PERFORMANCE EVALUATION OF EQUALIZATION TECHNIQUES FOR UNDERWATER ACOUSTIC COMMUNICATION

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Dedicated to

My Parents

Mrs B.Aparanjini Adbutha Rao

& Late. Mr B.Adbutha Rao

ABSTRACT

Underwater Acoustic Communication (UWAC) has been an active research area over a decade. Apart from regular communication inside the water, the applications include Remotely Operated Vehicles (ROV), Underwater Wireless Sensor Networks (UWSN), military and navigation applications, diving purposes, Autonomous Underwater Vehicles (AUV), underwater sports, etc. Communication inside the water is difficult due to factors like multipath, Inter Symbol Interference (ISI), Inter Carrier Interference (ICI), time variations of the channel, small available bandwidth and strong signal attenuation especially over long ranges. While at the physical layer, UWAC channels present many challenges for efficient communications, which feature both long delay spreads and serious Doppler effects. The waves and motions at the surface of the sea are the main causes for these effects.

It has been attempted in the present research to improve the performance of the systems reported in the literature in terms of BER versus Signal to noise ratio (SNR) by employing suitable additional techniques like equalization, coding, spatial diversity, Modulation techniques such as BPSK, QPSK, and 4-QAM are used in UWAC in order to reach longer distances inside water. The UWAC channel model with significant multipath interference, path loss and strong ambient noise is considered. Different equalization techniques are applied at the receiver to overcome the Intersymbol Interference (ISI) caused due to multipath propagation. Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) equalizers are used to reduce the errors caused due to the time varying and ambient noise effects in underwater channel. ZF comes at the cost of increasing the ambient noise; however; MMSE reduces all the noise levels in UWAC.

OFDM, a form of multicarrier modulation has been used for UWAC because of its ability to handle long dispersive channels reducing the complexity of the channel equalization. Coding techniques employed at transmitter and receiver decrease the errors in the system. An improved BER performance has been achieved in this research by employing Hamming code and LDPC codes in the existing OFDM system. It is further verified that the LDPC performs better than hamming code.

The three major issues with underwater acoustic propagation are attenuation, time varying multipath and low speed of sound. Multiple copies of a single transmission arrive at the receiver at slightly different times. Without diversity techniques, severe attenuation makes it difficult for the receiver to determine the transmitted signal. So, OFDM along with spatial diversity techniques to reduce the attenuation and Maximal Ratio Combining (MRC) to mitigate the

system against channel fading have been attempted. BER performance has also been evaluated with Filter Bank Multi Carrier (FBMC), an improved version of OFDM without cyclic prefix and high spectral efficiency than original OFDM. FBMC with Offset Quadrature Amplitude Modulation (OQAM) proved to be more efficient for UWAC environment.

Further, a 2×2 MIMO UWAC system with 4-QAM spatial modulation scheme to minimize the decoding complexity and to overcome the Inter Channel Interference (IChI) has been attempted. Spatial Modulation technique that helps in increasing the data rate in UWAC is used. Various factors in underwater channel such as spherical loss, absorption loss, and effect of temperature, salinity, pressure and Doppler Effect are taken into consideration in this aspect. The accomplishment of a MIMO in UWAC system highlighting both Line of Sight (LOS), i.e. the Rician fading and Non-Line of Sight (NLOS), i.e. the Rayleigh fading signal propagation, is assessed. In addition, the utilization of ZF equalizer estimates the transmitted data and effectively reduces the ISI. Because of various scattering effects in NLOS propagation, the error rate is considerably high when compared to that of the LOS propagation. BER investigation is carried out over different link distances under acoustic LOS propagation. A comparison of ZF and Least Mean Square (LMS) equalizers is made, which estimates the transmitted data proves a success of removing ISI.

Another equalization technique, called Vertical-Bell Laboratories Layered Space-Time (VBLAST), in which the received signal is regenerated from the most powerful signal. Nulling, Slicing and Cancelling of the interference signal are the three important steps followed in this technique. Interference Suppression and interference cancellation are carried out in VBLAST. So a comparison of ZF and VBLAST equalizers is carried out. The ISI caused due to multipath effect and scattering in UWAC can be reduced further by iterative process in VBLAST algorithm. A study is also made on how the distance between the transmitter and the receiver and the Doppler Effect has its impact on the performance of the system.

Apart from the simulations carried out throughout the work, an experimental Channel Impulse Response (CIR) was taken for BER analysis from a practical deep sea trial experiment by JAMSTEC with their permission. But in the experiment Hiroshi OCHI et al., were unable to demodulate the single channel receiver because of its complexity. To reduce the effects of noise in the receiver with high complexity ZF equalization technique is used and BER performance for this CIR has been compared with the theoretical values and found to be in good agreement.

The research outcome of this work has been published in the peer reviewed journals.

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LIST OF ABBREVIATIONS

5GNOW	5th Generation Non-Orthogonal Waveforms for Asynchronous Signalling
ADC	Analog to Digital Converter
AFB	Analysis Filter Bank
AM	Amplitude Modulation
AOA	Angle of arrival
AOD	Angle of departure
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CIR	Channel Impulse response
CIR	Channel Impulse Response
CP	Cyclic Prefix
DAC	Digital to Analog Converter
EM	Electro Magnetic waves
EMPHATIC	Enhanced Multi-Carrier Techniques for Professional Ad-hoc and Cell-based Communications
FANTASTIC5G	Flexible air interface for scalable service delivery within wireless communication networks of the 5th generation
FBMC	Filter Bank Multicarrier System
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FMT	Filtered Multitone
GFDM	Generalized Frequency Division Multiplexing
HDD	Hard disk drive
I&Q	In-Phase and Quadrature Phase
IChI	Inter Channel Interference
ICI	Inter Carrier Interference
IFFT	Inverse Fast Fourier Transform
ISI	Inter Symbol Interference
JAMSTEC	Japan Marine Science and Technology Centre
LDPC	Low Density Parity Check

LMS	Least Mean Square
LOS	Line of Sight
LPNM	L_p norm method
MAI	Multiple access interference
MCM	Multi-carrier modulation
MESS	Method of equally spaced scatterers
METIS	Mobile and Wireless Communications Enablers for Twenty-Twenty (2020) Information Society
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
ML	Maximum likelihood
ML	Maximum Likelihood
MMSE	Minimum Mean Square Error
M-PSK	M-ary Phase shift keying
M-QAM	M-ary Quadrature Amplitude Modulation
MRC	Maximum Ratio Combining
MSE	Mean Squared Error
MSE	Mean Square Error
MU	Multi user
NLOS	Non Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OQAM	Offset Quadrature Amplitude Modulation
OSIC	Ordered successive interference cancellation technique
OSIC	Ordered Successive Interference Cancellation
P/S	Parallel to Serial converter
PC	Personal Computer
PSD	Power Spectral Density
PSD	Power Spectral Density
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift keying
RF	Radio Frequency
RLS	Recursive Least Square

RMS	Root Mean Square
ROV	Remotely Operated Vehicles
RX	Receiver
S/P	Serial to Parallel converter
SC	Single Carrier
SFB	Synthesis Filter Bank
SISO	Single Input Single Output
SLC	Selective Combining
SM	Spatial Modulation
SNR	Signal to Noise Ratio
SONAR	Sound Navigation and Ranging
STBC	Space-Time Block Code
TVCIR	Time Variant Channel Impulse Response
TX	Transmitter
UFMC	Universal Filtered Multi-Carrier
UWA	Underwater Acoustics
UWAC	Underwater Acoustic Communication
UWSN	Underwater Wireless Sensor Network
VBLAST	Vertical Bell Laboratories Layered space-time architecture
ZF	Zero Forcing

