation level of M=16 has less than 3.5 10^{-3} BER and achieves 114 Kbps using RS(100, 92) error coding.

Diver scenario #2 provides much better communication performance than diver scenario #1 because the multipath signals arrive at the receive much later than the main OFDM pulse and with considerable level of attenuation. For diver scenario #1, the multipath signals arrive within the main OFDM pulse with less attenuation. Since for diver scenario#1 there is multipath propagation the equalizer parameters cannot be set perfectly due to present noise in the system, therefore the BER performance is worse than the diver scenario #2.

The simulation results reveal that diver scenarios affect the performance of the systems. The scenarios having considerable multipath signal provides worse performance, namely diver scenario#1. Therefore, communication system parameters shall be selected according to worst diver scenario.

- *Effect of boundary state scenarios on the communication performance:*

Boundary state scenarios define the boundary reflection losses due to wind on the surface and floor structure on the sea floor. In our simulations there are two boundary state scenarios as given in Table 5.16. It is found from the simulation results that worse Sea-State and more porosity sea floor conditions provide better performance. The reason for the better performance is that for worse conditions, the boundary losses increases, therefore the multipath reflection is received with less power. Since multipath reflection power is less, the equalizer parameters can be set more precisely and therefore better BER and data rate performance is achieved.

For boundary state scenario #1 and #2 with diver scenario #1, the delay spread profile with respect to distance between the divers is at most 2.2 msec and 1.8 msec respectively, as depicted in Figure 5.27.

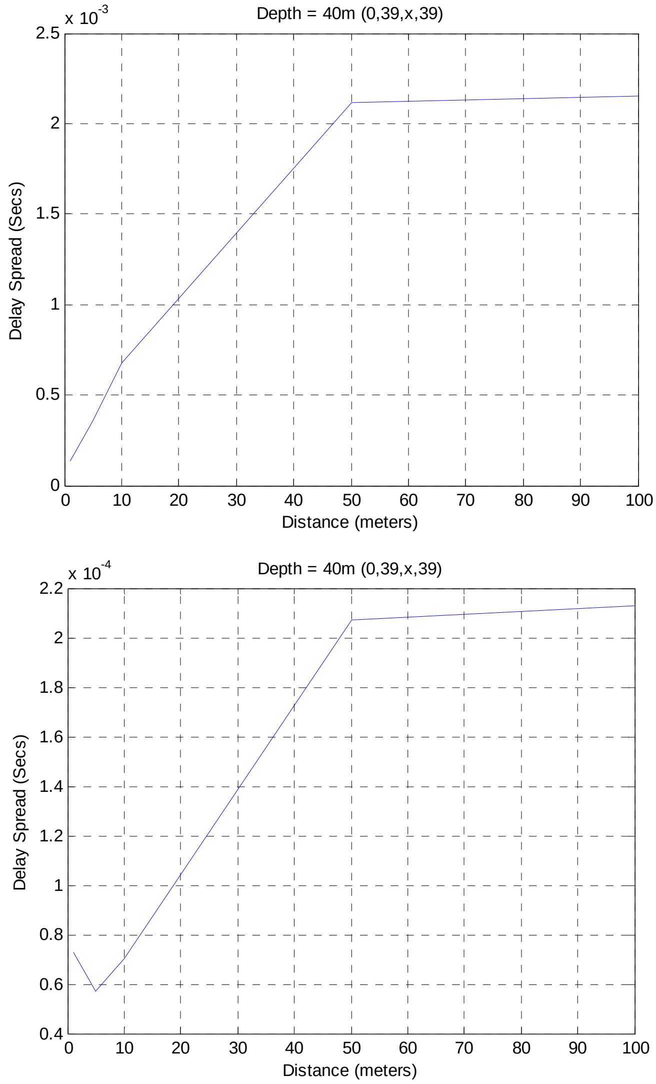


Figure 5.27: Delay spread profile of diver scenario#1 for boundary state scenario#1 and #2

The BER performance of diver scenario #1 for boundary state scenario #1 and #2 of OFDM communication system having pulse length 1 msec using equalizer in motionless case is depicted in Figure 5.28.

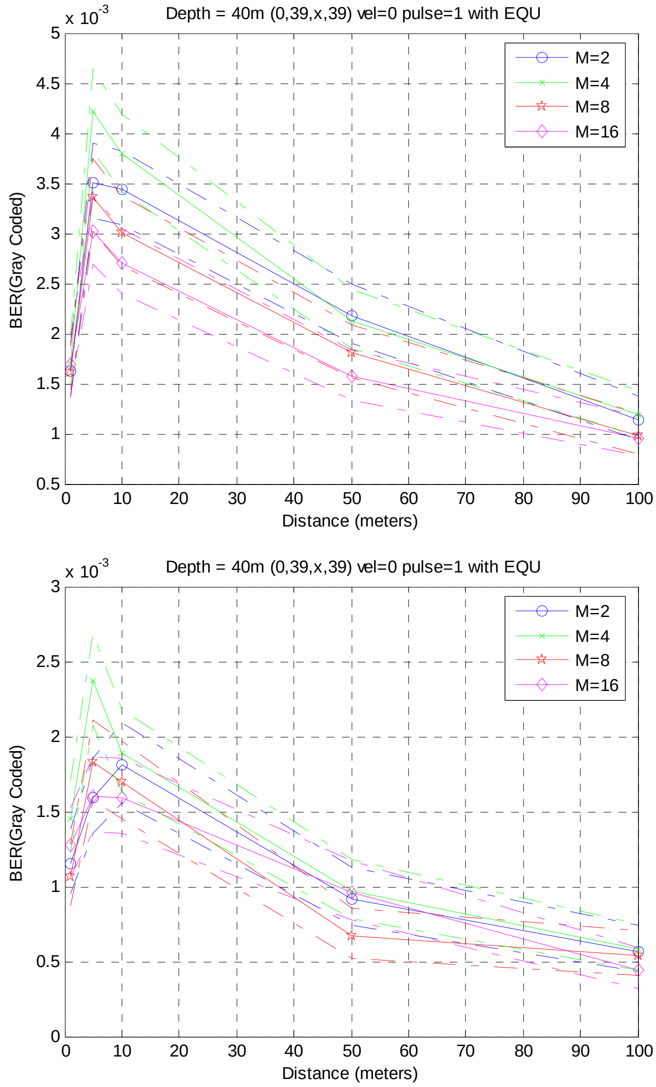


Figure 5.28: BER performance of the diver scenario#1 for boundary state scenario#1 and #2

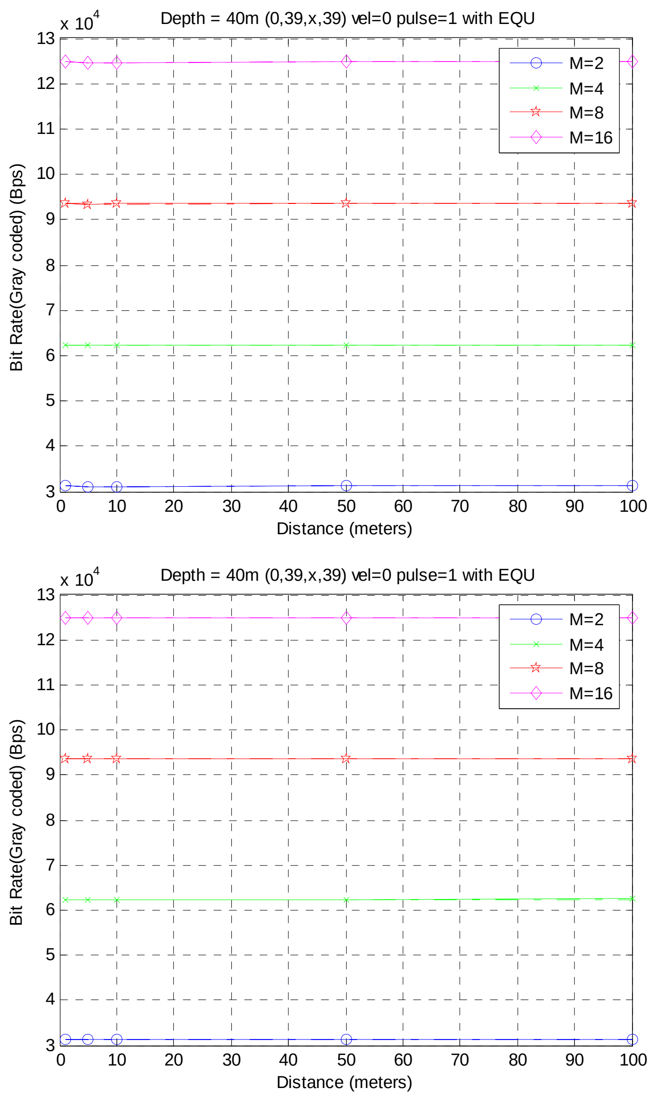


Figure 5.29: Bit rate performance of the diver scenario#1 for boundary state scenario#1 and #2

From Figure 5.28 and Figure 5.29, the effect of boundary state scenarios on the communication performance is observed. The BER performance of communication system for boundary state scenario #1 and #2 are less than 4 10^{-3} and 2.2 10^{-3} respectively providing both 125 Kbps bit rate for modulation level of M=16 respectively.

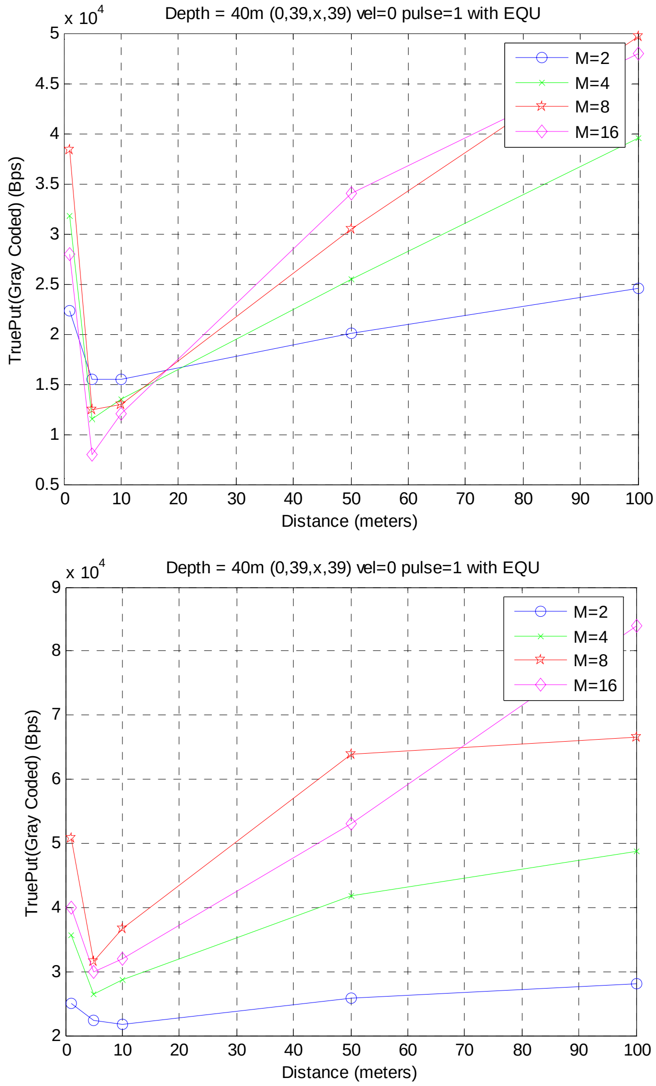


Figure 5.30: Trueput performance of the diver scenario#1 for boundary state scenario#1 and #2

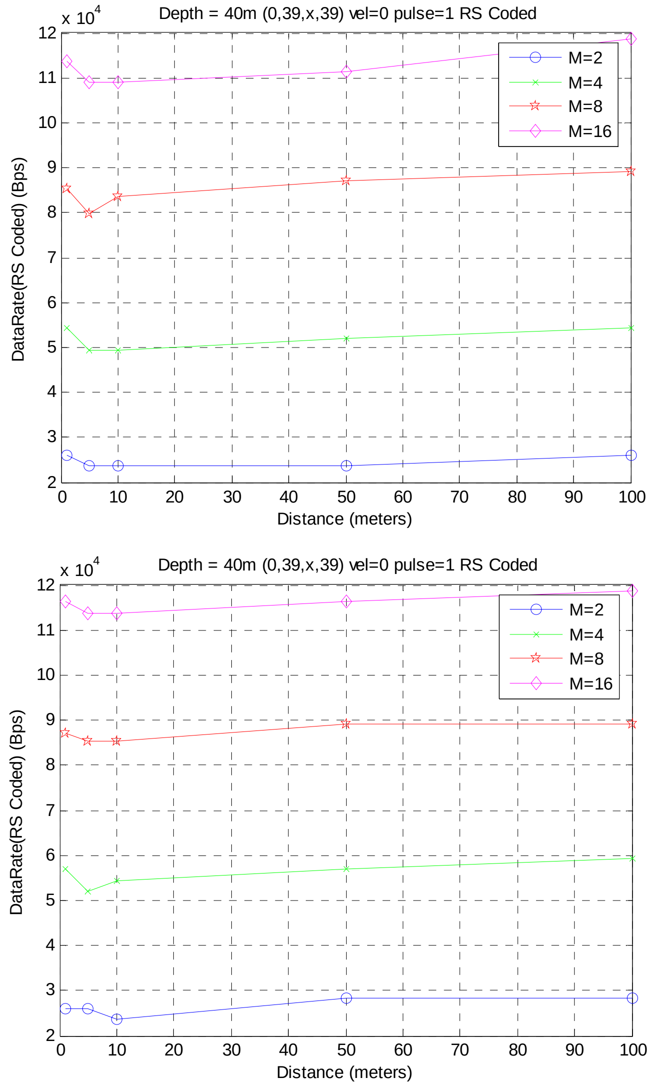


Figure 5.31: RS Coded data rate performance of the diver scenario#1 for boundary state scenario#1 and #2

From Figure 5.30 and Figure 5.31 the trueput performance and RS coded data rate performance is observed. The performance of boundary state scenario#2 is better than #1. For boundary state scenario#2, error coded data rate around 115 Kbps data rate is achieved whereas for scenario#1 around 110 Kbps data rate for modulation level of M=16.

Boundary state scenario#2 provides better BER and bit rate because the multipath signals for boundary state scenario#2 arrive with less power than scenario #1. Since the multipath signals are attenuated more, the equalizer parameters are set much precisely and better BER performance is achieved.

The simulation results reveal that boundary state scenarios affect the performance of the systems. The scenarios with more boundary losses provide better performance. Boundary state scenarios#1 provides worse performance. Therefore, communication system parameters shall be selected according to worst boundary state scenario.

- *Effect of Doppler Shift on communication performance in Doppler shift only environment:*

Doppler shift greatly affect the communication performance in OFDM communication systems because Doppler shift destroys the orthogonality of the carriers; therefore simple frequency domain equalizers fail to equalize the affected signal. Diver scenario #2 shows the effect of Doppler shift only because the multipath signals are attenuated sufficiently.

For diver scenario #2 with boundary state scenario #1 the delay spread profile with respect to distance is 1.8 msec, as depicted in Figure 5.22.

The BER and bit error performance for the diver scenario # 2 of OFDM communication system having pulse length 1 msec using equalizer in Doppler shift environment, where the relative velocity between the divers is 1 m/sec is depicted in Figure 5.32.

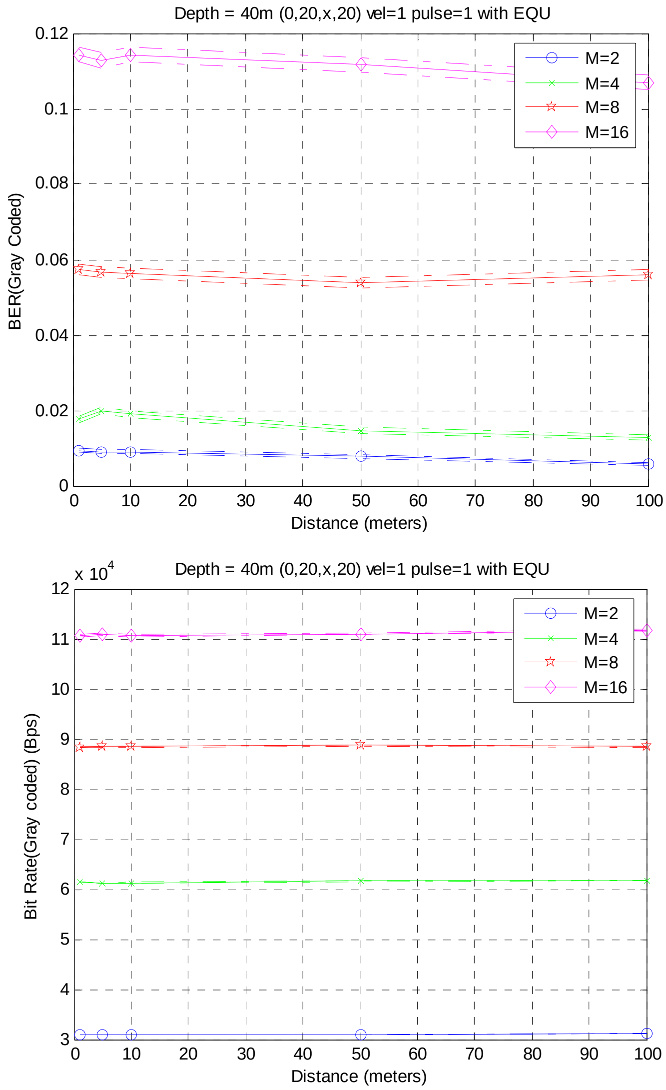


Figure 5.32: BER and bit rate performance of the diver scenario#2 and boundary state scenario#1 with Doppler shift (*v*=1 m/sec)

From Figure 5.32, the effect of Doppler shift on the communication performance is observed. The BER performance of communication system for diver scenario #2 with boundary state scenario #1 are around 150×10^{-3} providing around 110 Kbps bit rate for modulation level of M=16.

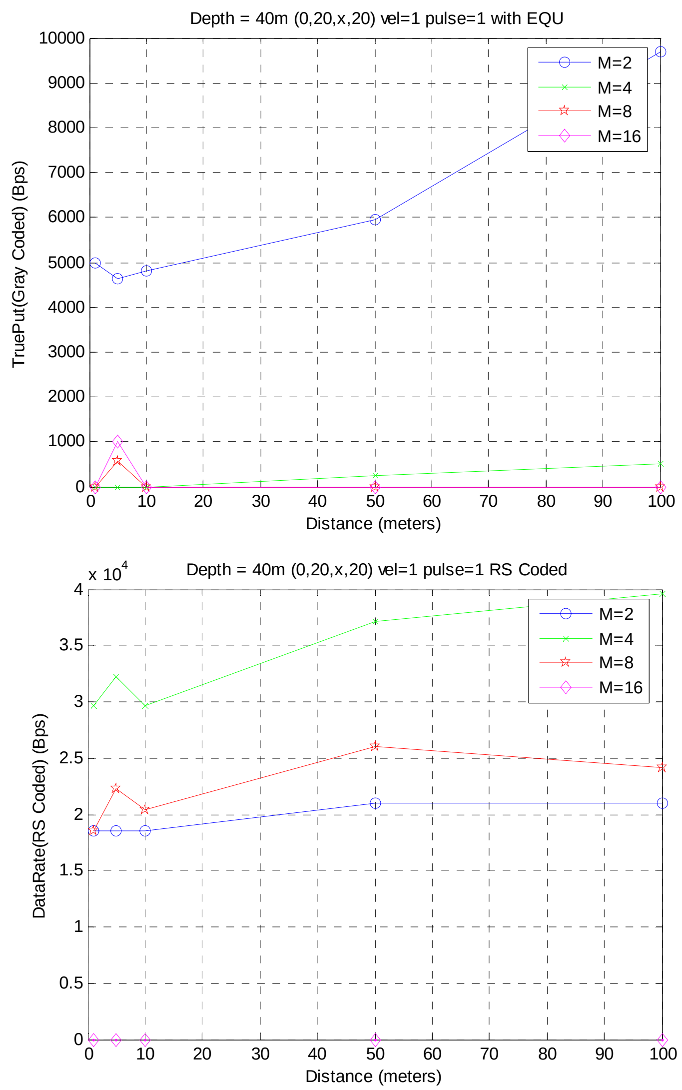


Figure 5.33: Trueput and RS coded data rate performance of the diver scenario#2 and boundary state scenario#1 with Doppler shift (v=1 m/sec)

From Figure 5.33, it is observed that the trueput performance of the communication system in Doppler shift environment is very low; therefore error coding is necessary. Using RS error coding with suitable parameters communication is made possible. At 50 m for modulation level of M=4, around 37 Kbps data using RS(50,30) error coding is achieved. It is worth mentioning that without using error coding for modulation level of M=8 and M=16, no communication is achieved without errors. Also it is observed from Figure 5.33 that using error coding, higher level of modulation does not always provide better data rate performance, in this scenario QPSK modulation provides the best communication performance.

In a Doppler shift environment, the BER performance is very low for higher order modulations. BER performance of this rate is not acceptable for digital communication systems unless special care is taken. The solution is either using lower modulation schemes or using error coding or changing the OFDM pulse length.

It was discussed in previous chapters that there is a trade of between the OFDM pulse length and the achievable data rate. Using shorter OFDM pulses provides resistance to Doppler shift and provides better BER. The pulses cannot be arbitrarily short because the achievable data rate decreases. The following figures depict the communication performance with respect to OFDM pulse length for distance between the divers 50 m.

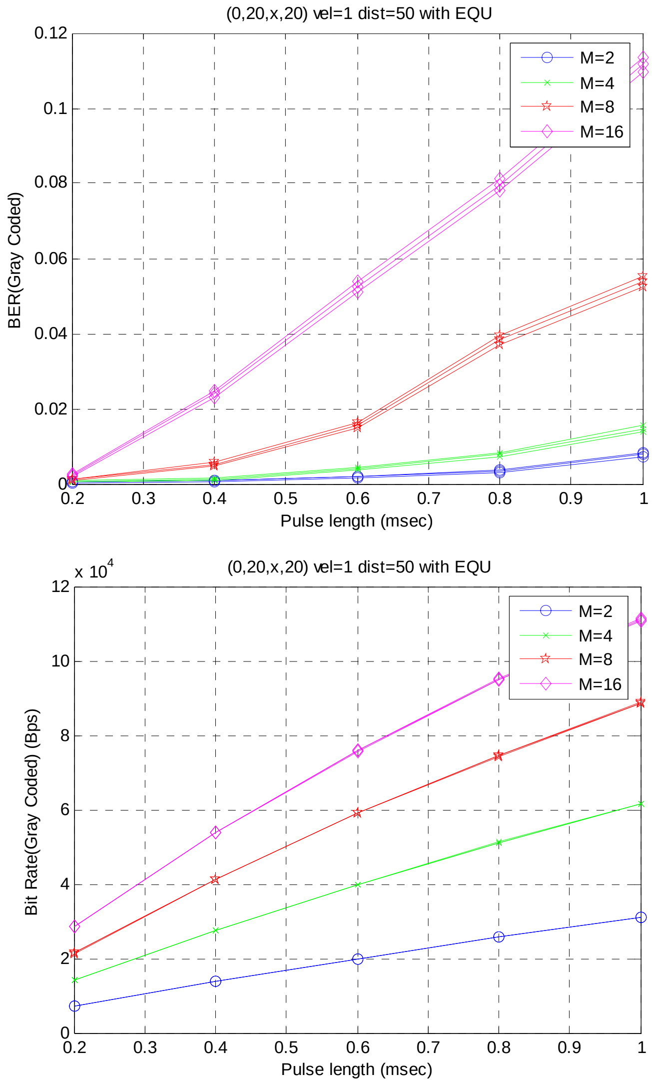


Figure 5.34: BER and bit rate performance of the diver scenario#2 and boundary state scenario#1 with Doppler shift (v=1 m/sec) with respect to OFDM pulse length

From Figure 5.34 the effect of OFDM pulse length on OFDM communication system in a Doppler shift environment is observed. As the OFDM pulse length increases the BER performance degrades considerably; therefore choosing OFDM pulse length long or level modulation higher does not guarantee higher data rate.

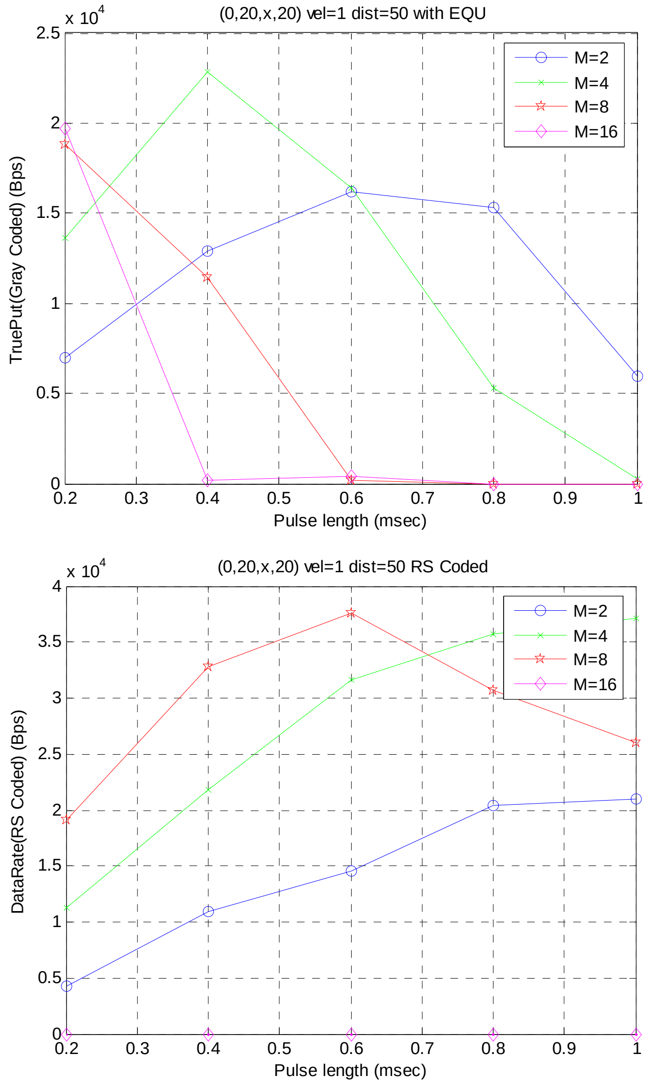


Figure 5.35: Trueput and RS coded data rate performance of the diver scenario#2 and boundary state scenario#1 with Doppler shift (v=1 m/sec) with respect to OFDM pulse length

From Figure 5.35, it is observed that the trueput performance of the communication system in Doppler shift environment is poor. At 50 m using RS error coding data rate around 37.6 Kbps data rate using RS(45,38) error coding is achieved for modulation level of M=8 for OFDM pulse length 0.6 msec.

At 100 m the communication system performance is depicted in APPENDIX E.3. The system under Doppler shift of relative velocity 1 m/sec, with 1 msec OFDM pulse length modulation level of M=4 achieves 39.6 Kbps using RS(50, 32) error coding.

At 100 m the communication system performs maximum RS coded data rate at 0.6 msec using modulation level of M=8 and achieves 39.6 Kbps using RS(45,40) error coding.

The trade of between the OFDM pulse length and BER and coded data rate is observed from Figure 5.34 and Figure 5.35. When OFDM pulse length is shorter, the system is more resistant to Doppler shift; therefore has better BER; however the data rate is lower. When OFDM pulse length is longer there are more carriers that carry data; however the resistance to Doppler shift is lower; therefore the data rate performance is poor. The performance is also dependent on the level of modulation. When the level of modulation is high, the ideal data rate is higher; however, the BER is poor therefore the overall data rate performance is poor.

The simulation results reveal that BER and data rate performance in a Doppler shift environment is very low, due to fact that Doppler shift destroys the orthogonality of the carriers. Since the orthogonality between the carriers is lost, the frequency domain equalizers fail to recover the affected signal, leaving considerable amount of error at the output. The communication performance is dependent on the OFDM pulse length, level of modulation and error correcting codes. There is a trade of between the pulse length and achievable data rate. This way the underwater communication system parameters have to be selected for the scenarios containing Doppler shift because it provides the worst case condition. When the system is designed for the worst case conditions, it provides that the system shall guarantee the same performance for all scenarios.

- *Worst case scenarios; effect of Doppler Shift and multipath on communication performance:*

We expect that the communication performance under the effect of Doppler shift and multipath with bad boundary state conditions shall provide the worst expected channel conditions. The reason is that the Doppler shift destroys the orthogonality of the carriers, and multipath propagation creates frequency selective fading. The frequency selective fading is overcame using frequency domain equalizers however due to Doppler effect, the frequency domain equalizers fail to equalize the OFDM signals.

For diver scenario #1 with boundary state scenario#1, the delay spread profile with respect to distance is 2.2 msec, as depicted in Figure 5.19.

The BER and bit error performance for the diver scenario # 1 of OFDM communication system having pulse length 1 msec using equalizer in Doppler shift environment where the relative velocity between the divers is 1 m/sec and multipath propagation is depicted in Figure 5.36.

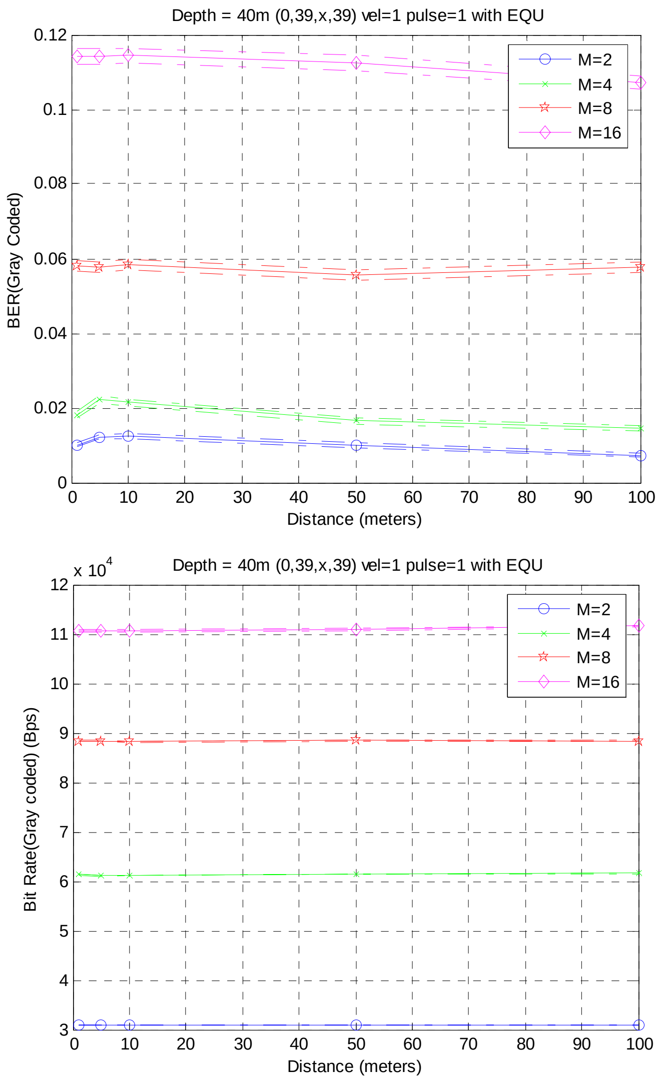


Figure 5.36: BER and bit rate performance of the diver scenario#1 and boundary state scenario#1 with Doppler shift (v=1 m/sec) and multipath

From Figure 5.36, the effect of Doppler shift and multipath propagation on the communication performance is observed. The BER performance of communication system for diver scenario #1 with boundary state scenario #1 are around 160 10^{-3} providing around 110 Kbps bit rate for modulation level of M=16.