LIST OF SYMBOLS

KHz	Kilo Hertz
m/s	Metres per second
Mb/s	Megabytes per second
m	Metres
kb/s	Kilobytes per second
Km	Kilometres
T_b	Bit Duration
E_b	Bit Energy
$\boldsymbol{\omega}_c$	Angular Frequency
f_c	Carrier Frequency
θ	Phase shift
r	Received vector
n	Ambient noise
P_e	Conditional Probability
T_s	Symbol duration
n(t)	Ambient noise
r_1,r_2	Received vectors
ET_Q	Minimum Symbol of Energy
M	Order of QAM
SL	Spreading loss
k	Spreading factor
r	Range
AL	Absorption Loss
A	Absorption coefficient
f	Frequency
d	Depth
t	Temperature
A	Temperature
P	Ocean depth (Pressure)
f_1,f_2	Relaxation Frequency

l	Distance
α	Absorption Coefficient
A_0	Unit normalizing factor
N_{th}	Thermal Noise
N_w	Noise caused due to motion of waves
N_s	Noise caused by the ship traffic
N_t	Noise due to turbulence
N	Total Noise
Z(f)	Zero Forcing equalizer
C(f)	Frequency response of the underwater channel
Y	Received signal
H	Underwater Channel
X	Transmitted Signal
$\hat{X}$	Estimate of X
W_{MMSE}	MMSE Equalizer weight
E [·]	Expected value operator
H^H	Hermittian matrix of H
SNR	Signal to noise ratio
Δf	Subcarrier spacing
K	Positive integer
T_u	Useful symbol duration
B	Bandwidth
N	No.of Subcarriers
T	OFDM Symbol duration
T_s	Sampling time
n	Message Length
k	Code word length
d_{min}	Minimum distance
G	Generator Matrix
H	Parity check matrix
c	Code word
m	Message word
$a_{m,n}$	Data sent on the m^{th} subcarrier at the n^{th} OQAM symbol

M	Number of subcarriers
g	Prototype function
f_0	Subcarrier spacing
T_0	QAM symbol duration
τ_0	Symbol duration of OQAM
$g_{m,n}$	Shifted version of prototype function
$H_{m,n}$	Complex valued channel frequency coefficients
N_t	Number of transmitters
N_r	Number of receivers
R_{SM}	Rate of Spatial Modulation
h_{11}, h_{12}, h_{21}, and h_{22}	Channel coefficients
c_R	Rician factor
$A_s(d)$	Spherical spreading loss
$A_a(d)$	Absorption loss
f_0	Doppler frequency
θ_0	Phase shift of the LOS component
f_{max}	Maximum Doppler frequency
v_R	Receiver's speed
f_c	Carrier frequency
c_s	Speed of the sound
λ	Wavelength
S_a	Salinity
f_T	Relaxation frequency
T	Hydrostatic temperature
P	Pressure
h_t	Water depth
e	Error signal
d	Desired signal
w	Weight vector
μ	Adaptive filters step size
$H^{\dagger}$	Pseudo-inverse of the matrix
$(w_i)_j$	jth row of (w_i)
$Q(.)$	Quantizer

(H_{k_i})	k_i^{th} Column of H
$(H)_{\bar{K}_i}$	Matrix obtained by making the columns $k_1, k_2, \ldots, k_i$ as zeros of H
$s(t)$	Transmitted signal
a,b	Amplitude of the I and Q phase components
$\boldsymbol{\omega}$	Angular frequency
θ	Phase coefficient

CHAPTER 1

INTRODUCTION

1.1 Introduction

Communicating inside the water is known as Underwater Communications.

About three quarters of the earth's superficial layer is enclosed with water, and almost 95percent of it flows through the seas. Exploring the ocean has become very prominent these days because of the rise in resource intake and mostly concentration on crude oil, minerals. Learning and discovering new environments is an essential human venture. One immense background which is still much strange is the underwater environment. Because of the atmosphere, just to acquire low transmission rates in short distances, underwater wireless communications present new and distinct challenges. This topic is complicated and many difficulties are involved in underwater communications, mainly water chemical composition, environmental variables, and the occurrence of several forms of noise. Actually, the underwater environment has many distinctive sorts that make it exceptional and relatively diverse from terrestrial radio propagation where outmoded communication systems are set up. Underwater environment is mainly effected by factors namely salinity, pressure, temperature, winds and their effects on waves etc., [1].

In contemporary years, underwater communication got high attention for applications such as unmanned submarines, underwater robots/vehicles, and sensor nodes, Remote control in the offshore oil industry, Pollution monitoring in environmental systems, Collection of scientific data, Disaster detection and early warning, underwater surveillance etc.

1.2 History

Study of the peculiar underwater world has never stopped in the history of humankind. Way back in 400 BC, Aristotle had invented that sound can be heard in both water and in air. In AD 1490, Leonardo da Vinci penned: "If you cause your ship to stop and place the head of a long tube in the water and place the other extremity to your ear, you will hear ships at great distances". In 1826, Charles Sturm and Daniel Colladon made the first ever measurement of the speed of the sound in water at Lake Geneva, Switzerland [2]. The light ships that were equipped with underwater bells that were used to measure the offshore distance and usage of stereo headphones in all directions were the first hands-on application of sound in underwater in the 1900s. In sequence with the tragic sinking of Titanic in 1912, L.F.Richardson filed a patent of echo ranging with sound in air and a patent application of echo ranging in water. Along with the application of submarine and underwater mines in World War I (1914–1918), considerable progress has been made in underwater acoustics, especially on the underwater echo ranging for submarine and mine detection. In 1914, Constantin and Chilowski conceived the idea of submarine detection by underwater echo ranging. Built on the discovery of the piezoelectric effect by Jacques Curie and Pierre Curie in 1880, Paul Langevin in 1918 used quartz (piezoelectric) transducers as source and receiver to extend one-way sound transmission to 8 km, and for the very first time observed clear echoes from a submarine at distances as large as 1500 m [3]. Between World War I and World War II, scientists started to understand some basic concepts of sound in water, such as sound refraction due to changes of water temperature, salinity and pressure. Development of underwater sound applications during this period can be found in echo ranging for commercial use, underwater tomography and fisheries acoustics. The research effort on underwater acoustics during World War II (1941–1945) was mainly focused on improving echo ranging systems which were later coined as "SONAR" (Sound Navigation and Ranging). During this period, topics relative to sonar system performance were extensively investigated, including the high-frequency acoustics, low-frequency sound propagation, ambient noise, etc. By the finale of World War II, the underwater sound had been primarily used for navigation and threat-finding. In 1945, an underwater telephone, which was technologically advanced by the Navy Underwater Sound Laboratory in the United States for the purpose of communication with submerged submarines, was the first application of underwater sound for communications. Since then, development on UWAC has been made in various underwater acoustic applications. For Underwater Acoustic Communication (UWAC) initially "Gertrude" or "underwater telephone" was developed with a frequency range of 2-25 KHz. And in the course of World Wars this area discovered numerous innovative applications like underwater wireless sensor network (UWSN), submarine communications, military surveillance and remotely operated vehicles (ROV), Oceanography, Marine archaeology, Offshore oil exploration, Rescue missions, Underwater sports, Military and Navigation purposes [4]. Although most of the functional conceptions have been implemented in RF applications, the key experiment has been on applying those models to the underwater channel [5].

1.3 Underwater Communication Media

For the signal transmission inside water, there are three main technologies available. One of them is Radio Frequency (RF) communication that attributes high data output at short distance suffering from Doppler Effect. Another technology is optical transmission that involves line-of-sight (LOS) propagation. Some investigations have been made about using optical signals for underwater applications. However, it was found that they can only flow through a limited range in very clear water environment, making them useless for underwater long-distance transmissions [6]. Another technology that's mostly used is acoustic communication which allows the longest range of communication at the cost of achieving low throughput. This technology is highly weakened by Doppler effects and high delay spread that heads to severe Inter Symbol Interference (ISI) [7]. The main advantage of using acoustic wave as principal carrier for wireless underwater communications is because it has low-loss at low frequencies (mainly up to 100 kHz) when compared to Electro Magnetic (EM) waves. However, bandwidth of the system is reduced because of the low speed of sound inside the water therefore suffering from large latency [8].

Table 1.1 Comparison of EM, Optical and Acoustic waves in Underwater[9]

Communication Paradigm	Propagation Speed	Data ranges	Communication ranges	Channel Dependency
EM	3.33×10^7 m/s	~Mb/s	≤10 m	Conductivity, Multipath
Optical	3.33×10^7 m/s	~Mb/s	10-100 m	Light Scattering, LOS communication, Ambient light noise
Acoustic	1500 m/s	~kb/s	~Km	Multipath, Doppler, Temperature, Pressure, Salinity, Ambient noise

Table 1.1 gives the propagation speed, data ranges, and communication ranges of individual media through which signal can be transmitted inside the water. Also the factors that the channel depends are tabulated.

The main characteristic of underwater channel involves constricted bandwidth, extended time, and serious ISI which seriously affects the systems stability and cause hindrances to high-rate UWAC. The three major factors that are reflected in underwater acoustic propagation are: attenuation that rises with the frequency of the signal, time-varying multipath propagation, and speed of the sound which is approximately 1500 m/s [10]. The extreme multipath effects that we come across in traditional UWAC also create ISI, which is a restrictive factor to succeed high data rate. These tough problems pose many hindrances for sustaining steadfast, high-speed, and long-range UWAC [11]. However, its limited bandwidth makes it adverse for short distances and bandwidth critical applications.

1.4 Motivation

Underwater world is the vast environment which is still to be explored. Apart from the RF Communication, the same technologies have been accepted for underwater communications. Usage of cables, EM waves and optical waves has its own disadvantages and so UWAC came into existence because of its capability of reaching higher distances than the former. UWAC has numerous uses that include fields like military, commercial and scientific uses. These applications lead in additionally improving the performance of the underwater system.

The major challenges in UWAC involves time variation in the channel, high ambient noise, bandwidth limitation and stretched multipath effect, spherical and absorption losses [12]. All these characteristics are a part of UWAC and so underwater systems pose new challenges and constraints. A key area of research in underwater acoustics is development of efficient modulation and detection systems, reducing the error rate for enhanced quality of service.

Because of the constant movement of medium and also slow propagation of sound Doppler Effect is caused in UWAC [13]. The ISI is caused by the multipath effect [14]. Orthogonal Frequency Division Multiplexing (OFDM) enables transmission of high data rate in long UWA channels. The main benefits of OFDM include robustness against frequency selective fading and narrowband interference [15]. Hence one of our main motive is to investigate OFDM as a low-complex, low maintenance substitute for bandwidth efficient UWAC with different techniques attached to it.

Single Input Single Output (SISO) system may suffer an extreme deprivation in the performance of UWAC as of a large portion of the power transmitted is focused away from the receiver. These issues are sorted out by Multiple Input Multiple Output (MIMO) systems which reduces the probability of loss of link, improves the error rate, and thereby increasing the performance [16]. Because of bandwidth limitations of UWAC channels, the data rates and spectral efficiencies attained by Underwater Acoustic (UWA) systems are normally much lower when compared to radio channels [17]. This motivated us to work more on MIMO for UWAC with different equalization techniques to further improve the performance.

The main objective of this work is to review the core features that are inborn to every single underwater wireless communication technology. Discussion is also made on how signal processing gets the possible solutions to existing practical challenges and also to increase the ability of communicating the data in the underwater environment.

1.5 Literature Survey

UWAC is a technique of transmitting and receiving messages underwater. In 1490, scientist Leonardo da Vinci said "*If you allow your ship to hold and place the head of a lengthy tube in the water and place the outer extreme to your ear, you will hear ships at a large distance from you*". But this part of work received a key initiative only in the initial 20th century when the disastrous sinking of Titanic constrained the research community to discover the field of underwater communication. The authors proposed that in spite of wide-ranging growth in the literature of UWAC it still continues to be one of the most interesting areas of wireless communication. Work has also been done on channel modelling where the purpose of this is to help in the assessment of signal processing algorithms in an effort to improve the attainment of field experiments. Discussion is also made on the Experimental noise model of UWAC. Adaptive modulation technique, Doppler compensation, Spatial Diversity and MIMO, Channel estimation and equalization and hybrid schemes are reviewed in detail [5].

Milica Stojanovic [18] gave the very basic of UWAC and its applications. After considering many drawbacks of different signals they came to a conclusion that Acoustic waves are the best ways for wireless transmission of signals inside water. The major issues in UWAC are time varying multipath that influence signal design and processing. This multipath propagation causes ISI. To attain higher data rates the more refined systems based on phase coherent signalling methods must allow for significant ISI in the received signal.

Milica Stojanovic [19] et al., proposed about the channel modelling in UWAC with ambient noise which means the background noise of the quiet deep sea. Main noises which contribute to ambient noise are shipping, wind, thermal noise and temperature. Multipath propagation in the water body is ruled by two effects: sound reflection both at surface and bottom, Sound refraction in water and reflection at any objects. After attaining some depth, the temperature touches a constant flat of 4°C, and from there onwards, the speed of the sound increases. Motion of the transmitter or receiver plays a key role in changing the channel response. This is initiated by the Doppler Effect, which causes shifting and spreading of the frequency. This paper also gave an overview about the path loss that depends on the frequency of the signal. Power spectral density (PSD) of the ambient noise for various values of wind speed is estimated.

In the year 2015 K.Chithra[20] et al., proposed that OFDM is an developing technology in wireless communication for achieving high data rates. Due to the harmful effect of spreading of time and frequency, reaching high data rate in UWAC is thought-provoking. As OFDM deals effectively with multipath delay spread, it is used in underwater communications. Limited channel BW is used efficiently in OFDM because of the overlapping between the subcarriers. To eliminate ISI, guard time is announced for each OFDM symbol. This guard time is chosen to be higher than the likely delay spread such that ISI due to multipath components is minimized. By this OFDM, the limited UWAC bandwidth can be utilized well. The sub-carriers are orthogonal to each other and hence allow overlap in frequency with the adjacent carriers without causing Inter carrier interference (ICI). Better spectral efficiency is another advantage of orthogonality in OFDM when compared to other multi carrier techniques. Besides being more suitable to overcome frequency selective fading and multipath effects, OFDM also has implementation advantages, such as avoiding ISI and ICI, over other multi-carrier communication schemes. OFDM is more unaffected by frequency selective fading, when we divide the wide band frequency selective channel into narrowband flat fading sub channels. Inverse Fast Fourier Transform (IFFT) and Fast Fourier Transform (FFT) techniques are the most efficient techniques to instrument the modulation and demodulation functions respectively.

In the fading channels, MIMO system improves the channel capacity significantly. This means that the transmission rate is significantly increased. The influences of modulation schemes such as M-ary Phase shift keying (M-PSK), M-ary Quadrature Amplitude Modulation (M-QAM), carrier frequency and the Doppler Effect to quality of the received signal are taken into account. In addition, MIMO system also creates the spatial diversity which reduces Bit Error Rate (BER) when the system is operated [21]. The combination of MIMO with OFDM to form MIMO-OFDM technique will combine above mentioned advantages of both techniques to archive the reliable transmission for underwater wireless communication. The MIMO-OFDM system continuously is simulated with the different channel equalizer included Minimum Mean Square Error (MMSE) and Zero Forcing (ZF) equalizers. The dependence of received signal quality on number of antenna, channel equalizations, modulation schemes, carrier frequency and the Doppler Effect is considered.

For designing UWA channel, the authors in [22] have proposed the channel model of UWAC with all the factors involved in it. A new geometry-based shallow UWAC channel model was developed assuming that the surface and the bottom of the ocean are rough. The Angle of arrival (AOA), Angle of departure (AOD), scattering effect, absorption loss and the parameters such as temperature, pressure and salinity are considered in the channel modelling. Statistics of AOD and AOA are affected by the distribution of scatterers which play a key role in channel modelling. The equations of LOS part of the Time Variant Channel Impulse Response (TVCIR), Doppler frequency, total distance between the Transmitter (TX) and the Receiver (RX), propagation loss coefficient because of spherical spreading, absorption loss coefficient are calculated. Parameters such as Temperature, Salinity, and Pressure are considered in the shallow water. For the parameterization of the UWA channel simulator, a new technique called the method of equally spaced scatterers (MESS) is proposed. The piece of the MESS is matched with that of the L_p-norm method (LPNM).

Recent research have focussed on the possibility of Filter Bank Multicarrier Systems (FBMC) systems for UWAC [23]. The authors suggested using a Filtered Multitone (FMT) system with comparatively wideband subcarriers. Simulation results presented that FMT outperforms OFDM even in varying channel qualities, however experimental data were not convincing in this matter. The main intention of choosing FMT is because of its simpler structure and its easy applicability in MIMO systems. Depending on the category of configuration of the channel, factors that illustrate the UWA propagation comprise transmission loss, propagation delay, ambient noise, multipath propagation and Doppler spread. Transmission loss is mainly distance and frequency dependent. It is mainly affected by geometrical spreading, scattering and absorption. In this paper it is proved that FBMC (particularly OFDM- Offset Quadrature Amplitude Modulation (OQAM)) is a better option for video transmission in UWAC where high data rates are required for conveying good quality video in the given limited acoustic bandwidth.