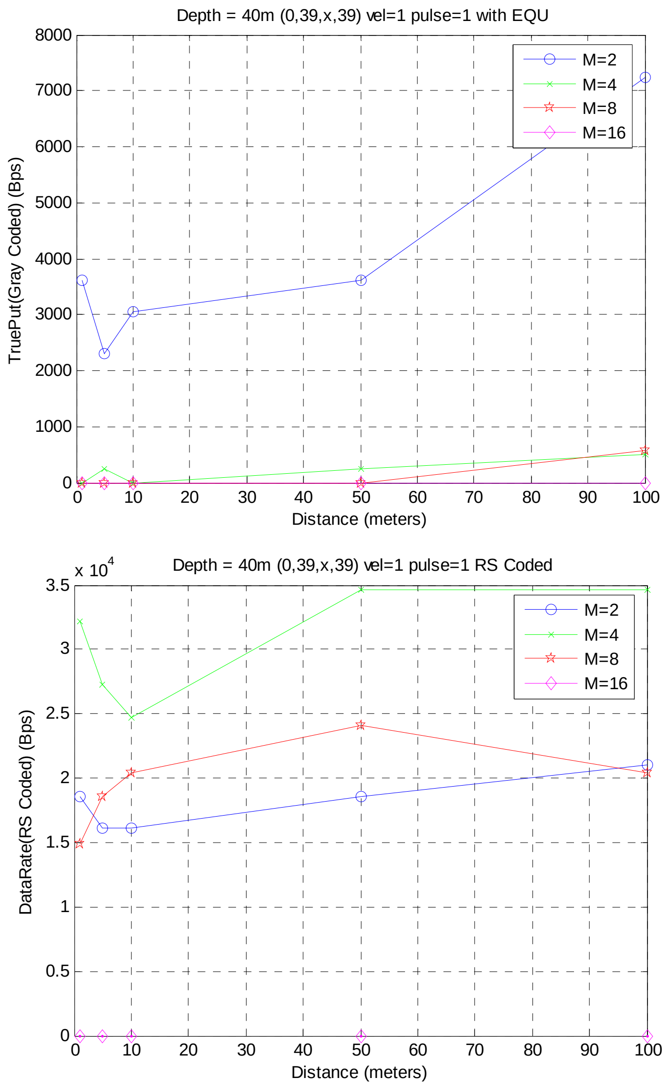
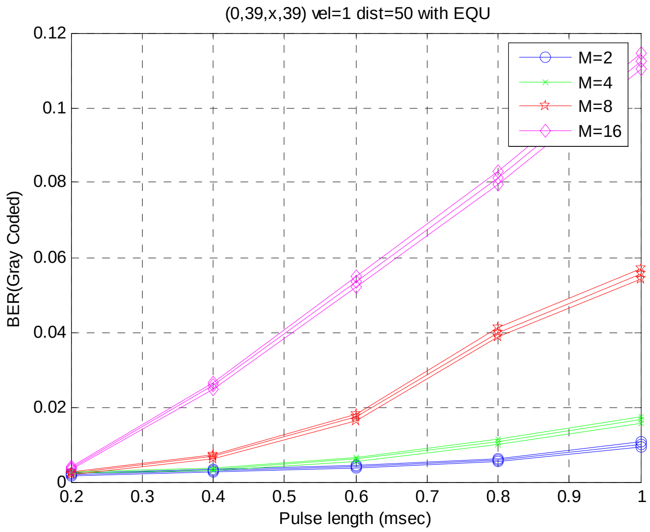


Figure 5.37: Trueput and RS coded data rate performance of the diver scenario#1 and boundary state scenario#1 with Doppler shift (*v*=1 m/sec) and multipath

From Figure 5.37, it is observed that the trueput performance of the communication system in Doppler shift environment and multipath is very low; therefore error coding is necessary. Using RS error coding with suitable parameters, communication is made possible at 50 m for modulation level of M=4, around 35 Kbps data rate is achieved using RS(50,30) error coding. Like the previous case, without using error coding for modulation level of M=8 and M=16 no communication is achieved without errors. It can be observed from Figure 5.37 that using error coding, higher level of modulation not always provides better data rate performance, in this scenario QPSK modulation provides the best communication performance.

Like the previous case, the communication is possible either using error coding or using low level of modulation or short OFDM pulse length selection.

The effect of OFDM pulse length shall reveal the effect under both Doppler shift and multipath propagation. The trade of between the OFDM pulse length and achievable data rate is depicted in the following graphs for distance 50 m.



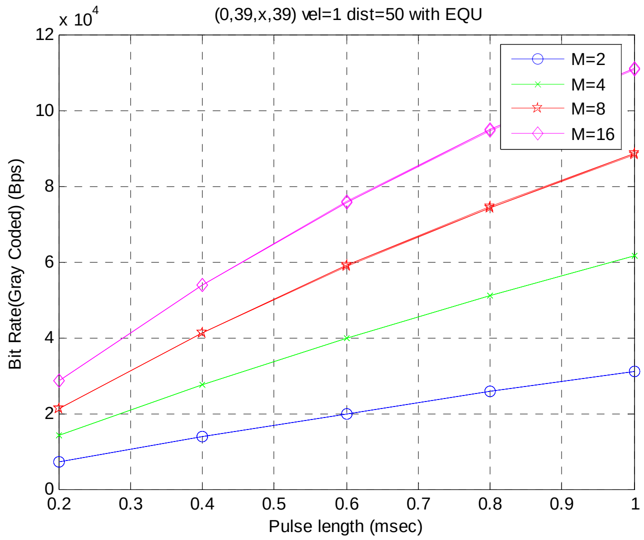


Figure 5.38: BER and bit rate performance of the diver scenario#1 and boundary state scenario#1 with Doppler shift (v=1 m/sec) and multipath with respect to OFDM pulse length

From Figure 5.38, it is observed that the BER increases with OFDM pulse length like the previous case. The reason for BER increase is that for longer pulse lengths, the resistivity to Doppler shift decreases. For Doppler shift and multipath propagation scenarios, the BER performance is very close to only Doppler shift case because the effect of multipath propagation is almost overcame using frequency domain equalizer. However, from the trueput and RS coded data rate performances the difference shall be observed.

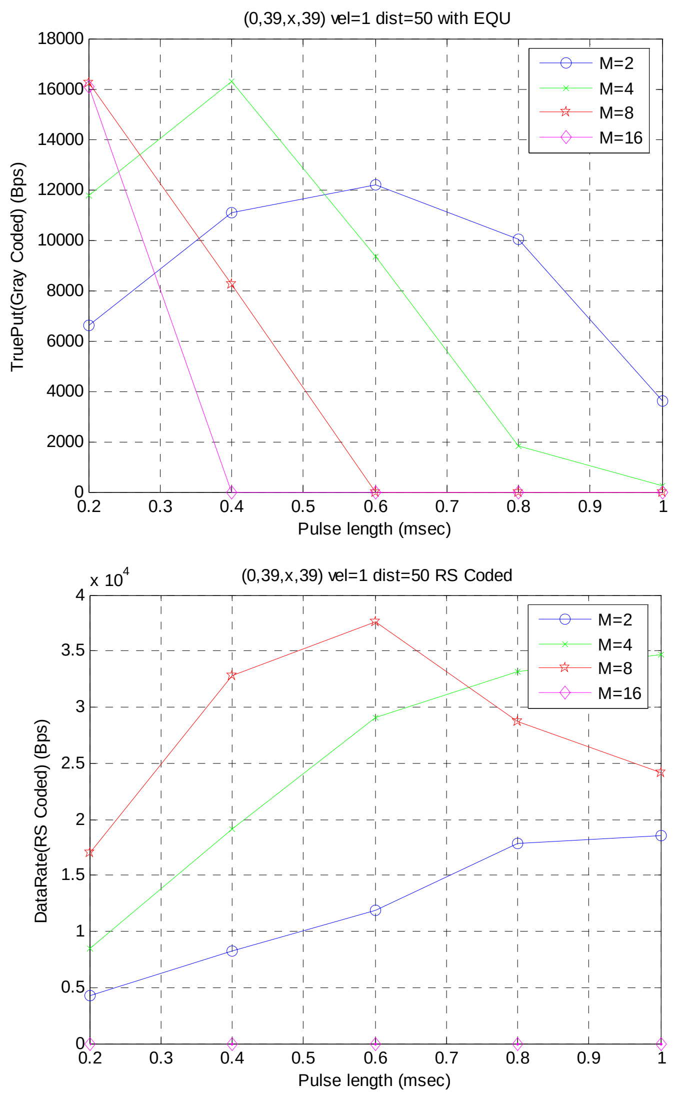


Figure 5.39: Trueput and RS coded data rate performance of the diver scenario #1 and boundary state scenario #1 with Doppler shift (v=1 m/sec) and multipath with respect to OFDM pulse length

From Figure 5.39, it is observed that the trueput performance of the communication system in Doppler shift environment is poor like the previous case. The performance is slightly worse than the previous case, because the frequency domain equalizer almost has the same equalization capability with the previous case. However there is slight difference, which is due to the fact that the lost orthogonality by Doppler shift affects the frequency domain equalizer parameters. Using RS(45,38) error coding data rate around 37.6 Kbps data rate is achieved for modulation level of M=8 at OFDM pulse length 0.6 msec.

At 100 m the communication system performance is depicted in APPENDIX E.4. The system under Doppler shift of relative velocity 1 m/sec, with 1 msec OFDM pulse length modulation level of M=4 achieves 34.6 Kbps using RS(50, 28) error coding.

At 100 m the communication system performs maximum RS coded data rate at 0.6 msec using modulation level of M=8 and achieved 39.6 Kbps using RS(45,40) error coding.

For diver scenario #3 with boundary state scenario #1 at 50 m in Doppler shift environment, the communication system performance is depicted in APPENDIX E.5. The system under Doppler shift of relative velocity 1 m/sec, with 1 msec OFDM pulse length modulation level of M=4 achieves 32.1 Kbps using RS(50, 26) error coding.

At 50 m the communication system performs maximum RS coded data rate at 0.6 msec using modulation level of M=8 and achieved 35.6 Kbps using RS(45,36) error coding.

For diver scenario #3 with boundary state scenario #2 at 50 m in Doppler shift environment, the communication system performance is depicted in APPENDIX E.6. The system under Doppler shift for relative velocity 1 m/sec, with 1 msec OFDM pulse length and modulation level of M=4 achieves 37.1 Kbps using RS(50, 30) error coding.

At 50 m the communication system performs maximum RS coded data rate at 0.6 msec using modulation level of M=8 and achieved 37.6 Kbps using RS(45,38) error coding.

Comparing this case with the previous case, which contains only Doppler shift, both performances are low, however the performance is lower with the Doppler shift and multipath propagation case. The reason is that the Doppler shift destroys the orthogonality. The loss in orthogonality avoids the frequency domain equalizers' parameters from being set accordingly. This leads to considerable BER and low trueput. In order to overcome the low performance, error coding has to be used along with frequency domain equalizer. The problem can also be overcame using shorter OFDM pulses that shall have more resistivity to dopper shift, however shorter pulses leads to fewer carriers; therefore less data rate. There is a trade of between the data rate and OFDM pulse length, which defines the resistance to Doppler shift as depicted in Figure 5.39.

5.3 Discussion

The underwater acoustic communication system is a wideband multi-user digital system that uses OFDM spread spectrum technique. The communication system has several parameters that have to be optimized to get guaranteed performance in every condition and scenario. The parameters to be set are transmission power, OFDM pulse length, level of modulation and error correcting code parameters. There is trade of between the communication parameters and the achievable data rate.

The spread spectrum OFDM technique is selected for its inherent capability of rejecting multipath signals. The capability is made possible by using frequency domain equalizers. In order to preserve the orthogonality between the carriers, cyclic extension has to be added at the end of the OFDM pulses. The cyclic extension has to be as long the maximum expected delay spread of the communication system. In our environment, where the total distance between the divers shall be at most 100 m and the depth shall be as long as 100 m, the maximum expected delay spread is 5.4 msec, for boundary state scenario #1 and Sea-State-0. The cyclic extension therefore is selected 5.4 msec for the OFDM communication system.

The acoustic transmission power shall be adjusted according to the distance between the transmitter and the receiver. The distance between the users is gathered using RTS/CTS packet exchange.

The simulation results shows that in motionless case for diver scenario #1 and boundary state scenario #1 at using 1 msec OFDM pulse length and modulation level of M=16 the BER decreased from 140 10^{-3} to less than 4 10^{-3} providing 118 Kbps error coded data rate using a frequency domain equalizer. Similarly with the same scenario for Doppler shift environment the BER decreased from 250 10^{-3} to less than 180 10^{-3}. The underwater communication system shall employ a simple frequency domain equalizer, whose parameters are set using RTS/CTS packet exchange.

The communication scenario and conditions shall vary during the operational usage. According to the scenarios and conditions, the communication channel and therefore the achievable data rate shall change. If we find the worst conditions and set the communication parameters accordingly, we shall have guaranteed performance for all operational usage. In order to find the worst conditions several simulations are performed, including changing divers', positions varying Sea-State and sea floor conditions and changing mobility of the users.

To find the worst diver positions, diver state scenarios are created. The BER performances of the communication system, which has 1 msec OFDM pulse length and modulation level of M=16, for scenarios #1, #2 and #3 are less than 4.5 10^{-3}, 1.5 10^{-3} and 3.5 10^{-3} providing 110 Kbps, 120 Kbps and 114 Kbps error coded data rate respectively. It is observed from the results that diver scenario #1, for which both divers are 1 m beneath the surface, is the worst diver position for the communication system performance.

Similarly the boundary state conditions affect the communication performance. For diver scenario #1, OFDM pulse length 1 msec and modulation level of M=16, BER performance of boundary state scenario #1 and #2 are less than 4 10^{-3} and 2.2 10^{-3} providing 110 Kbps and 120 Kbps error coded data rate respectively. It is concluded from the results that the good Sea-State and rigid sea floor conditions provide poor communication performance.

When the conditions are not stationary, the communication system performances degrade considerably. This is due to the fact that relative velocity between the divers create Doppler shift at the received signals. The Doppler shift destroys the orthogonality of the carriers, which can not be perfectly equalized with simple equalizers.

For diver state scenario #2, which has only the Doppler shift effect to the communication, BER performance of around 115 10^{-3} is achieved for modulation level of M=16 and OFDM pulse length of 1 msec. At 50 m distance, for modulation level of M=4 and OFDM pulse length of 1 msec, error coded data rate of 37 Kbps is achieved. At 50 m distance, maximum data rate of 37 Kbps is achieved for 0.6 msec OFDM pulse length and M=8 level of modulation. For 100 m distance, maximum data rate of 39 Kbps is achieved for 0.6 msec OFDM pulse length and M=8 level of modulation.

The communication channel in general has both the mobility and multipath impairments. For diver state scenario #1, for OFDM pulse length of 1 msec and modulation level of M=16, 160 10^{-3} BER is achieved. At 50 m distance, for pulse length of 1 msec and modulation level of M=4, 35 Kbps is achieved. At 50 m distance, the maximum error coded (RS(50,38)) data rate of 37 Kbps is achieved for OFDM pulse length of 0.6 msec and modulation level of M=8. At 100 m distance, maximum error coded (RS(50,40)) data rate of 39 Kbps is achieved for 0.6 msec OFDM pulse length and M=8 level of modulation.

For diver state scenario #3 with boundary state scenario #1 at 50 m distance using 0.6 msec OFDM pulse length and modulation level of M=8, 35.6 Kbps error coded (RS(50,36)) data rate is achieved. Similarly for boundary state scenario #2 using 0.6 msec OFDM pulse length and modulation level of M=4, 37.6 Kbps error coded (RS(50,38)) data rate is achieved.

The OFDM communication system performance is poor when users are mobile. The performance is even worse when users are mobile beneath the boundaries because this way there is considerable multipath propagation from the boundaries. The frequency domain equalizers fail to equalize the affected signal and for error free communication, forward error correcting codes has to be used. For our system, we shall use RS error codes.

From the simulation results, the worst diver condition is at diver scenario #1 and #3. For diver scenario #1 and #3, with OFDM pulse length 0.6 msec and modulation level of M=8, 37 Kbps and 35.6 Kbps error coded data rate at 50 m respectively. System performance in diver scenario #3 is worse than scenario #1; however, scenario #3 is not much probable diver scenario that can be experience in normal diving conditions.

The specifications of the underwater communication system and optimum communication parameters to achieve guaranteed performance are listed in Table 5.18.

Transmission center frequency	300 KHz
Total Bandwidth	200 KHz
Transducer	Wideband Acoustic Transducer
OFDM pulse length	0.6 msec
Level of Modulation (M)	8
RS code parameters	RS(50,38)
Transmission power	Adjusted for 300^{th} KHz carrier at certain distance for 1 10^{-3} BER
Channel Sounding and Equalization	RTS/CTS Packet Exchange Frequency Domain Equalization
Maximum relative velocity	1 m/sec
Maximum expected Doppler Shift	200 Hz @ 300 KHz
Maximum expected Delay Spread	5.4 msec
Cyclic Extension	5.4 msec
BER	15 10^{-3}
Achievable Data Rate	37.6 Kbps

Table 5.18: Optimum communication system parameter for guaranteed performance

Choosing communication system parameter for diver scenario #1 in Doppler shift environment shall provide guaranteed performance for every condition and scenario in a diving session.

The underwater communication system shall have multi-user capability. In a network based topology more than one user shall occupy the shared spectrum and shared medium at the same time. In Section 3.1.5 , the needed data rate for user applications is discussed. For low bit rate data applications, each user shall require around 2 Kbps. For high bit rate data application, which is voice, each user shall require at most 9.6 Kbps and on the average 5 Kbps using IS-95 QCELP voice coding algorithm. Totally, one user shall approximately require on the average 7 Kbps data rate.

The communication system is capable of providing 37.6 Kbps data rate using the overall spectrum for the worst case scenarios. Since each user require only 7 Kbps, the shared spectrum can be allocated to different users by assigning different carriers to different users, and provide multi-user communication. A rough estimation of how many users can be occupied at the same time within the total spectrum is given in (5.1).

$$\text{Number of Users} \approx 37.6 \text{ Kbps} / 7 \text{ Kbps} \approx 5 \text{ Users} \qquad (5.1)$$

The system shall support on the average 5 user to communicate at the same time by assigning different users, different OFDM carriers. In normal diving session, it is expected that users shall occupy the channel for periods of time and within the remaining time shall remain silent. This way the communication system, like a trunk radio system, could occupy more than 5 users with certain Grade of Service (GOS) [9, 77-86].

(5.1) depicts a pessimistic expression for how many users can occupy the channel at the same time because it is achieved for the worst case conditions. For better conditions, where the users are stationary or a mobile with a relative velocity much less than 1 m/sec, better communication performances are achieved. For example for M=16 and pulse length 1 msec, motionless, however frequency selective fading case, 110 Kbps data rate is achieved. When the system can support 110 Kbps then total number of users that can communicate at the same time would be around 16.

From the discussion, it can be concluded that the communication system can provide more than 5 Users if the system can adopt its parameters according to the changing conditions. The adaptive algorithm shall require more payload for MAC protocol, however in the end shall occupy more users' communication at the same time.

For changing conditions, the channel conditions shall be gathered using RTS/CTS packet exchange, like gathering the distance between the divers. During the packet exchange channel properties, such as distance, multipath and mobility parameters can be obtained and the communication system shall be adapted to the changing conditions. The adaptive algorithm shall decide on the communication parameters by measuring the bit error rate performance of the current system.

Chapter 6

Conclusion

In this work, a spread spectrum digital, multi-user communication system for SCUBA divers is investigated and proposed. The system shall provide divers communication within total distance of 100 m and total depth of 100 m. The communication system investigated in this work provides not only voice communication but also telemetry and diver specific data as well.

The spread spectrum communication is made available by specially designed wideband acoustic transducer. The acoustic transducer allows wideband communication by the help of the recent developments in ceramics. The system shall have 200 kHz bandwidth around 200 kHz center frequency.

The proposed system in this work has a layered architecture, comprising of *application layer*, *network layer*, *link layer* and *physical layer*. In this work, we mainly focused on *application layer*, *link layer* and *physical layer*.

The top layer of the system, *application layer*, contains the data source, which is voice, telemetry and diver specific data. The voice shall be compressed and coded with IS-95 QCELP voice coder, which is already a proven voice coder for IS-95 CDMA communication systems. The voice coder shall compress voice and adjust the data rate according to the voice activity and silent periods. The coder shall provide at most 9.6 Kbps and on the average 5 Kbps voice data.

The telemetry and diver specific data shall require at most 2 Kbps. On the average the data rate shall be around 7 Kbps for a regular diving session for a SCUBA diver.

The network layer of the communication shall provide routing of the packets within the divers. In this work, we have little research on *network layer*. *Network layer* architecture and design of *network* parameters are left as a future work. Even though we have little work on the network layer, the design parameters are that the system shall have an ad-hoc network architecture, providing better battery life time, more coverage, better traffic allocation by restricting the coverage of each user.

The data link layer of the communication system shall coordinate the access of each user to the shared medium by issuing a suitable MAC protocol. The data link layer shall also provide error correcting capability by adding FEC codes to the data. For the MAC protocol, we took account of propagation time of the acoustic waves and considered already proven MAC protocols for the air EM wave communication systems; namely CSMA/CA. The CSMA/CA, also know as MACA, protocol provides good performance for air communication system by avoiding *hidden*, *exposed* terminal problem and packet collisions; however it is far from an efficient protocol for underwater communication due to long propagation times of acoustic waves. The MACA protocol avoids the *hidden*, *exposed* terminal problem by issuing RTS/CTS packet exchange between the transmitter and the receiver. The RTS/CTS packets are exchanged for every message for air communication systems. For the underwater communication system instead of using MACA protocol with its entire features, some properties of the protocol are used for our advantage and others are omitted. Within the RTS/CTS packet exchange, channel properties are gathered. Distance between the divers, transmission power level, equalizer parameters can be set prior transmission of the data by issuing RTS/CTS packet exchange. The RTS/CTS packets can be used to probe the acoustic channel and adjust the communication parameters, such as level of modulation, FEC parameters. The channel probing packets, RTS/CTS are transmitted at a much higher power in order to set the communication parameters more precisely, such as frequency domain equalizer parameters. Instead of exchanging RTS/CTS packets for all the messages, the exchange shall be done with a certain repeating frequency to maintain the certain communication performance. For the underwater communication system, the MACA protocol shall be modified in order to take account of the long propagation times of the acoustic waves, to provide better performance and better access of each user to the shared medium. The details of the modified protocol are left as a future work. The repeating frequency of the RTS/CTS packet exchange in order to maintain the required performance, the equalizer parameters and the packet structure are left as a future work.

The data link layer also provides error correction. The underwater communication system is a digital system and the digital data is compressed audio and low data rate data; therefore, an error in the received packet means that the packet shall be dropped. On the other hand dropping a packet for the real time communication system shall lead to latency in voice communication; therefore, FEC codes are needed to maintain the integrity of each packet. In our work, we chose Reed-Solomon FEC codes to maintain required performance in bad channel conditions. The RS code parameters are chosen according to the channel properties and frame error rate. The frame error rate is the rate of dropped frames due to errors. Dropping 1% of the frames in a voice communication shall not interrrupt the communication; therefore, RS code parameters are selected in order to provide 1% FER.

In this work, we mainly focused on physical layer and spread spectrum communication method. We chose OFDM or COFDM spread spectrum technique. COFDM is a special kind of OFDM system, where the data is error coded to gain communication performance. OFDM is selected upon several spread spectrum systems such as CDMA, FHSS because of it inherent ability of combating channel imperfections, like multipath fading, Doppler shift and channel frequency response. Due to pulse design criteria condition a burst and wait communication is required. Multi-user communication requirement dictates the use and feasibility of OFDM. OFDM is a special kind of multi-carrier communication technique, where the entire spectrum is split up into carriers and all the carriers are used at the same time to transmit data. OFDM systems have inherent ability of resolving multipath signals using frequency domain equalizers. Frequency domain equalizer makes the system much easier than time domain equalizer systems. The frequency domain equalizer parameters shall be set by using RTS/CTS packet exchange that contains a known sequence of data.

OFDM communication systems are preferred over single carriers systems or other spread spectrum systems because OFDM systems' easier implementation. Since data is carried over several carriers in frequency domain, DFT and IDFT algorithm are used to modulate and create the data packets. With today's electronics technology, DFT and IDFT algorithms are easily implemented using field programmable gate arrays (FPGA); therefore, the modulator and the demodulator of the communication are contained mostly in a single IC. This makes the communication system easier as compared to other techniques. Implementing the communication system using software know as software defined radio (SDR). In SDR, the baseband and intermediate frequency (IF) of the communication system is implemented in software and the high frequency components are implemented separately. For underwater acoustic communication the overall communication system can be implemented in software due to the fact that the transmission frequency is not as high as air EM communications. Since OFDM requires DFT and IDFT for the modulator and demodulator, the implementation of the communication system for underwater communication that uses OFDM is easier to implement than the other spread spectrum techniques.

OFDM has inherent ability to avoid frequency selective fading using the frequency domain equalizer. For the equalizer to perfectly equalize the faded signal, the orthogonality of the carriers have to be maintained. The orthogonality of the carriers are maintained using the cyclic extension of the OFDM pulse.

When the OFDM pulse is cyclically extended, the multipath pulses arriving within OFDM pulse does not destroy the orthogonality. When the orthogonality is maintained, using a known sequence of data, frequency domain equalizer parameters are set. The transmitted data are equalized in frequency domain using the equalizer parameters. The orthogonality cannot be maintained when there is motion between the divers, because the Doppler shift destroys the orthogonality of the carriers. In certain scenarios some carriers can be in deep fade. In these circumstances, other techniques like using error correcting codes or pulse length reduction is used to avoid the errors. The OFDM system that uses error correcting codes is called COFDM.

Simulations are performed in order to find the performance of the OFDM communication system while changing the communication parameters. For simulations the underwater communication channel is modeled as 5-Ray propagation, a line of sight path along with 4 multipath signals. The channel frequency response is frequency and range dependent. The multipath signal behavior from the boundaries is modeled according to Sea-State and porosity. The motion between the divers is modeled in the simulations. The maximum relative velocity between the divers is 1 m/sec. According to the model the maximum expected delay spread is found to be 5.4 msec. and the maximum Doppler shift that the received signal will face is 200 Hz at 300 kHz.

In our work, we assumed that the maximum expected delay spread is 5.4 msec. The OFDM pulse is cyclically extended to maintain the orthogonality. The cyclic extension is set to the maximum expected delay spread, which is 5.4 msec, to allow the maintenance of orthogonality for all cases. We also assumed that the distance between the divers is known by use of RTS/CTS packet exchange. The frequency domain equalizer parameters are set within the RTS/CTS packet exchange using a known sequence of data. According to the distance between the divers, the transmission power is adjusted in order to have 1 10^{-3} BER for the 300^{th} kHz carrier. The OFDM pulse length, level of modulation and RS error code parameters are the communication parameters to be set in order to achieve the best performance for all conditions.

After the simulation results are observed, the worst conditions are observed when Sea-State is 0; that is there is little wind and therefore there are strong multipath signals from the sea surface and porosity is 0.2; that is the sea floor is rigid and therefore there are strong multipath signals from the sea floor; also the relative velocity between the divers is 1 m/sec. The multipath affected signals are closely equalized using the frequency domain equalizer because the orthogonality is maintained; however, the Doppler shift affected signals can not be equalized using frequency domain equalizers because the orthogonality is lost due to Doppler shift.

From the simulation results, it is observed that there is trade of between the OFDM communication parameters; namely between OFDM pulse length, level of modulation and achievable error coded data rate.

The OFDM pulse length defines the number of carries and number of carriers define the achievable data rate. Increasing in OFDM pulse length provides better data rate performance; however performance degrades when the divers are in motion and the received signal is affected by Doppler shift. In Doppler shift environment, increasing OFDM pulse length results in decreased performance, because the resistivity to Doppler shift decreases. On the other hand when the OFDM pulse length is decreased the resistivity to Doppler shift increases; however this time there are fewer carriers that carry data therefore the data rate performance is poor. Similarly, increasing the level of modulation provides better data rate performance; however, in non-stationary scenarios the performance of the system is lower than low level modulation cases due to high level of errors. Therefore, increase in level of modulation does not provide better data rate performance in non-stationary conditions.

When the communication system performance are observed from the simulation results, it is concluded that the scenarios that have only multipath propagation have good performances and the scenarios, which have both multipath and Doppler shift have the worst performance. For multipath only scenarios the performance is marginally better when the Sea-State conditions are bad and sea floor structure is soft.

Choosing the OFDM communication in this kind of trade off needs careful consideration. The reason is that the optimum parameters may vary from scenario to scenario. For this reason, the communication parameters should be chosen for the worst case performance scenarios. When the parameters are set for the worst case performance; namely multipath and Doppler affected scenarios then guaranteed performances are achieved for better cases. From the simulations, the worst performance is achieved when there is both multipath and Doppler shift; namely diver scenario #1 with boundary state scenario #1 and when the relative velocity between the divers is 1 m/sec. The error coded data rate in this circumstance is 37.6 Kbps with 15 10^{-3} BER. The data rate is achieved when OFDM pulse length of 0.6 msec, M=8 and RS code parameters, RS(50,38).

Each user on the average requires 7 Kbps data rate for voice and data communication. Since the achievable data rate performance is 37.6 Kbps the overall spectrum can be shared between many users. The share of the spectrum is achieved by allocating each user different sets of carriers. This way many users can use the shared spectrum at the same time.

When the communication system parameters are chosen for the worst case performance, the system may occupy 5 user's simultaneous communication assuming that each user creates 7 Kbps data on the average. It is not likely for each user to generate traffic at the same time simultaneously all the time; therefore, with certain GOS more users can be occupied in the same spectrum at the same time.

From the simulation results, it is observed that the communication system performance is better when the divers are stationary. For M=16, RS(100,90) and pulse length 1 msec case, motionless case, around 110 Kbps data rate is achieved for diver scenario #1 with boundary state scenario #1. For this case, around 16 users can occupy the channel at the same time, by allocating different users different carriers.

When the system parameters are set to worst case performance, the system guarantees to achieve the same performance for all cases. However, this statement may be relaxed. The worst case performance shall not always be faced. In circumstances where better channel conditions are available, the need for setting the communication system parameters for the worst performance is unnecessary. The communication system could adapt its parameters to changing conditions.

The communication system can adapt its OFDM pulse length, level of modulation, error correction code parameters according to the changing conditions. Achieving the adaptation is simply provided by using the RTS/CTS packet exchange. RTS/CTS packet exchange is discussed in previous chapters to provide frequency domain equalizer parameters to be set, along with distance gathering and transmission power level setting. The packet exchange can also be used to probe the channel for the communication channel properties, like multipath fading or Doppler shift. After the RTS/CTS packet exchange, the communication system parameters are set and higher data rate performance is achieved. In case the conditions are bad, guaranteed 37.6 Kbps data rate is achieved and when the conditions are better at most 110 Kbps is achieved.

The adaptive communication system adds overhead to the overall communication system. The reason is that the adaptive system not only adds extra overhead on RTS/CTS packets exchange but also adds MAC overhead, which is due to allocating carriers to different users in an adaptive system and adapting to the communication parameters to changing conditions. The network topology, algorithms and MAC algorithms for adaptive communication system need considerable research and are left as a future work.

In this work a spread spectrum underwater acoustic communication system using OFDM as spread spectrum technique, supporting multi-user capability is proposed. The main research is made on the data link layer, the physical layer and application layer. The research about other layers is left as a future work. The proposed communication system is set to provide around 37 Kbps data rate for the worst case conditions and guarantees to provide the same performance for the better case performances as well. The proposed communication system provides multi-user communication. Around 5 users can occupy the spectrum at the same time, by assigning different carriers to different users.

For the future work, network and MAC algorithms shall be studied and the resulting work shall provide an adaptive communication system according to the changing conditions for underwater communication. After the related future work, it is expected to propose a communication system that has the same capabilities with the current proposed system; however providing better data rate performance up to 110 Kbps according to the changing conditions.

APPENDIX A

Carrier Sense Media Access (CSMA) Based Media Access Control (MAC) Protocols

Carrier sense media access (CSMA) based protocols such as carrier sense media access with collision avoidance (CSMA/CA) and media access with collision avoidance (MACA) protocols coordinates the access of users to the shared medium by taking account of the channel state information. The channel state information is taken into account by listening to the carrier in the medium [5], [44].

The CSMA based protocols especially CSMA/CA and MACA provides collision free communication, while avoiding the *hidden* and *exposed* node problem [4], [5], [44], [49], [50]. The *hidden* and *exposed* node problems are depicted in Figure 6.1.