In recent times, Spatial Modulation (SM) is suggested in RF MIMO technique, which is proficient of overtaking many standard schemes of MIMO transmission with low execution and computational complications [24]. The data to be transmitted in SM is divided into 2 carrying units namely signal constellation diagram and a spatial constellation diagram. If we keenly observe at the research works conducted on Multi user (MU)-SM to date, it is obvious that much of the work have been focused on uplink multiple–access scenarios.

To encode the MIMO high data rate data, a new technique known as Vertical Bell Laboratories Layered space-time architecture (VBLAST) architecture and Space-Time Block Code (STBC) encoder came into existence [25]. VBLAST/ZF algorithm can be operated as both an equalizer as well as a detector. While ZF algorithm as non-linear detector is built on ordered successive interference cancellation technique (OSIC). The channel of UWAC is used considering the ambient noise, IFFT at the transmitter and FFT at the receiver. Here a realistic channel model that is based on a time varying wideband channel is considered. And it is observed that error floor in the BER performance is introduced by path dependent Doppler and angle spreading. Turbo decoder that is based on user- specific spreading sequence de-spreads the detected acoustic information and Log-Map decoding algorithm is used to de-interleave and decode to get the estimated data. VBLAST performs better in terms of BER to Signal to Noise Ratio (SNR).

In the year 2018, Paul C.Etter in [26] gave a detailed description about the Channel modelling and various factors to be considered in developing the same for UWAC. Applications and the techniques used in UWAC are addressed. Physical and chemical properties of water are highlighted. This book also gave an insight that the low speed of the sound is dependent on the temperature of the water, salinity, and depth of the water.

Literature survey that has been done in the initial days of the research is tabulated below to identify the research gaps and to draw a clear cut problem statement.

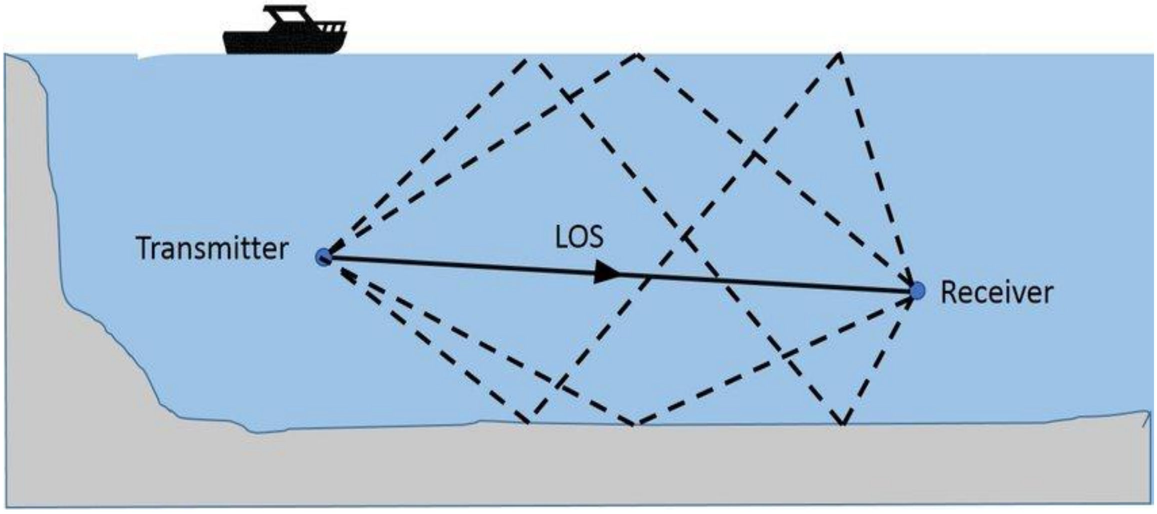
Table 1.2 Summary of Literature Survey

Research Paper Title	Journal and Year	Outcome of the paper	Limitations/Conclusions drawn
Underwater communication implementation with OFDM [20]	Indian Journal Of Geomarine Sciences,2015	This paper investigates on how OFDM finds its suitability for underwater communications. Due to the detrimental effect of time and frequency spreading, achieving high data rate in underwater	Fading channel impairments are not considered in this model

		communication is challenging. The wireless underwater communication with OFDM scheme was tested using underwater transducers in a water tank and the results are presented.	
An analysis of MIMO-OFDM for underwater communications[21]	International Congress Ultra Mod Telecommunication Control System Work, 2011.	In this paper, MIMO-OFDM system for underwater channel at frequency of several ten kHz and bandwidth of several kHz is analysed via simulation.	MIMO along with OFDM is considered.
A geometry-based channel model for shallow underwater acoustic channels under rough surface and bottom scattering conditions [22]	5^{th} International Conference for Communications and Electronics 2014	In this paper, a new geometry-based shallow UWA channel model under the assumption that the surface and the bottom of the ocean are rough was derived considering the Angle of Arrival (AOA) and Angle of Departure (AOD).	The model was limited only for SISO.

Performance Evaluation of Filter bank Multicarrier Systems in an Underwater Acoustic Channel [23]	2016 IEEE 27th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications - (PIMRC): Fundamentals and PHY	A comparison study of OFDM and FBMC in UWAC has been done. Turbo equalization technique is applied at the receiver for better BER performance	Only limited to video transmission of the data making the system complicated.
Multi-user spatial modulation MIMO [24]	2014 IEEE Wireless Communications and Networking Conference (WCNC)	This paper proposed Spatial Modulation (SM) technique for MIMO technique which outperforms the conventional MIMO in terms of computational and implementation complexity	The work from this paper is used for underwater channel.
Performance of Turbo Coded MIMO-OFDM System for Underwater Communications[25]	International Conference on Communication and Signal Processing, 2014	In this paper, investigates on the performance of turbo coded MIMO-OFDM system in underwater communications is done considering the realistic UWA channel.	The research is limited to ZF equalizer which comes at the expense of increased noise

1.6 Underwater Environment



Picture 1.1 Basic UWAC Model

Study of sound and its behaviour in the sea is known as Ocean acoustics. As the acoustic wave travels from side to side in the sea, objects that are underwater vibrate that creates sound-pressure waves alternately compressing and decompressing the water molecules. Almost in all directions, sound waves radiate like ripples on the surface of a pond from the source. The compressions and decompressions that are associated with sound waves are distinguished as pressure changes by the structures in our ears and most natural sound receivers such as a hydrophone, underwater microphone, etc.,**.** The information from the sound source as shown in Picture 1.1, reaches the receiver i.e., the hydrophone through different routes. There is always LOS propagation from the TX to the RX. Some information is either reflected at the surface of the sea or at the ocean bottom. Reflections from sea surface, bottom of the sea and other obstacles cause strong multipath effect in UWAC. ISI and destruction of original signal is caused because the transmitted signal is reflected many times before reaching the receiver and also many delayed copies of the same signal are also received [27]. Apart from the reflections from ocean surface and bottom temperature, salinity also differs from virtual layers with varying reflection and refraction properties also add to multipath propagation. Time variability of the acoustic channel are caused by surface waves [15]. The information reached at the receiver are also affected by the ambient noise whose details are explained in the upcoming chapters.

1.7 Problem Statement

- Study various modulation techniques and its impact along with equalization techniques in improving the performance of UWAC.
- Validation of OFDM in UWAC along with some coding and diversity techniques.
- Comparative study of OFDM and FBMC in UWAC.
- High speed and increased data rate with MIMO that combines with advanced equalization techniques in UWAC.
- Study of single Channel Impulse response (CIR) from a practical experimentation and its impact with a linear equalizer.

1.8 Research Objectives

The main research goals of the work are

- To improve the performance of UWAC (SNR vs. BER) using equalization technique i.e.., for Binary Phase Shift Keying (BPSK), Quadrature Phase Shift keying (QPSK) and Quadrature Amplitude Modulation 4-(QAM).
- To evaluate the BER using spatial diversity techniques for OFDM based UWAC.
- To investigate the performance of UWAC using coding techniques in OFDM
- Performance comparison of UWAC with OFDM and FBMC.
- To analyze ZF, Least Mean Square (LMS) and VBLAST equalization techniques for a MIMO based UWAC under fading conditions.
- To study the effect of equalization for a practical CIR in UWAC.

Pranitha, B, Anjaneyulu, L, "Review of Research Trends in Underwater Communications-A Technical Survey", International Conference on Communication and Signal Processing, April 6-8, 2016, India, Page no: 1443-1447.