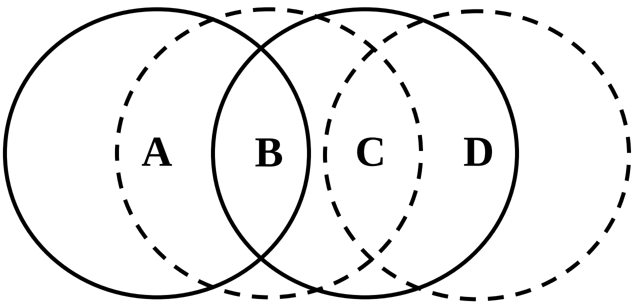


Figure 6.1: Hidden and exposed node problem scenario

In a communication scenario depicted in Figure 6.1, A and C can hear B's transmission while they cannot hear each other. Using CSMA protocol, each node senses the medium whether or not there is an ongoing transmission. When A has a packet to send B, it listens to the carrier and if there is no ongoing transmission it transmits immediately, however at the same time if C has a packet to send to B, it senses the medium and if there is no ongoing transmission it transmits immediately. Since A and C has no information about their transmission, A's and C's transmission collide at B, this in turn creates loss of packets. In this case, C and A are *hidden* from each other [5], [49], [50].

The exposed node problem can be defined with the similar scenario depicted in Figure 6.1. When A has a packet to send to B and C has a packet to send to D, C should defer its transmission not to interfere B's reception. However, deferring a transmission to D is not necessary because the intended transmission is not on B. This case is called *exposed* node problem. C should not defer its transmission provided that B has the capability to deal with the interference generated by node C [5], [49], [50].

CSMA protocol cannot solve *hidden* and *exposed* node problem, because the protocol only listens to the carrier before transmission. However, with some modification CSMA/CA protocol can solve the problem. In CSMA/CA protocol, when a node has a packet to send it first initiates Request to Send (RTS) packet in order to inform the receiver that the node has a packet to send. After the receiver receives the RTS packet, the receiver transmits a Clear to Send (CTS) packet in order to inform the transmitter that the receiver is ready to receive the packet. The purpose of RTS, CTS packet exchange is to inform the neighboring nodes that there shall be a transmission and the neighbors should defer their transmission while packet transmission. MACA protocol is a modified version of CSMA protocol, which includes the length of the packet in the RTS and CTS packets. During the packet exchange, for the case depicted in Figure 6.1, when C has a packet to send to B, however receives a CTS from B, it knows that B shall receive a packet from A and its transmission shall interfere at B if it transmits its packet. This way *hidden* terminal problem is avoided. Similarly, if C receives a CTS and C has a packet to send to D, C does not have to defer its transmission to D because the intended receiver is not B, provided that B can separate two transmissions. This way, C can transmit to D without interrupting B's reception. This way *exposed* terminal problem is avoided [5], [49], [50].

Using the MACA protocol, the packet duration is included in the RTS/CTS packets. Any node receiving RST and/or CTS packet defers their transmission knowing how long the ongoing transmission shall take place [5], [49], [50].

After RTS, CTS packet exchange, the data packet is transmitted. In order to know the packet is received perfectly, acknowledgment (ACK) has to be used in order to let the transmitter that the receiver received the packet successfully. When an ACK is included in the transmission the media access protocol is called MACAW [4], [5], [49], [50].

APPENDIX B

Network Topologies and Ad-Hoc Networking

There are different types of networks topologies, centralized, distributed and multi-hop [4], [5]. In centralized topology, all data packets are routed through a central node, which is called the *hub*. This topology is suitable for deep water acoustic networks, because at the surface a sensor with both an acoustic and an RF transceiver transmits the collected data from the underwater to the shore. A major disadvantage of this configuration is that when the hub fails, the whole communication fails. In decentralized routing, each node has the information about the router, to which the node is connected and does not know the overall network architecture. It's the routers duty to forward the packets to destination. In multi-hop topology, also known as ad-hoc network, each node has the information about its neighbors and communication is established through the neighbors. Messages are transferred from the source to the destination by hopping from node to node. The advantage of ad-hoc networking is that when a node fails on the route, the message can be transferred to the destination via another node. On the other hand, by hopping, overall network energy lasts longer because at each hop, node has to transmit its messages to shorter distances than direct communications. The scenario for an ad-hoc network is depicted in Figure 6.2.

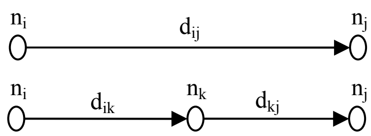


Figure 6.2: Single hop and multi-hop networking topology

For the network topologies depicted in Figure 6.2, communication between n_i and n_j is done for the single-hop topology directly and for the multi-hop topology over neighbor n_k. The transmission powers for the n_i node for the two scenarios are different. For the underwater communication the transmission power level of each node can be calculated given that the nodes know the distance between it neighbors. The transmission power level is provided in Table 6.1.

$n_i \rightarrow n_j$	$P_{tx} \propto 20\log d_{ij} + \alpha d_{ij}$
$n_i \rightarrow n_k$	$P_{tx} \propto 20\log d_{ik} + \alpha d_{ik}$

Table 6.1: Transmission power for node n_i for the single hop and multi-hop network scenarios

The transmission power depicted in Table 6.1, states that the node lifetime of n_i in in multi-hop topology is greater. However, in multi-hop network case, there is a need for an intermediate node; therefore the overall energy consumption including the intermediate node has to be calculated.

$n_i \rightarrow n_j$	$P_{tx} \propto 20\log d_{ij} + \alpha d_{ij}$
$n_i \rightarrow n_k \rightarrow n_j$	$P_{tx} \propto (20\log d_{ik} + \alpha d_{ik}) + (20\log d_{kj} + \alpha d_{kj})$

Table 6.2: Overall transmission power need of the single hop and multi-hop network scenarios

In Table 6.2, overall transmission power need for the scenarios is provided. It can be proved that the overall network lifetime can be longer for the multi-hop network topology. The transmission power levels for the multi-hop network is lower, however for the overall network lifetime calculations, node processing power needs and the initialization of the multi-hop network should be addressed. Multi-hop networks are often built with suitable routing and initialization protocols that also includes the processing power needs and network initialization. With suitable routing and initialization protocols, ad-hoc networking not only brings longer network lifetime, but also brings longer network range [4], [5], [51].

APPENDIX C

Rms Delay Spread and Mean Delay in the Underwater Acoustic Channel at 200 kHz at Maximum Range of Depth and Range

Sea-State-0 **10dB loss**
Porosity n=0.4 **35dB loss**

Depth (m)	Dist. (m)	Delay Spread (sec)	Mean Delay (sec)
h=1	d=1	$6.2\ 10^{-6}$	$1.6\ 10^{-5}$
	d=10	$2.2\ 10^{-6}$	$0.5\ 10^{-7}$
	d=30	$7.5\ 10^{-7}$	$2.0\ 10^{-8}$
	d=50	$4.5\ 10^{-7}$	$1.5\ 10^{-8}$
	d=70	$2.7\ 10^{-7}$	$1.0\ 10^{-8}$
	d=90	$2.2\ 10^{-7}$	$0.9\ 10^{-8}$
	d=100	$1.9\ 10^{-7}$	$0.7\ 10^{-8}$
h=10	d=1	$1.78\ 10^{-4}$	$2.85\ 10^{-6}$
	d=10	$6.8\ 10^{-5}$	$1.43\ 10^{-4}$
	d=30	$5.0\ 10^{-5}$	$1.5\ 10^{-6}$
	d=50	$3.8\ 10^{-5}$	$1.4\ 10^{-6}$
	d=70	$2.9\ 10^{-5}$	$2.5\ 10^{-6}$
	d=90	$2.4\ 10^{-5}$	$0.7\ 10^{-6}$
	d=100	$2.2\ 10^{-5}$	$0.6\ 10^{-6}$
h=20	d=1	$1.78\ 10^{-4}$	$1.15\ 10^{-6}$
	d=10	$1.24\ 10^{-3}$	$1.43\ 10^{-4}$
	d=30	$1.2\ 10^{-4}$	$3.54\ 10^{-4}$
	d=50	$1.2\ 10^{-4}$	$3.0\ 10^{-6}$
	d=70	$9.0\ 10^{-5}$	$2.0\ 10^{-6}$
	d=90	$8.0\ 10^{-5}$	$2.0\ 10^{-6}$
	d=100	$7.5\ 10^{-5}$	$6.0\ 10^{-6}$
h=40	d=1	$1.78\ 10^{-4}$	$3.5\ 10^{-7}$
	d=10	$1.28\ 10^{-3}$	$1.43\ 10^{-4}$
	d=30	$2.77\ 10^{-3}$	$3.54\ 10^{-4}$
	d=50	$2.2\ 10^{-4}$	$5.07\ 10^{-4}$
	d=70	$2.1\ 10^{-4}$	$6.25\ 10^{-4}$
	d=90	$2.1\ 10^{-4}$	$6.0\ 10^{-6}$
	d=100	$2.1\ 10^{-4}$	$5.0\ 10^{-6}$
h=50	d=1	$1.78\ 10^{-4}$	$2.5\ 10^{-7}$
	d=10	$1.28\ 10^{-3}$	$1.43\ 10^{-4}$
	d=30	$2.77\ 10^{-3}$	$3.54\ 10^{-4}$
	d=50	$2.2\ 10^{-4}$	$5.08\ 10^{-4}$
	d=70	$2.7\ 10^{-4}$	$6.25\ 10^{-4}$
	d=90	$2.8\ 10^{-4}$	$7.2\ 10^{-4}$
	d=100	$2.5\ 10^{-4}$	$7.6\ 10^{-4}$
h=70	d=1	$1.78\ 10^{-4}$	$1.5\ 10^{-7}$
	d=10	$1.28\ 10^{-3}$	$1.0\ 10^{-5}$
	d=30	$2.77\ 10^{-3}$	$3.55\ 10^{-4}$
	d=50	$3.75\ 10^{-3}$	$5.0\ 10^{-4}$
	d=70	$4.47\ 10^{-3}$	$6.25\ 10^{-4}$
	d=90	$3.2\ 10^{-4}$	$7.2\ 10^{-4}$
	d=100	$3.2\ 10^{-4}$	$7.6\ 10^{-4}$
h=90	d=1	$1.78\ 10^{-4}$	$1.0\ 10^{-7}$
	d=10	$1.28\ 10^{-3}$	$5.0\ 10^{-6}$
	d=30	$2.77\ 10^{-3}$	$3.53\ 10^{-4}$
	d=50	$3.76\ 10^{-3}$	$5.07\ 10^{-4}$
	d=70	$4.5\ 10^{-3}$	$6.25\ 10^{-4}$
	d=90	$5.05\ 10^{-3}$	$7.2\ 10^{-4}$
	d=100	$5.32\ 10^{-3}$	$7.65\ 10^{-4}$
h=100	d=1	$1.78\ 10^{-4}$	$1.0\ 10^{-7}$
	d=10	$1.28\ 10^{-3}$	$4.0\ 10^{-6}$
	d=30	$2.77\ 10^{-3}$	$3.54\ 10^{-4}$
	d=50	$3.76\ 10^{-3}$	$5.06\ 10^{-4}$
	d=70	$4.5\ 10^{-3}$	$6.25\ 10^{-4}$
	d=90	$5.07\ 10^{-3}$	$7.2\ 10^{-4}$
	d=100	$5.32\ 10^{-3}$	$7.65\ 10^{-4}$

Sea-State-0 10dB loss
Porosity n=0.2 15dB loss

Depth (m)	Dist. (m)	Delay Spread (sec)	Mean Delay (sec)	Depth (m)	Dist. (m)	Delay Spread (sec)	Mean Delay (sec)
h=1	d=1	$6.0\ 10^{-5}$	$1.85\ 10^{-5}$	h=50	d=1	$1.92\ 10^{-4}$	$8.0\ 10^{-7}$
	d=10	$1.35\ 10^{-5}$	$3.45\ 10^{-6}$		d=10	$1.48\ 10^{-3}$	$7.15\ 10^{-5}$
	d=30	$4.55\ 10^{-6}$	$1.18\ 10^{-6}$		d=30	$2.82\ 10^{-3}$	$4.54\ 10^{-4}$
	d=50	$2.7\ 10^{-6}$	$7.2\ 10^{-7}$		d=50	$2.22\ 10^{-3}$	$6.72\ 10^{-4}$
	d=70	$1.94\ 10^{-6}$	$5.1\ 10^{-7}$		d=70	$2.36\ 10^{-3}$	$7.56\ 10^{-4}$
	d=90	$1.51\ 10^{-6}$	$3.9\ 10^{-7}$		d=90	$2.24\ 10^{-3}$	$7.65\ 10^{-4}$
	d=100	$1.36\ 10^{-6}$	$3.6\ 10^{-7}$		d=100	$2.16\ 10^{-3}$	$7.9\ 10^{-4}$
h=10	d=1	$2.09\ 10^{-4}$	$6.6\ 10^{-6}$	h=70	d=1	$1.37\ 10^{-4}$	$5.0\ 10^{-7}$
	d=10	$5.7\ 10^{-4}$	$1.68\ 10^{-4}$		d=10	$1.42\ 10^{-3}$	$4.1\ 10^{-5}$
	d=30	$3.8\ 10^{-4}$	$8.2\ 10^{-5}$		d=30	$3.17\ 10^{-3}$	$4.05\ 10^{-4}$
	d=50	$2.5\ 10^{-4}$	$6.2\ 10^{-5}$		d=50	$3.81\ 10^{-3}$	$6.55\ 10^{-4}$
	d=70	$1.88\ 10^{-4}$	$4.8\ 10^{-5}$		d=70	$4.55\ 10^{-3}$	$8.3\ 10^{-4}$
	d=90	$1.46\ 10^{-4}$	$3.75\ 10^{-5}$		d=90	$2.96\ 10^{-3}$	$9.3\ 10^{-4}$
	d=100	$1.33\ 10^{-4}$	$3.45\ 10^{-5}$		d=100	$3.04\ 10^{-3}$	$9.54\ 10^{-4}$
h=20	d=1	$2.06\ 10^{-4}$	$3.0\ 10^{-6}$	h=90	d=1	$1.2\ 10^{-4}$	$2.0\ 10^{-7}$
	d=10	$1.29\ 10^{-3}$	$1.87\ 10^{-4}$		d=10	$1.37\ 10^{-3}$	$2.5\ 10^{-5}$
	d=30	$1.05\ 10^{-3}$	$3.66\ 10^{-4}$		d=30	$3.2\ 10^{-3}$	$3.78\ 10^{-4}$
	d=50	$8.35\ 10^{-4}$	$1.56\ 10^{-4}$		d=50	$4.14\ 10^{-3}$	$5.94\ 10^{-4}$
	d=70	$6.6\ 10^{-4}$	$1.48\ 10^{-4}$		d=70	$4.54\ 10^{-3}$	$8.0\ 10^{-4}$
	d=90	$5.42\ 10^{-4}$	$1.29\ 10^{-4}$		d=90	$5.14\ 10^{-3}$	$9.55\ 10^{-4}$
	d=100	$4.96\ 10^{-4}$	$1.19\ 10^{-4}$		d=100	$5.4\ 10^{-3}$	$1.01\ 10^{-3}$
h=40	d=1	$1.95\ 10^{-4}$	$1.2\ 10^{-6}$	h=100	d=1	$1.12\ 10^{-4}$	$2.0\ 10^{-7}$
	d=10	$1.49\ 10^{-3}$	$9.4\ 10^{-5}$		d=10	$1.35\ 10^{-3}$	$2.0\ 10^{-5}$
	d=30	$1.64\ 10^{-3}$	$4.74\ 10^{-4}$		d=30	$3.14\ 10^{-3}$	$1.64\ 10^{-4}$
	d=50	$1.97\ 10^{-3}$	$6.06\ 10^{-4}$		d=50	$4.3\ 10^{-3}$	$5.65\ 10^{-4}$
	d=70	$1.89\ 10^{-3}$	$6.56\ 10^{-4}$		d=70	$4.55\ 10^{-3}$	$7.65\ 10^{-4}$
	d=90	$1.66\ 10^{-3}$	$2.66\ 10^{-4}$		d=90	$5.12\ 10^{-3}$	$9.4\ 10^{-4}$
	d=100	$1.59\ 10^{-3}$	$2.66\ 10^{-4}$		d=100	$5.4\ 10^{-3}$	$1.01\ 10^{-3}$

Sea-State-1 14dB loss
Porosity n=0.4 35dB loss

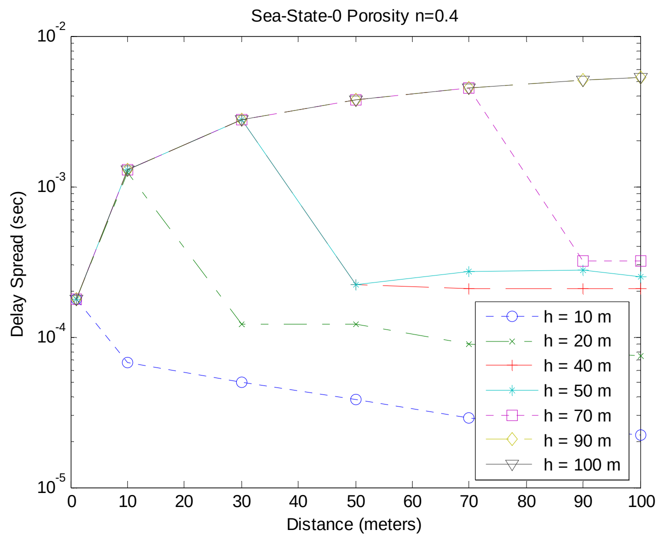
Depth (m)	Dist. (m)	Delay Spread (sec)	Mean Delay (sec)	Depth (m)	Dist. (m)	Delay Spread (sec)	Mean Delay (sec)
h=1	d=1	$6.8\ 10^{-6}$	$6.45\ 10^{-6}$	h=50	d=1	$1.12\ 10^{-4}$	$1.0\ 10^{-7}$
	d=10	$1.9\ 10^{-6}$	$8.0\ 10^{-8}$		d=10	$8.1\ 10^{-4}$	$5.78\ 10^{-5}$
	d=30	$6.6\ 10^{-7}$	$3.0\ 10^{-8}$		d=30	$1.76\ 10^{-3}$	$1.44\ 10^{-4}$
	d=50	$4.0\ 10^{-7}$	$1.5\ 10^{-8}$		d=50	$2.1\ 10^{-4}$	$2.06\ 10^{-4}$
	d=70	$2.5\ 10^{-7}$	$1.2\ 10^{-8}$		d=70	$2.6\ 10^{-4}$	$2.54\ 10^{-4}$
	d=90	$2.2\ 10^{-7}$	$0.9\ 10^{-8}$		d=90	$2.4\ 10^{-4}$	$2.92\ 10^{-4}$
	d=100	$1.8\ 10^{-7}$	$1.0\ 10^{-8}$		d=100	$2.4\ 10^{-4}$	$3.09\ 10^{-4}$
h=10	d=1	$1.13\ 10^{-4}$	$1.15\ 10^{-6}$	h=70	d=1	$1.12\ 10^{-4}$	$0.6\ 10^{-7}$
	d=10	$6.5\ 10^{-5}$	$5.8\ 10^{-5}$		d=10	$8.1\ 10^{-4}$	$4.4\ 10^{-6}$
	d=30	$5.0\ 10^{-5}$	$2.0\ 10^{-6}$		d=30	$1.76\ 10^{-3}$	$1.43\ 10^{-4}$
	d=50	$3.4\ 10^{-5}$	$1.4\ 10^{-6}$		d=50	$2.38\ 10^{-3}$	$2.07\ 10^{-4}$
	d=70	$2.6\ 10^{-5}$	$1.0\ 10^{-6}$		d=70	$2.85\ 10^{-3}$	$2.55\ 10^{-4}$
	d=90	$2.05\ 10^{-5}$	$1.0\ 10^{-6}$		d=90	$3.0\ 10^{-4}$	$2.94\ 10^{-4}$
	d=100	$1.9\ 10^{-5}$	$0.8\ 10^{-6}$		d=100	$3.05\ 10^{-4}$	$3.1\ 10^{-4}$
h=20	d=1	$1.13\ 10^{-4}$	$5.0\ 10^{-7}$	h=90	d=1	$1.12\ 10^{-4}$	$4.0\ 10^{-8}$
	d=10	$7.75\ 10^{-4}$	$5.8\ 10^{-5}$		d=10	$8.1\ 10^{-4}$	$2.6\ 10^{-6}$
	d=30	$1.2\ 10^{-4}$	$1.43\ 10^{-4}$		d=30	$1.76\ 10^{-3}$	$1.43\ 10^{-4}$
	d=50	$1.04\ 10^{-4}$	$3.0\ 10^{-6}$		d=50	$2.39\ 10^{-3}$	$2.06\ 10^{-4}$
	d=70	$0.9\ 10^{-4}$	$3.0\ 10^{-6}$		d=70	$2.85\ 10^{-3}$	$2.55\ 10^{-4}$
	d=90	$7.0\ 10^{-5}$	$2.5\ 10^{-6}$		d=90	$3.21\ 10^{-3}$	$2.94\ 10^{-4}$
	d=100	$6.5\ 10^{-5}$	$2.0\ 10^{-6}$		d=100	$3.38\ 10^{-3}$	$3.1\ 10^{-4}$
h=40	d=1	$1.12\ 10^{-4}$	$2.0\ 10^{-7}$	h=100	d=1	$1.12\ 10^{-4}$	$0.5\ 10^{-7}$
	d=10	$8.1\ 10^{-4}$	$5.8\ 10^{-5}$		d=10	$8.1\ 10^{-4}$	$2.2\ 10^{-6}$
	d=30	$1.76\ 10^{-3}$	$1.44\ 10^{-4}$		d=30	$1.76\ 10^{-3}$	$1.43\ 10^{-4}$
	d=50	$2.2\ 10^{-4}$	$2.06\ 10^{-4}$		d=50	$2.39\ 10^{-3}$	$2.06\ 10^{-4}$
	d=70	$2.1\ 10^{-4}$	$2.54\ 10^{-4}$		d=70	$2.85\ 10^{-3}$	$2.55\ 10^{-4}$
	d=90	$2.2\ 10^{-4}$	$4.0\ 10^{-6}$		d=90	$3.22\ 10^{-3}$	$2.94\ 10^{-4}$
	d=100	$2.1\ 10^{-4}$	$0.9\ 10^{-5}$		d=100	$3.38\ 10^{-3}$	$3.11\ 10^{-4}$

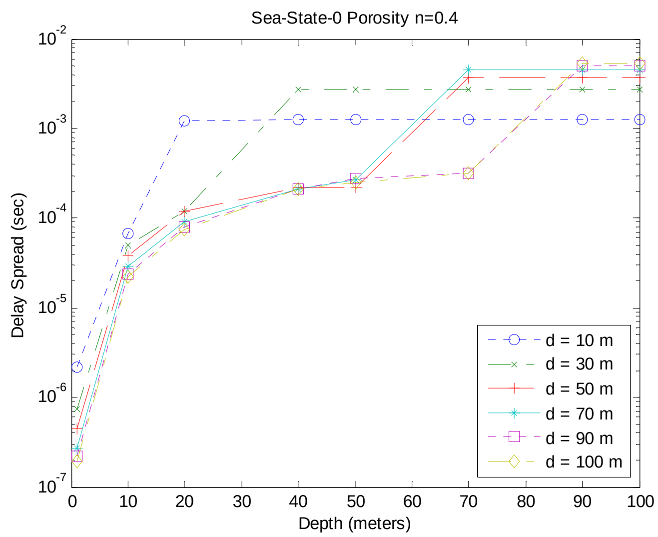
Sea-State-1 **14dB loss**
Porosity n=0.2 **15dB loss**

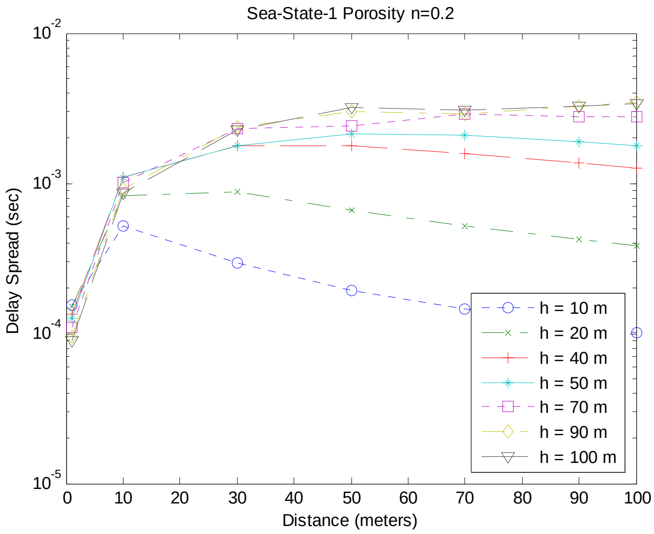
Depth (m)	Dist. (m)	Delay Spread (sec)	Mean Delay (sec)	Depth (m)	Dist. (m)	Delay Spread (sec)	Mean Delay (sec)
h=1	d=1	$5.3\ 10^{-5}$	$9.55\ 10^{-6}$	h=50	d=1	$1.25\ 10^{-4}$	$5.0\ 10^{-7}$
	d=10	$1.03\ 10^{-5}$	$2.44\ 10^{-6}$		d=10	$1.09\ 10^{-3}$	$4.4\ 10^{-5}$
	d=30	$3.48\ 10^{-6}$	$8.3\ 10^{-7}$		d=30	$1.78\ 10^{-3}$	$2.42\ 10^{-4}$
	d=50	$2.1\ 10^{-6}$	$4.95\ 10^{-7}$		d=50	$2.13\ 10^{-3}$	$3.67\ 10^{-4}$
	d=70	$1.48\ 10^{-6}$	$3.6\ 10^{-7}$		d=70	$2.09\ 10^{-3}$	$3.72\ 10^{-4}$
	d=90	1.15 10-6	$2.8\ 10^{-7}$		d=90	$1.89\ 10^{-3}$	$3.08\ 10^{-4}$
	d=100	$1.04\ 10^{-6}$	$2.48\ 10^{-7}$		d=100	$1.79\ 10^{-3}$	$3.21\ 10^{-4}$
h=10	d=1	$1.53\ 10^{-4}$	$3.8\ 10^{-6}$	h=70	d=1	$1.09\ 10^{-4}$	$2.6\ 10^{-7}$
	d=10	$5.15\ 10^{-4}$	$9.3\ 10^{-5}$		d=10	$1.01\ 10^{-3}$	$2.54\ 10^{-5}$
	d=30	$2.95\ 10^{-4}$	$6.9\ 10^{-5}$		d=30	$2.33\ 10^{-3}$	$1.92\ 10^{-4}$
	d=50	$1.94\ 10^{-4}$	$4.6\ 10^{-5}$		d=50	$2.42\ 10^{-3}$	$3.52\ 10^{-4}$
	d=70	$1.44\ 10^{-4}$	$3.4\ 10^{-5}$		d=70	$2.9\ 10^{-3}$	$4.58\ 10^{-4}$
	d=90	$1.13\ 10^{-4}$	$2.68\ 10^{-5}$		d=90	$2.8\ 10^{-3}$	$5.06\ 10^{-4}$
	d=100	$1.02\ 10^{-4}$	$2.42\ 10^{-5}$		d=100	$2.75\ 10^{-3}$	$5.16\ 10^{-4}$
h=20	d=1	$1.5\ 10^{-4}$	$1.78\ 10^{-6}$	h=90	d=1	$9.5\ 10^{-5}$	$1.50\ 10^{-7}$
	d=10	$8.21\ 10^{-4}$	$1.0\ 10^{-4}$		d=10	$9.1\ 10^{-4}$	$1.54\ 10^{-5}$
	d=30	$8.85\ 10^{-4}$	$1.5\ 10^{-4}$		d=30	$2.34\ 10^{-3}$	$1.43\ 10^{-4}$
	d=50	$6.6\ 10^{-4}$	$1.43\ 10^{-4}$		d=50	$3.02\ 10^{-3}$	$2.91\ 10^{-4}$
	d=70	$5.2\ 10^{-4}$	$1.19\ 10^{-4}$		d=70	$2.88\ 10^{-3}$	$4.3\ 10^{-4}$
	d=90	$4.25\ 10^{-4}$	$9.8\ 10^{-5}$		d=90	$3.28\ 10^{-3}$	$5.26\ 10^{-4}$
	d=100	$3.85\ 10^{-4}$	$9.0\ 10^{-5}$		d=100	$3.43\ 10^{-3}$	$5.56\ 10^{-4}$
h=40	d=1	$1.33\ 10^{-4}$	$6.8\ 10^{-7}$	h=100	d=1	$8.95\ 10^{-5}$	$1.2\ 10^{-7}$
	d=10	$1.09\ 10^{-3}$	$5.9\ 10^{-5}$		d=10	$8.62\ 10^{-4}$	$1.24\ 10^{-5}$
	d=30	$1.79\ 10^{-3}$	$2.6\ 10^{-4}$		d=30	$2.28\ 10^{-3}$	$1.33\ 10^{-4}$
	d=50	$1.77\ 10^{-3}$	$3.34\ 10^{-4}$		d=50	$3.21\ 10^{-3}$	$2.68\ 10^{-4}$
	d=70	$1.57\ 10^{-3}$	$2.68\ 10^{-4}$		d=70	$3.05\ 10^{-3}$	$3.96\ 10^{-4}$
	d=90	$1.36\ 10^{-3}$	$2.98\ 10^{-4}$		d=90	$3.27\ 10^{-3}$	$5.08\ 10^{-4}$
	d=100	$1.27\ 10^{-3}$	$2.46\ 10^{-4}$		d=100	$3.42\ 10^{-3}$	$5.52\ 10^{-4}$

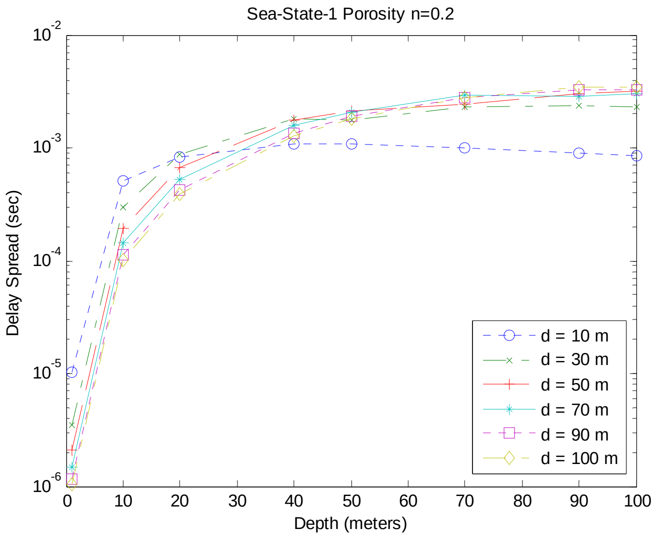
APPENDIX D

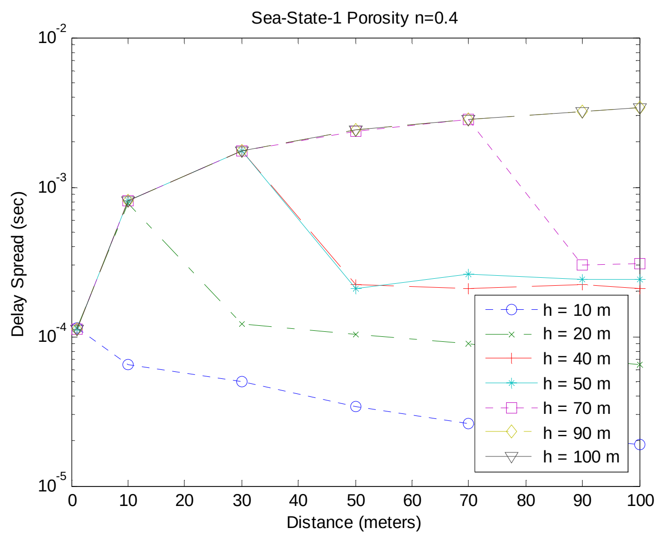
Delay Spread Profile of Various Boundary Condition Scenarios