CHAPTER 2

EQUALIZATION TECHNIQUES FOR BPSK, QPSK, 4-QAM IN UWAC FOR SISO SYSTEM

Research has been lively for over the last 10 years on improving the performance of Underwater Acoustic Communication (UWAC). This chapter deals with modulation techniques such as BPSK, QPSK, and 4-QAM in UWAC for long distance propagation. The vital key characteristics of UWAC such as multipath, interference and strong ambient noise are talked about. Zero Forcing (ZF) and Minimum Mean Square Error (MMSE) equalizers are used to overcome the Inter symbol Interference (ISI) caused due to the multipath. However, ZF comes at the expense of increased noise but MMSE moderates all the noise levels.

2.1 INTRODUCTION

Present day it is very essential to observe the condition of our oceans and rivers because of the increasing commercial subsea activity. Sound propagation is affected by physical and chemical properties of seawater. Generally underwater acoustic signal suffers attenuation due to spreading and absorption losses. Moreover, subject to channel geometry, multipath fading may occur and produce noteworthy ISI at the receiver hydrophone. Understanding and establishing a good channel model estimates the Signal-to-Noise ratio (SNR) or Bit Error Rate (BER). Underwater environment is very unstable. Therefore, system Design approach of underwater channel to increase the data rate and overcome the effects of multipath and time variations include

(i) Choice of modulation

(ii) Choice of equalization techniques at the receiver side

Modulation is introduced in UWAC to reach to a longer distance as it is not possible to send low frequency signals over long distance. However some of the modulation schemes are more suited for other communications [28]. Modulation Techniques for Underwater Optical Wireless Communications are compared [29]. They concluded that the restricted available range and the requirement for line of sight are manageable by optical communication. The higher speed can be attained by better-quality communications and long distances can be reached by less noise by increasing the SNR. S. Sendra et al [30] performed several tests underwater to check few parameters such as the minimum depth, distance between the TX and the RX and signal transmission characteristics at different frequencies and modulations. In any traditional modulation classification method, initially signal needed to be extracted followed by classification and identification. The modulation sorting method is likely to adjust to the characteristics of Underwater channel in the same way with the enhancement of modulation classification requirements in UWAC [31]. In the 1990s focus was made on Single Carrier (SC) coherent Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM) signalling for UWAC optimizing the data rates in accordance to the occupied bandwidth. Though these modulation methods offered high spectral efficiencies, difficult receivers that need to equalize widespread Channel Impulse Response (CIR) while tracking time variations and phase distortions were required [12].

Due to the complex UWAC systems, identification of modulation during actual communication is very difficult. So to reduce the complexity of the system, in this work, focus is made on basic modulation techniques namely BPSK, QPSK and 4-QAM. These three modulation techniques are used at the transmitter side in UWAC system model (explained in 2.2) and they are passed through UWAC channel that is clearly explained in section 2.3. Demodulation is done at the receiver and the shortcomings of this communication system are overcome by equalization techniques. Zero Forcing (ZF) and Minimum mean square error (MMSE) are the equalization techniques used here and their performances are compared with respect to bit error rate (BER). These two equalization techniques are generally considered to be superior over other equalization techniques. Even though they are not ideal, the MMSE receiver satisfies another criterion of minimizing the mean squared error (MSE) and ZF is known in eliminating the interference completely [32].

2.2 MODULATION TECHNIQUES

Modulation is the modification of a carrier signal in accordance with an information signal. The two different types of modulation techniques are analog and digital modulation techniques which are explained in Fig 2.1.

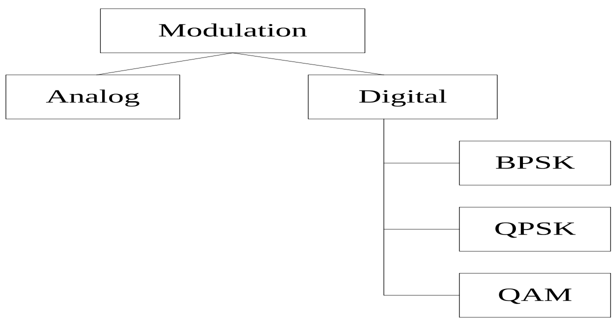


Fig 2.1 Classifications of Modulation Techniques

Digital modulation has many advantages such as high information capacity, large data security, and quicker system availability with high quality of communication. Compared to analog communication, these digital modulation techniques convey larger amounts of data therefore it is of high demand. They need a demodulator at the receiver block which helps in recovering the message from the received signal i.e., it performs the contrary job compared with modulator like splitting the information signal and carrier. Decision of the modulation scheme plays a key role as the signal demodulation and identification are built on right modulation classification. The general modulation methods used for radio communications can be reformed for UWAC. However some of them are exclusively suited to the unique UWAC channel than others. The commonly used modulation methods in UWAC are MPSK (BPSK, QPSK, and 8PSK) and M-QAM. Here we study three modulation schemes BPSK, QPSK and 4-QAM. Further on a detailed theoretical explanation of the modulation schemes are given.

2.2.1. BPSK

Binary phase shift keying (BPSK) which is basic form of Phase Shift Keying (PSK) is a widespread digital modulation scheme that shifts the carrier sine wave 180° for every change in binary state. The phase transitions occur at the zero crossing points making it coherent [33]. In BPSK the signal has to be compared to a sine carrier of the same phase in the demodulation. BPSK technique is less complex in comparison with other modulation techniques as we know that in underwater the bandwidth is very less that's why BPSK consume low BER as well at low SNR [34]. The carrier wave modulation in BPSK is done by changing the phase by π and input binary bit by 0 for '0' and '1' respectively. This is done for each bit intervalT_b. To simulate the change in the phase of π radians for 0 and 1, the binary data 0 and 1 are drawn to -1 and +1, respectively, according to the relation $n = 2 * m - 1$, where $m = [0,1]$.

BPSK and QPSK modulations are ideal from error protections point of view, however BPSK is used transmitters that are low-cost and does not require high speeds [35]. Here the binary bits 1 and 0 are represented by $+\sqrt{E_b}$ and $-\sqrt{E_b}$. A BPSK signal is described by the following equations

$$s_1(t) = \sqrt{\left(\frac{2E_b}{T_b}\right)} \cos(\omega_c t + \theta)(\theta = o) \tag{2.1}$$

$$s_2(t) = \sqrt{\left(\frac{2E_b}{T_b}\right)} \cos(\omega_c t + \theta + \pi) = -s_1(t) \tag{2.2}$$

T_b is the duration of the bit, E_b is the energy of the bit, ω_c is the angular frequency that is given by $\omega_c = 2\pi f_c$ and the initial phase θ can be taken as zero. The received vector r is the vector sum of the signal and noise that is given by

$$r(t) = s(t) + n \tag{2.3}$$

n represents the ambient noise explained in Section 2.3.

In this modulation '0's and '1's are equally likely to occur. The average BER is calculated as

$$BER = \frac{1}{2}P_e(0) + \frac{1}{2}P_e(1) = \frac{1}{2}erfc\left(\sqrt{\frac{E_b}{N}}\right) \tag{2.4}$$

For demodulating a BPSK signal, equal maintenance of both coherent detector's frequency and the carrier signal at the transmitter is needed which further leads to complex receivers. In BPSK, data rate and the symbol rate are the same. Generally this is caused as a single bit is carried by a single carrier in this modulation. This proves that BPSK is not bandwidth efficient when compared to other modulation types. But bandwidth has to be increased to increase the data rates in UWAC, [36]. To get rid of this disadvantage, QPSK multi-level modulation techniques came into existence. Here modulation levels greater than two are considered as the input of the transmitter. Therefore, these techniques are well-thought-out to be more bandwidth efficient.

2.2.2. QPSK

Using four equi spaced points on the constellation diagram with four phases, QPSK can encode two bits per symbol, with gray coding to reduce the BER. This modulation scheme has two advantages. (i) It doubles the data rate keeping the same bandwidth of the signal. (ii) It maintains the data rate but bandwidth needed is half of it [37]. QPSK is an exceptional case in PSK wherein M=4, and each symbol signifies 2 bits given by [38]

$$s_i(t) = \sqrt{\frac{2E_b}{T_s}}\cos\left(2\pi\omega_c t + (2i-1)\frac{\pi}{4}\right) \qquad 0 \le t \le T_s \tag{2.5}$$

In computing we have

$$P_e = \frac{1}{2}erfc\left(\sqrt{\frac{E_b}{N}}\right) \tag{2.6}$$

In this modulation technique, dual binary bits are denoted by one complex symbol making it complicated in UWAC as it requires more transmission power. Decoding at the receiver is done by estimating the phase states of the transmitted signal inside the water. So we move forward with a bandwidth efficient 4-QAM modulation.

2.2.3. 4-QAM

An analog/digital modulation scheme that conveys both analog message signals/ digital bit streams where the modulation of the amplitudes of two carrier waves is done using the ASK in digital modulation scheme/amplitude modulation (AM) in analog modulation scheme is known as QAM modulation [32]. Their main advantage includes high Bit Packaging Ratio, increased Bandwidth efficiency and channel capacity, catering more number of customers. Multiplicand of 2 such as 2, 4, 6,8,16 etc. are used as points on the constellation in QAM. Both amplitude and phase differences are used to represent binary data in this scheme i.e., it has both in-phase and Quadrature-phase (I and Q) signals [39] as below

$$s_I\left(t\right)=\sum_{k=-\infty}^{\infty}\sqrt{\frac{ET_Q}{T}}g_T\left(t-kT\right)cos\left(2I_k+1-\sqrt{M}\right) \tag{2.7}$$

$$s_Q\left(t\right)=\sum_{k=-\infty}^{\infty}\sqrt{\frac{ET_Q}{T}}g_T\left(t-kT\right)sin\left(2I_k+1-\sqrt{M}\right) \tag{2.8}$$

ET_Q is the minimum energy of the symbol. Here M=4. If we calculate the BER in most generalized form, we have

$$P_Q=\frac{2}{\sqrt{M}}\sum_{i=1}^{\sqrt{M}/2}Q\left(\frac{\left(2i-1\right)d}{\sqrt{N/2}}\right) \tag{2.9}$$

Further, as we evaluate P_Q it is expressed as

$$P_Q=Q\sqrt{\frac{2E_b}{N}} \tag{2.10}$$

On expressing in terms of error function we have

$$P_e=\frac{1}{2}erfc\left(\sqrt{\frac{E_b}{N}}\right) \tag{2.11}$$

QAM modulation has the advantages of noise and bandwidth efficiency inside the water, however it also has the disadvantage of complex receivers. This modulation scheme is given to an underwater channel that is explained in Section 2.3

A comparative table for the above given modulation techniques is given below to understand the pros and cons of them individually.

Table 2.1 Comparison table for the Modulation Techniques

Modulation Techniques	Advantages	Disadvantages
BPSK	1. Efficient in long distance communication 2. Very simple 3. Power efficient modulation technique	1. Low data rate 2. Not bandwidth (BW) efficient
QPSK	1. It has high noise immunity 2. Low error probability 3. Efficient BW utilization when compared to QPSK	1. Not power efficient 2. More Complex
4-QAM	1. Efficient BW utilization 2. Increased channel capacity	1. Complex receivers

2.3 UNDERWATER CHANNEL

The present day challenges include communicating underwater which has harmful effects such as time and frequency spreading. In the design of traditional wireless communication systems, the acoustic wave that propagate with attenuation that depends on frequency and delay plays a major role. For any system designer, attenuation behaviour as a function of frequency is much needed as it gives support technically for the deciding the frequency bands to be used in the communication. At low frequencies this acoustic signal suffers little attenuation while it increases at higher frequencies. As explained earlier low bandwidth and low speed of sound are the two major issues that might obstruct high output underwater communications. Where in low bandwidth executes a limitation on the quantity of bits transmitted in each channel application and low propagation speed increases the round-trip time and so the Doppler Effect. The absorption of impurities and the ambient noise neighbouring the object proposed mainly decides the underwater channel characteristics [40].

The attenuation and loss caused by reflection in underwater are the reasons for time spread along with multipath. The relative motion between the TX and RX causes Doppler effect which influences the frequency spreading [41]. Propagation speed is considered to be the main variance between RF and UWAC channel [42].

The modulation techniques considered in this work increases the speed of sound waves inside the water which has major disadvantages such as the large delay spread, Doppler spread, and the frequency dependent propagation loss [43]. As shown in fig 2.2 the reflections from the ocean surface and bottom causes interference. Additional spreading occurs because of the rough surfaces. Along with the multiple reflections there is also direct Line of Sight (LOS) propagation between the TX and RX.

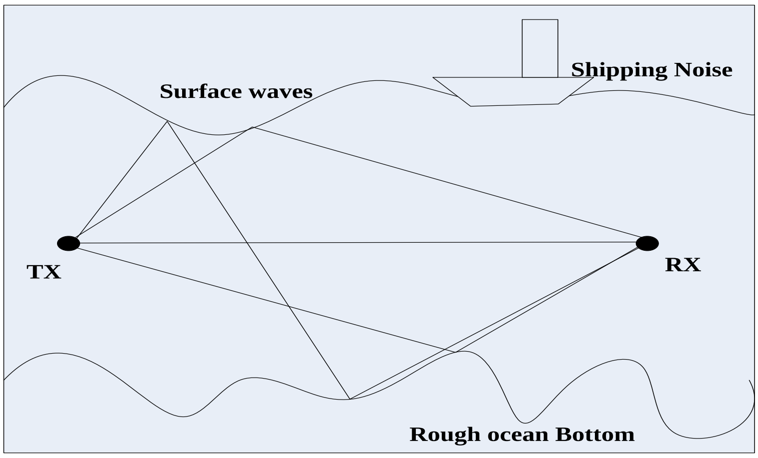


Fig 2.2. UWAC Channel with multipath

In modelling the underwater channel the attenuation initiated by frequency absorption, scattering loss at the surface and the bottom of the ocean and ambient noise are considered. Spreading loss and absorption loss are considered in this work. When the wave front moves away from the surface then that place is covered by the energy of the sound signal causing spreading loss which is given by

$$SL(r) = k \times 10 \log(r) \tag{2.12}$$

It is calculated in dB. At this point *k* is the spreading factor, and *r* is the range measured in meters. *k*=2 in unbounded spreading and *k*=1 for bounded spreading. This spreading loss has a high influence on a short distance transmission having a logarithmic relation with the range '*r*' [44].

The gluey roughness and the iconic moderation signify the heat energy loss when the sound wave is propagating outside in underwater. This is called the absorption loss given by

$$AL(r, f) = 10\log(\alpha(f)) \times r \tag{2.13}$$

It is measured in dB. Here α is the absorption coefficient that is frequency dependent. An experiential formula for α that changes with frequency, pressure and temperature was proposed by Fisher and Simmons, Francois and Garrison [45]

$$\alpha(f,d,t) = \frac{A_1 f_1 f^2}{f_1^2 + f^2} + \frac{A_2 P_2 f_2 f_2^2}{f_1^2 + f^2} + A_3 P_3 f^2 \tag{2.14}$$

In the above equation d denotes the depth; t defines the temperature in °C, A is the temperature effect, P is the depth of the ocean used to calculate the pressure and f_1,f_2 are the relaxation frequencies. For a distance l and frequency of the signal f, attenuation/path loss is given by [46]. Spreading and absorption losses together contribute for path loss.

$$A(l,f) = A_0 l^k \alpha(f)^l \tag{2.15}$$

The unit normalizing factor A_0 is conveyed in dB as

$$\frac{10\log A(l,f)}{A_0} = k.10logl + l.10log\alpha(f) \tag{2.16}$$

At lower frequencies, Thorps proposed an empirical formula for the absorption coefficient [47].

$$10log\alpha(f) = 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 2.75.10^{-4} f^2 + 0.003 \tag{2.17}$$

The frequency and the absorption coefficient (dB/Km) are related exponentially as shown in Fig 2.3.