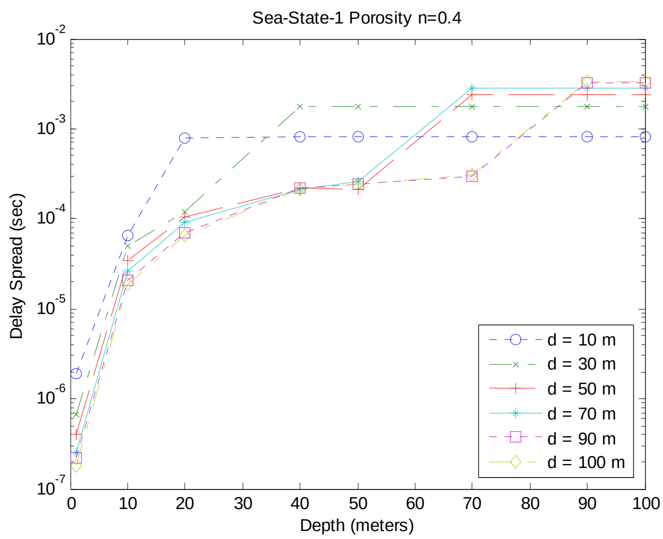



Sea-State-1 Porosity n=0.2
Delay Spread (sec)
Distance (meters)
h = 10 m
h = 20 m
h = 40 m
h = 50 m
h = 70 m
h = 90 m
h = 100 m


Sea-State-1 Porosity n=0.2
Delay Spread (sec)
Depth (meters)
d = 10 m
d = 30 m
d = 50 m
d = 70 m
d = 90 m
d = 100 m



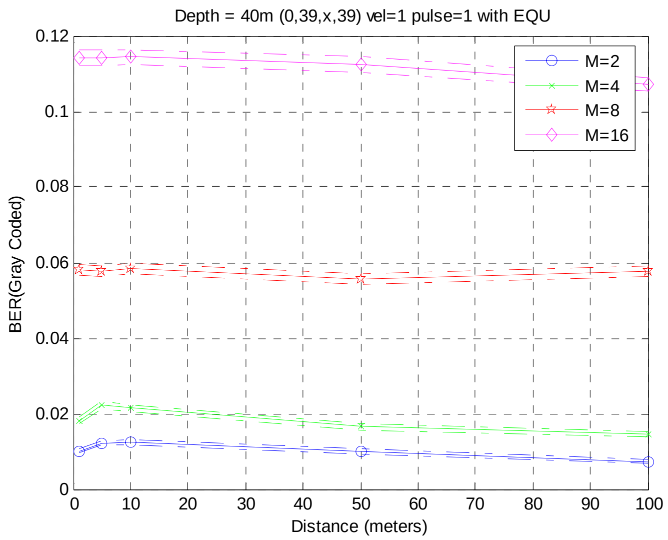
Sea-State-1 Porosity n=0.4
Delay Spread (sec)
Distance (meters)
h = 10 m
h = 20 m
h = 40 m
h = 50 m
h = 70 m
h = 90 m
h = 100 m

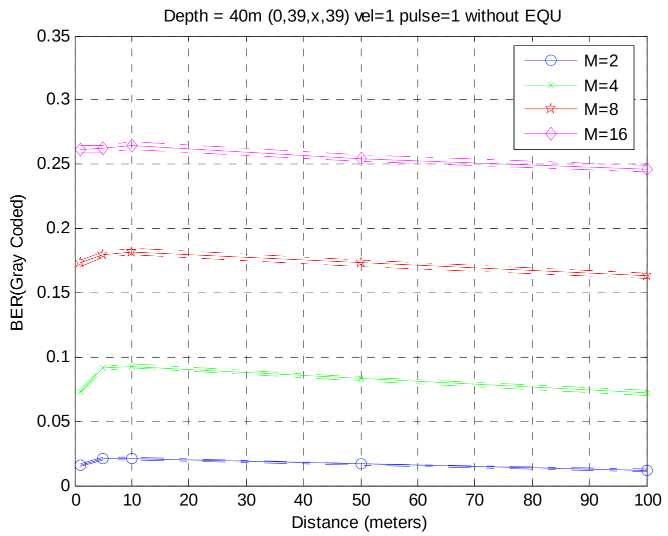


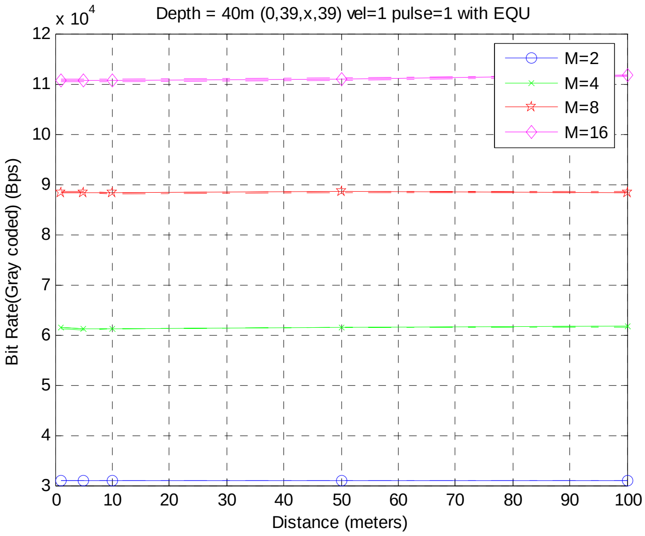
Sea-State-1 Porosity n=0.4
Delay Spread (sec)
Depth (meters)
d = 10 m
d = 30 m
d = 50 m
d = 70 m
d = 90 m
d = 100 m

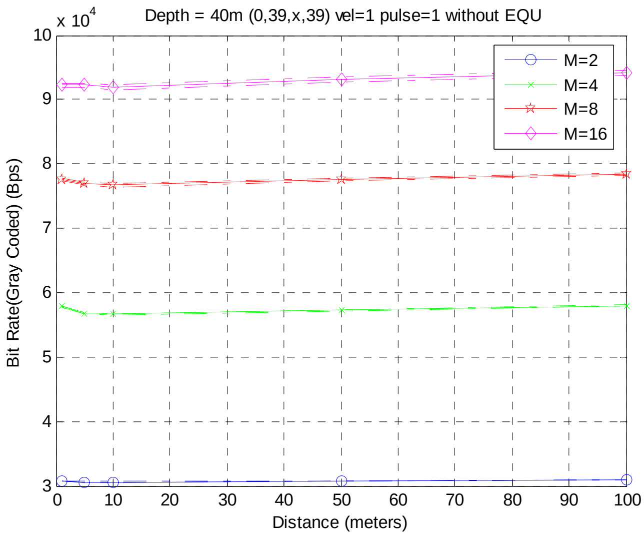
APPENDIX E
APPENDIX E.1

Communication Performance of Diver State Scenario#1 and Boundary State Scenario#1 with Doppler Shift



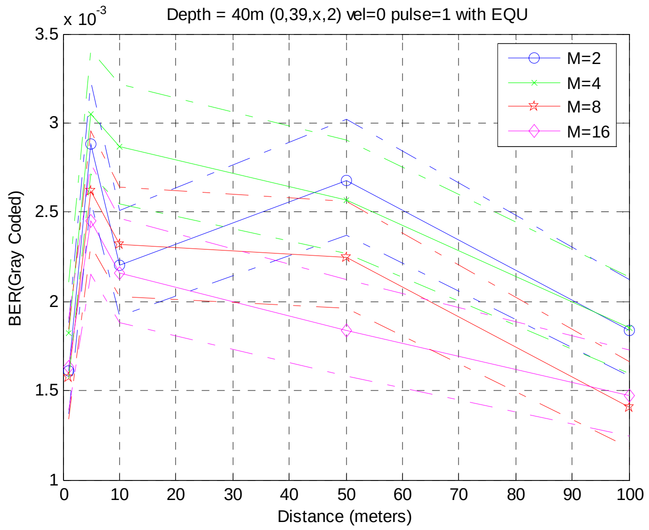


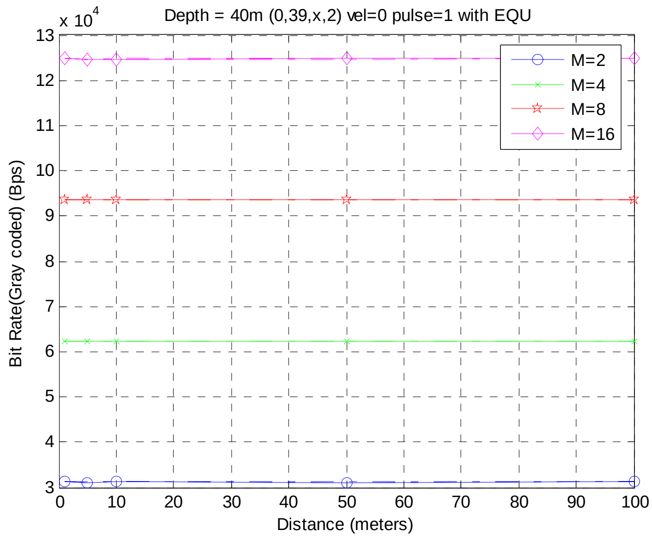

Depth = 40m (0,39,x,39) vel=1 pulse=1 with EQU
x 10^4
Bit Rate(Gray coded) (Bps)
Distance (meters)
M=2
M=4
M=8
M=16

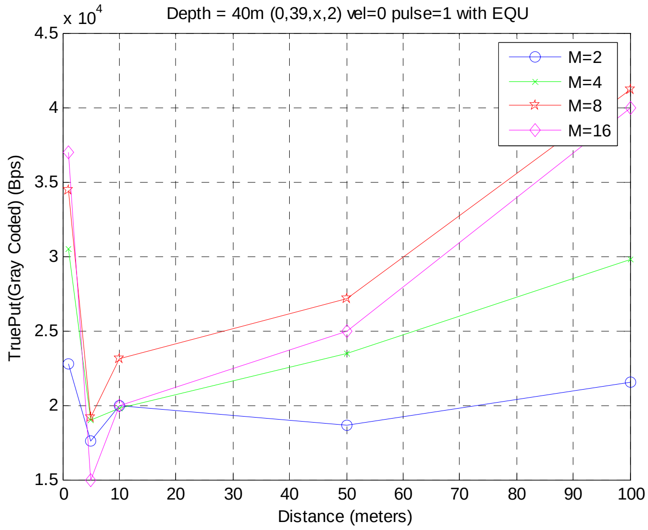

Depth = 40m (0,39,x,39) vel=1 pulse=1 without EQU
x 10^4
Bit Rate(Gray Coded) (Bps)
Distance (meters)
M=2
M=4
M=8
M=16

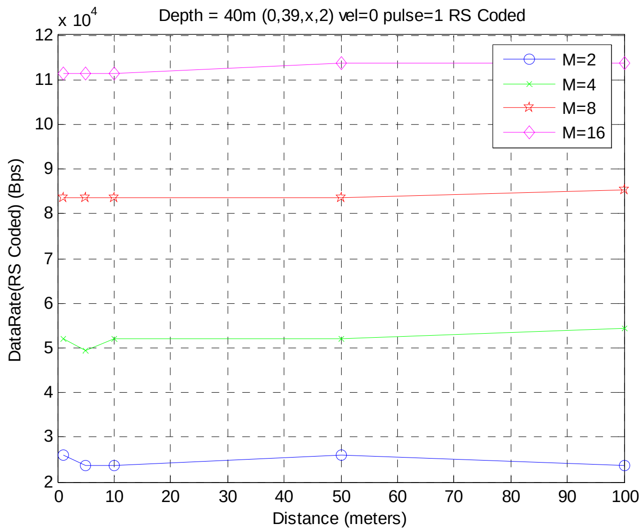
APPENDIX E.2

Communication Performance of Diver State Scenario#3 and Boundary State Scenario#1



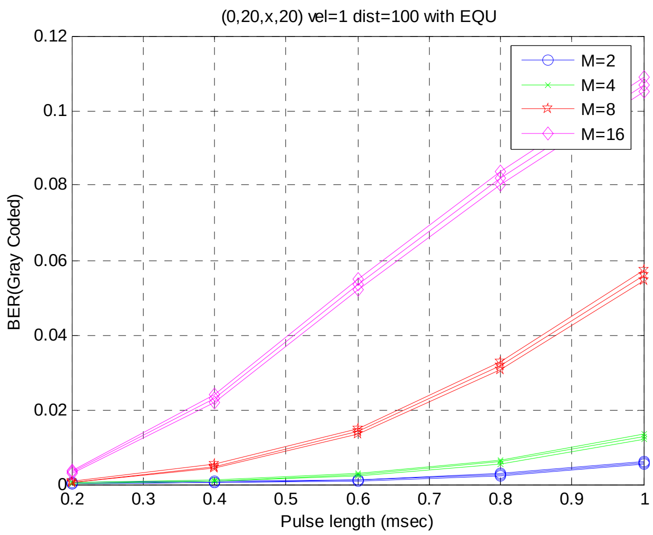


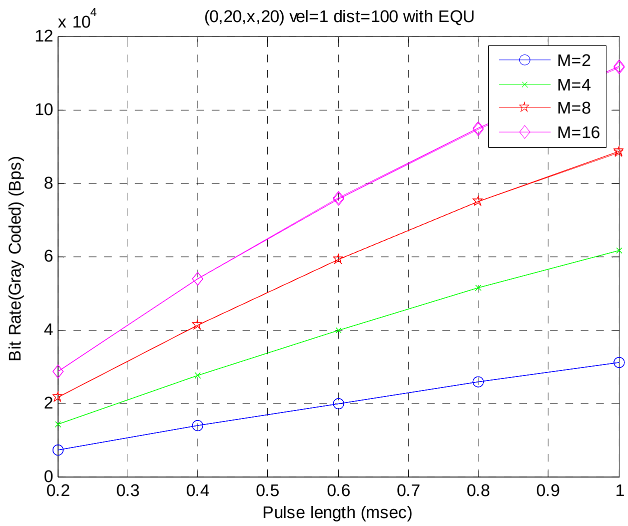

Depth = 40m (0,39,x,2) vel=0 pulse=1 with EQU
x 10^4
4.5
4
3.5
3
2.5
2
1.5
TruePut(Gray Coded) (Bps)
0
10
20
30
40
50
60
70
80
90
100
Distance (meters)
M=2
M=4
M=8
M=16

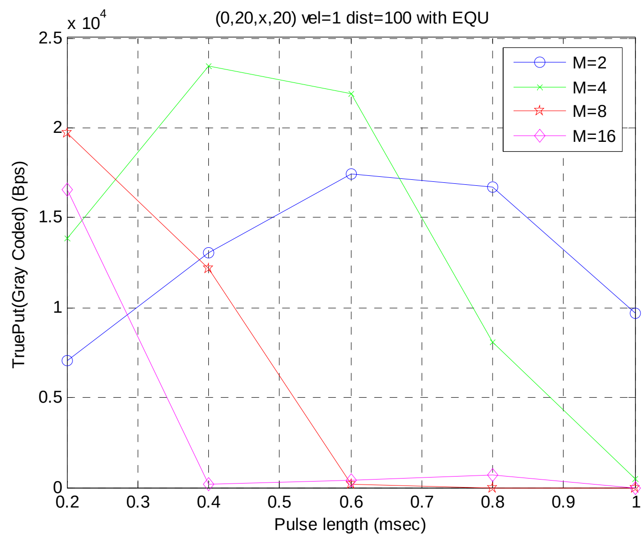

Depth = 40m (0,39,x,2) vel=0 pulse=1 RS Coded
x 10^4
12
11
10
9
8
7
6
5
4
3
2
DataRate(RS Coded) (Bps)
0
10
20
30
40
50
60
70
80
90
100
Distance (meters)
M=2
M=4
M=8
M=16

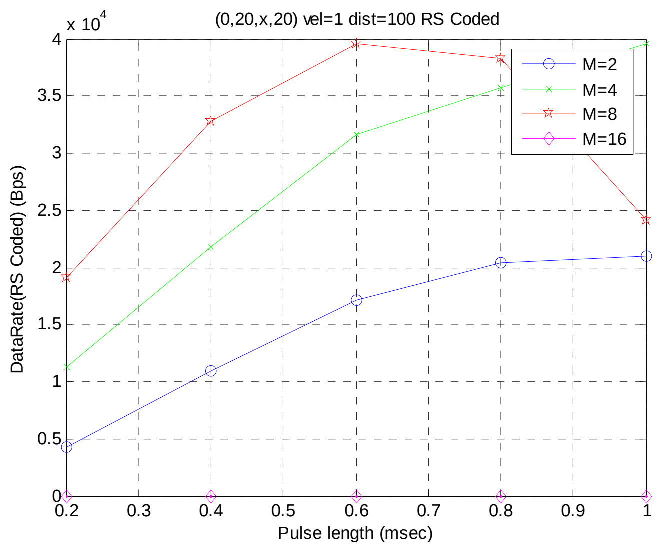
APPENDIX E.3

Communication Performance of Diver State Scenario#2 and Boundary State Scenario#1 with Doppler Shift with Doppler Shift