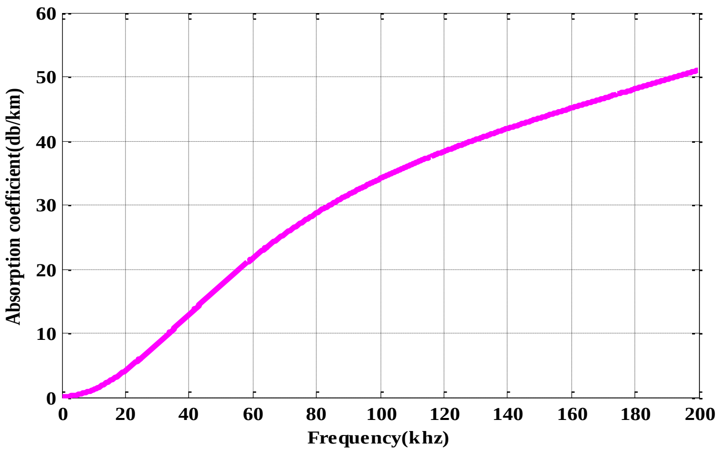


Fig 2.3. Frequency vs. Absorption Coefficients (dB/Km)

The four different noises considered in UWAC are the thermal noise N_{th}, noise due to the motion of the waves N_w, Noise produced by the ship traffic N_s and the turbulent noise N_t. The equivalent equations are given by [19].

$$N_{th} = 10^{\frac{((-15+20\log(f))}{10}} N_{th_{off}} \tag{2.18}$$

$$N_w = 10^{\frac{(50+(7.5(\sqrt{w}))+(20log10(f))-(40log10(f+0.04))}{10}} N_{w_{off}} \tag{2.19}$$

$$N_s = 10^{\frac{((40+(20(s-0.5))+(26log10(f))-(60log10(f+0.03)))}{10}} N_{s_{off}} \tag{2.20}$$

$$N_t = 10^{\frac{((17-30log10(f))}{10}} N_{t_{off}} \quad (2.21)$$

Total Noise $N = N_{th} + N_w + N_s + N_t$ (2.22)

The signal gets attenuated inside the water because of this ambient noise producing very high BER [48]. These ambient noise and multipath in the underwater channel can be overcome by using equalization techniques explained in Section 2.4.

Different types of ambient noise deep inside the water and the effect of them arises at particular frequency ranges. At f < 10 Hz, earthquakes, turbulence in the ocean and atmosphere, distant storms, and underwater volcanic eruptions occurs. Effect of distant shipping occurs at 10 < f < 100 Hz. At 100 Hz < f <100 kHz ranges the wind speed is considered and at f > 100 kHz, thermal noise is the main problem. The density of ambient noise power spectrum and frequency are inversely proportional to each other. They may change with respect to the depth of the water, ocean location and time. Biological noise caused by marine animals, ice cracking etc., cause external interference that occurs at a frequency range of 100 Hz<f<200 kHz. These noise properties are influenced by the area of the ocean and might be irregular [49]. Before applying the equalization techniques to overcome ISI, the theoretical and practical values are evaluated and SNR to BER graph is as shown in fig 2.4 (a), (b) and (c).

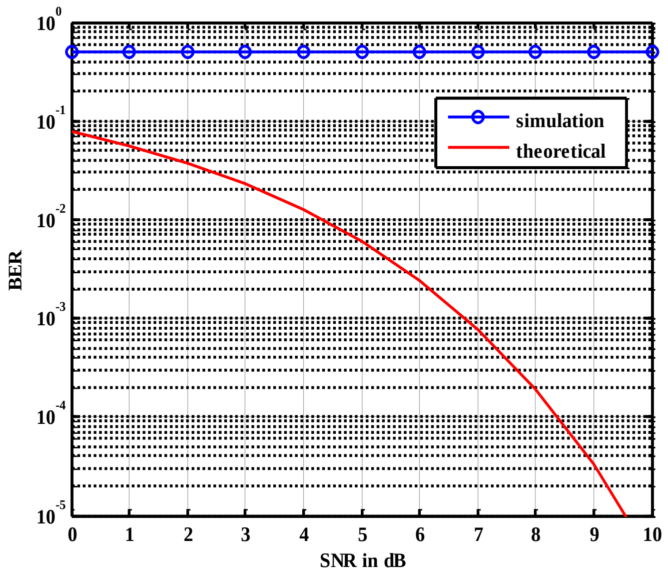


Fig 2.4 (a) SNR vs. BER for BPSK modulation (without applying equalization techniques)

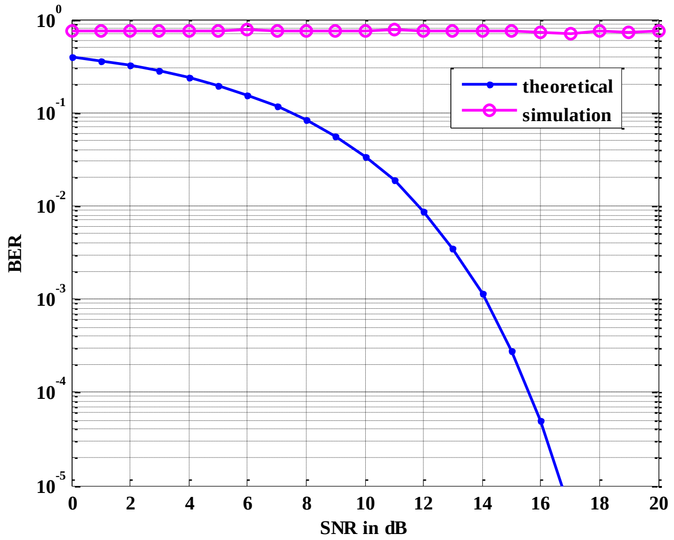


Fig 2.4 (b) SNR vs. BER for QPSK modulation (without applying equalization techniques)

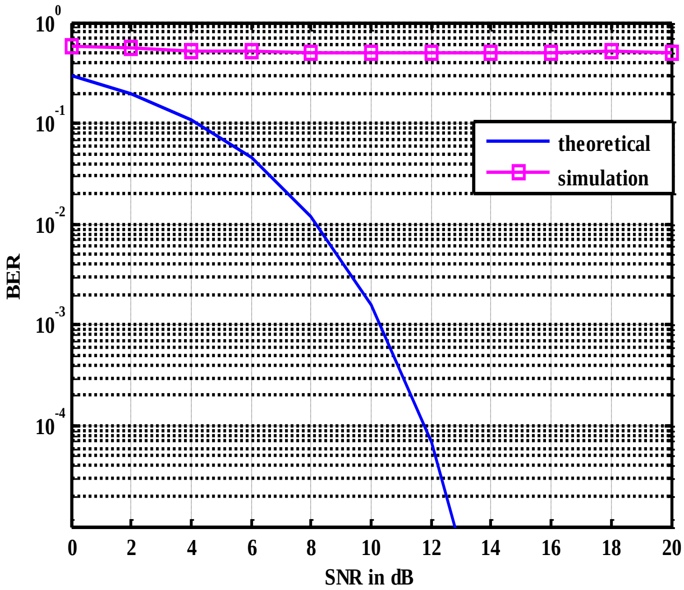


Fig 2.4 (c) SNR vs. BER for 4-QAM modulation (without applying equalization techniques)

In the above-shown graphs, we individually consider various modulation schemes namely BPSK, QPSK, and 4-QAM. However, the practical and theoretical values never match with each other because of the transmission channel noise, interference, distortion, attenuation, wireless multipath fading, etc. Also practically digitally modulated signals require higher BW to transmit the data which is the toughest part in UWAC. Section 2.4 gives a detailed description of the equalizers used at the receiver that reduces the above shown effects, improving the performance of the UWAC system.

2.4 EQUALIZATION TECHNIQUES

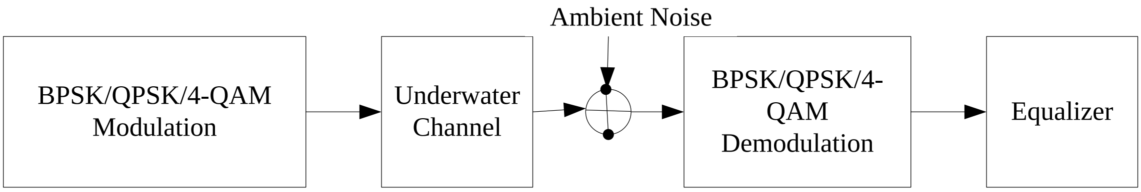


Fig 2.5 Block diagram of Equalization techniques

In any radio channel, if the modulation BW is more than that of a coherence BW, ISI occurs. In a time dispersive channel, equalization compensates the ISI created by multi path. Therefore, this equalizer must be adaptive in this unknown time varying channel. This equalizer simulation is done at the receiver along with the demotion signal as the baseband complex envelope expression can be used to represent baseband waveform. As we are aware that underwater channel introduces severe ISI and ICI in the received signal, the equalizer is proficient of eliminating and compensating the distortions. Equalization is the reversal of distortion incurred by a signal transmitted through a channel. Fig 2.5 explains the equalization model of a UWA transceiver.