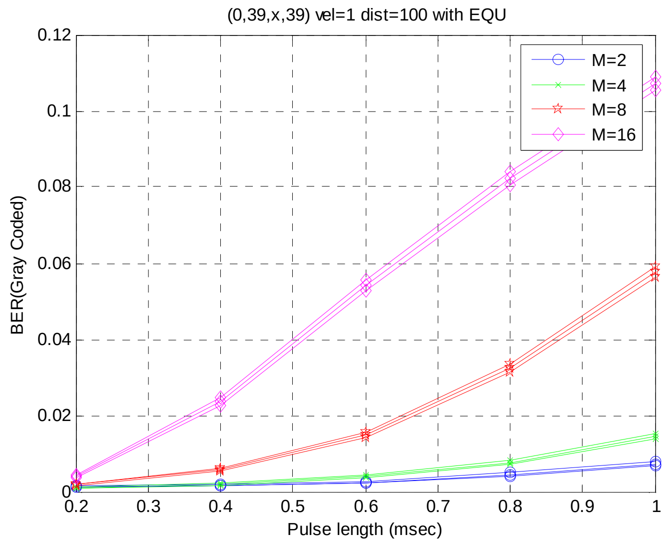


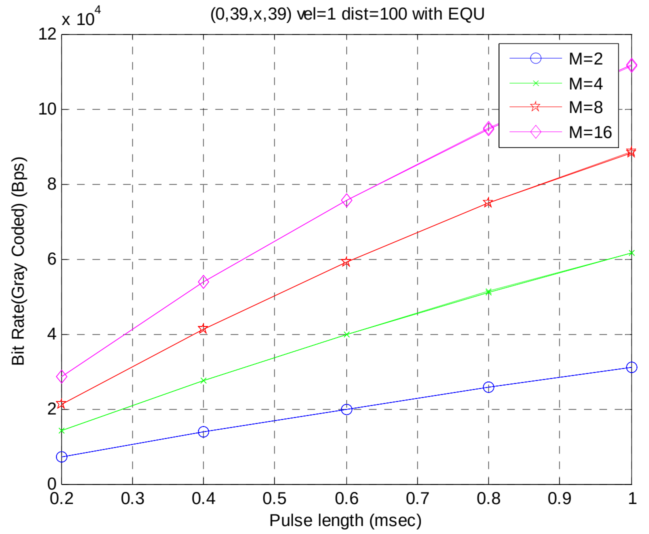

(0,20,x,20) vel=1 dist=100 with EQU
x 10^4
TruePut(Gray Coded) (Bps)
Pulse length (msec)
M=2
M=4
M=8
M=16
0
0.5
1
1.5
2
2.5
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

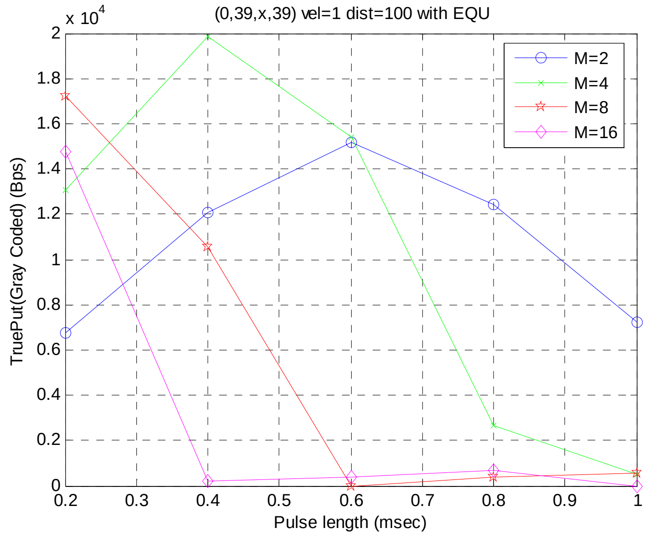

(0,20,x,20) vel=1 dist=100 RS Coded
x 10^4
DataRate(RS Coded) (Bps)
Pulse length (msec)
M=2
M=4
M=8
M=16
0
0.5
1
1.5
2
2.5
3
3.5
4
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

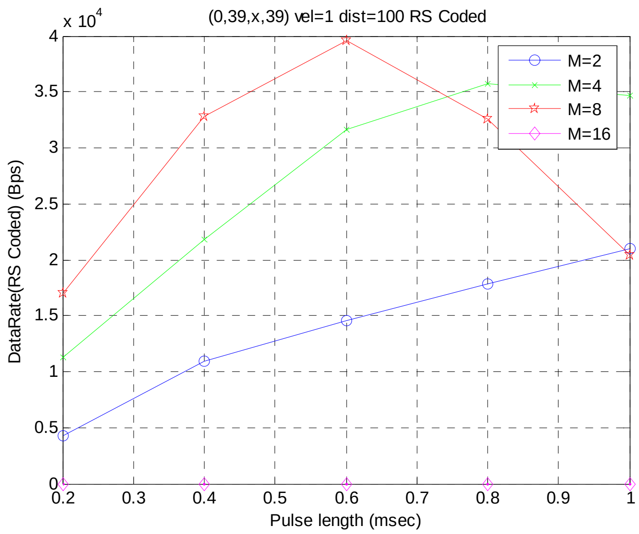
APPENDIX E.4

Communication Performance of Diver State Scenario#1 and Boundary State Scenario#1 with Doppler Shift



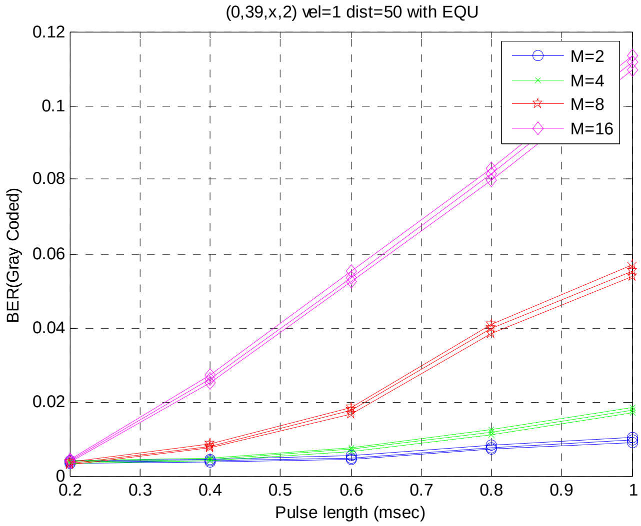


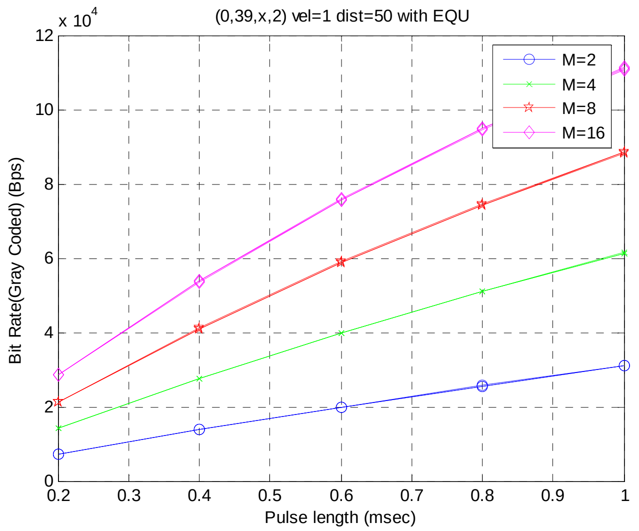

(0,39,x,39) vel=1 dist=100 with EQU
x 10^4
TruePut(Gray Coded) (Bps)
Pulse length (msec)
M=2
M=4
M=8
M=16
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

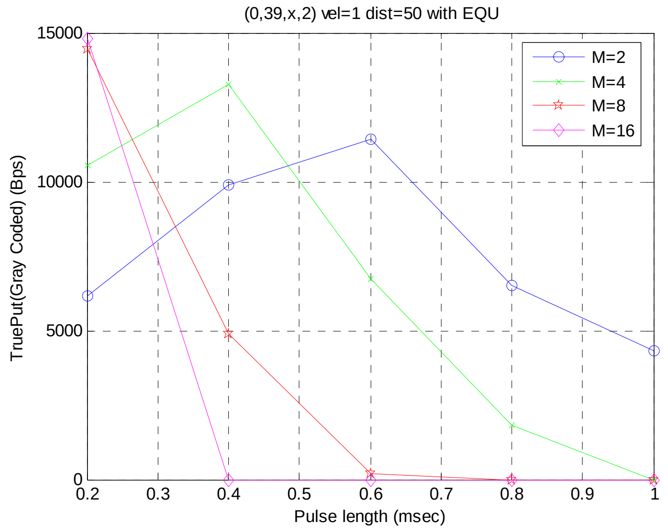

(0,39,x,39) vel=1 dist=100 RS Coded
x 10^4
DataRate(RS Coded) (Bps)
Pulse length (msec)
M=2
M=4
M=8
M=16
0
0.5
1
1.5
2
2.5
3
3.5
4
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

APPENDIX E.5

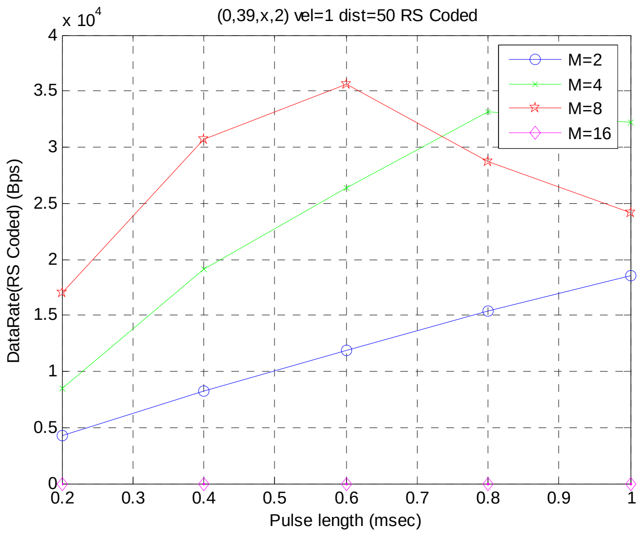
Communication Performance of Diver State Scenario#3 and Boundary State Scenario#1 with Doppler Shift







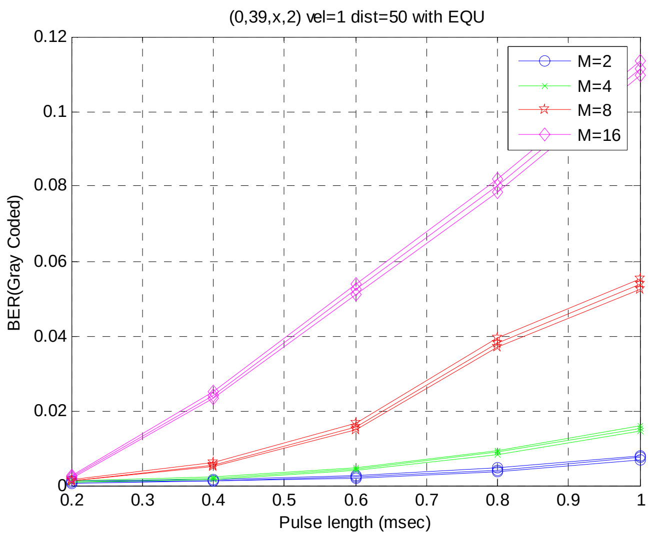
(0,39,x,2) vel=1 dist=50 with EQU
TruePut(Gray Coded) (Bps)
Pulse length (msec)
M=2
M=4
M=8
M=16
15000
10000
5000
0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

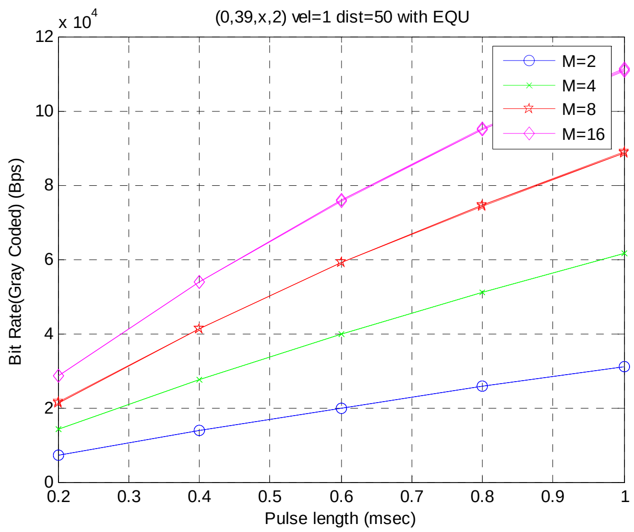


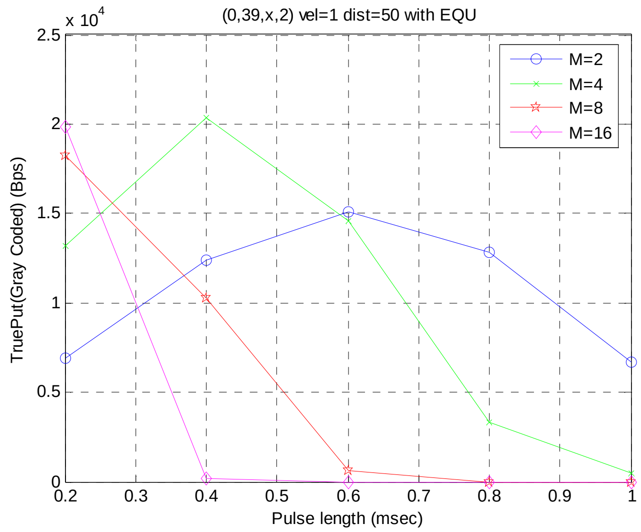
(0,39,x,2) vel=1 dist=50 RS Coded
x 10^4
DataRate(RS Coded) (Bps)
Pulse length (msec)
M=2
M=4
M=8
M=16
4
3.5
3
2.5
2
1.5
1
0.5
0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

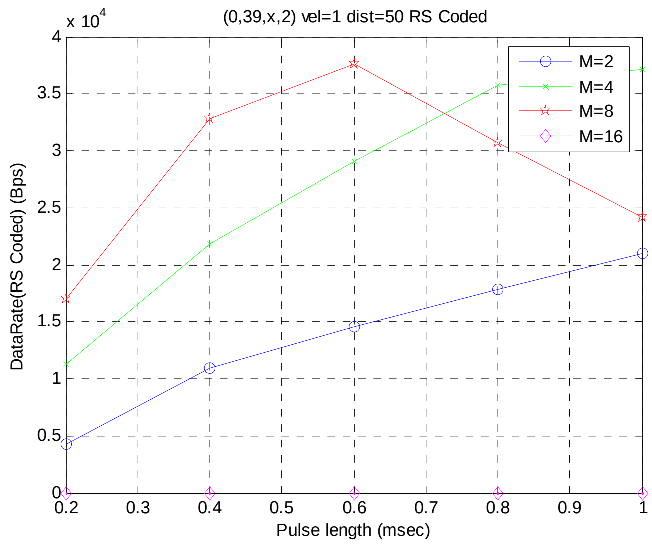
APPENDIX E.6

Communication Performance of Diver State Scenario#3 and Boundary State Scenario#2 with Doppler Shift






(0,39,x,2) vel=1 dist=50 with EQU
x 10^4
2.5
2
1.5
1
0.5
0
TruePut(Gray Coded) (Bps)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Pulse length (msec)
M=2
M=4
M=8
M=16


(0,39,x,2) vel=1 dist=50 RS Coded
x 10^4
4
3.5
3
2.5
2
1.5
1
0.5
0
DataRate(RS Coded) (Bps)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Pulse length (msec)
M=2
M=4
M=8
M=16

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