Multipath exists in UWAC as the channel is time variant resulting in ISI, the major disadvantage of high speed UWAC. This ISI causes errors at the receiver destructing the transmitted data. Usually in Single input single output (SISO) case, a large amount of transmitting power is directed away from the receiver resulting in severe ruin of the performance. To fight the channel deviations in UWAC effective equalization methods need to be used [50]. In this work linear ZF and MMSE equalizers are used. In ZF equalizer, inverse is applied to the channel frequency response that repairs the transmitted signal at the receiver. The name Zero forcing itself states that ISI becomes zero in a noiseless case. This will be advantageous when ISI is significant compared to noise. While in MMSE, extra noise effects also become less along with ISI. The flow chart Fig 2.6 clearly depicts the flow in which equalization techniques are adjusted for UWAC. In practical UWAC, MMSE algorithm is considered for communication performance and computational complexity [51]. When the channel's frequency response has a minor value, MMSE equalizer does not increase the noise as much as ZF does.

2.4.1. ZF Equalization Technique

ZF Equalizer, proposed by Robert Lucky is a linear equalization technique which inverts the channel frequency response [52]. A ZF equalizer is framed to reduce the least square estimate of the transmitted signal vector. Since it is the pseudo-inverse of the channel matrix it is purely a function of the channel state or the channel matrix [53].

The zero forcing equalizer $Z(f)$ is given by

$$Z(f) = \frac{1}{C(f)} \tag{2.23}$$

Where *C(f)*, the underwater channel's frequency response fulfils the condition

$$C(f)Z(f) = 1 \tag{2.24}$$

The received data in general is given by

$$Y = HX + N \tag{2.25}$$

Here *H* is the underwater channel, *X* and *Y* are the transmitted and received signals and *N* is the ambient noise explained in Section 2.3. Once the ZF equalizer is applied, we have the estimate of *X* as

$$\hat{X} = H^{-1}(HX + N) \tag{2.26}$$

$$\hat{X} = H^{-1}HX + H^{-1}N \tag{2.27}$$

$$\hat{X} = IX + H^{-1}N \tag{2.28}$$

The ZF Equalizer eliminates the ISI on a condition of channel being noiseless. However, when the channel is noisy, amplification of the noise is done greatly at frequencies *f* where the channel response has a small magnitude while inverting the channel. Considering this, ZF equalizer neglects the effect of noise completely and is not regularly for wireless links. However, it performs well for channels with high SNR. The ZF equalizer overlooks the additive noise and solves the problem. One of the drawbacks regarding this equalizer is ignoring the effect of additive ambient noise, which may lead to overall performance degradation due to noise enhancement. We observe that as we estimate the transmitted data by applying the inverse matrix, we get the data at the cost of increased noise. To reduce this, we choose MMSE Equalizer explained in Section 2.4.2.

2.4.2 MMSE Equalization Technique

A Minimum Mean Square Error (MMSE) estimator is a measure of estimator quality that minimizes the mean square error (MSE). The main characteristic of MMSE equalizer is that it minimizes the total noise power and ISI components in the output but does not usually eliminate ISI completely. The equalizer output is

$$y = WHx + Wn \tag{2.29}$$

The MMSE equalizer weight is

$$W_{MMSE} = \underset{w \in C^{N\times M}}{\operatorname{argmin}} E\,[\|x - w(Hx + n)\|]2 \tag{2.30}$$

And the estimated transmitted data becomes

$$\hat{x} = \left(H^H H + \frac{1}{SNR} I_N\right)^{-1} H^H y \tag{2.31}$$

Where E [·] is the expected value operator. There are similarities between the expressions for computing the MMSE and the ZF equalizers. In the high SNR regime, W_{MMSE} is close to W_{ZF}. Moreover, for the low SNR regime, the regularization by SNR copes with noise enhancement holding up the equalizer from introducing large gains when the channel has a signal spectral null in its frequency response [54]. MMSE depends on both prior knowledge as well as data. If prior knowledge is weak compared to data then it will ignore prior knowledge, otherwise the estimator will be biased towards the prior mean. But generally, prior information always improves the estimation accuracy. MMSE estimated symbols are then equalized to remove the noises and to compensate ISI. MMSE estimation is used, as it is suitable for practical deployment in underwater [55].

2.5 SIMULATION RESULTS

Once these basic modulation schemes and equalization techniques are applied to the data that is being transmitted to the underwater channel, the BER to SNR of both the theoretical and practical data that is collected and calculated at the receiver. In the theoretical part it's more about the signal that is transmitted with a defined value of signal to noise ratio (E_b/N_o). While in the practical data considered and received, the signal with modulation schemes applied to it is passed through the underwater channel. In this underwater channel all the low frequency components, path loss model, ambient noise models are considered. The spreading loss and absorption loss inside the water caused due to the time varying multipath propagation are also taken into account.

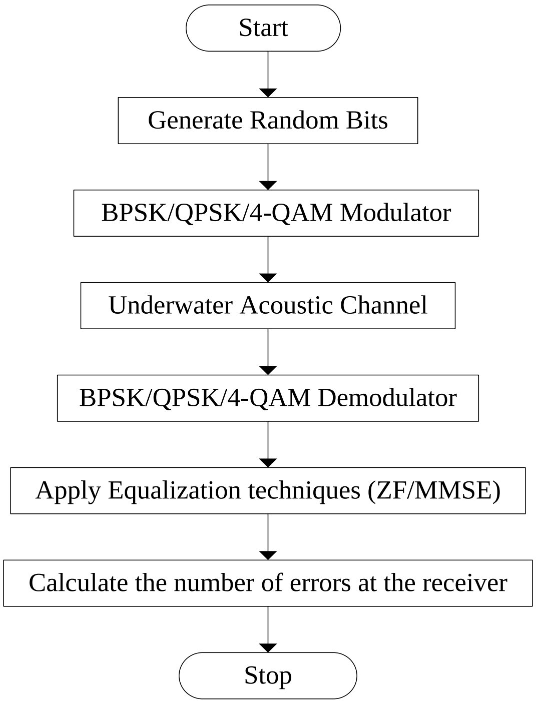


Fig 2.6 Flowchart for Equalization Technique

Fig 2.6 shows the flowchart of the equalization technique applied for UWAC.

2.5.1. After applying equalization techniques

(a) FOR BPSK MODULATION

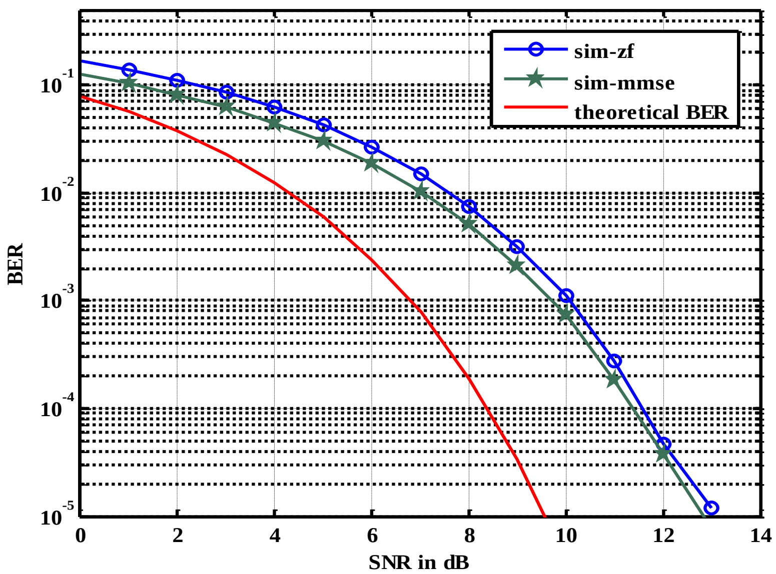


Fig 2.7 (a) SNR vs. BER for BPSK modulation (after applying equalization techniques)

As observed in fig 2.7 (a), when both ZF and MMSE equalization schemes are applied to BPSK modulated data in underwater channel, we observe that theoretical performance is better than the practical equalized data. This is because of the disadvantages of the BPSK modulation where one bit is supported by one single analog carrier making the data rate in bits per second and the symbol rate equal. It is almost half when compared to QPSK modulation technique and many times less compared to other higher modulation techniques such as 16QAM, 64QAM etc. For this reason it is not bandwidth efficient, which is one of the major drawbacks of UWAC. The noise is amplified at low SNR in ZF Equalizer, while in MMSE it decreases the noise. However, at high SNR both ZF and MMSE equalizers perform in the same way.

(b) FOR 4-QAM MODULATION

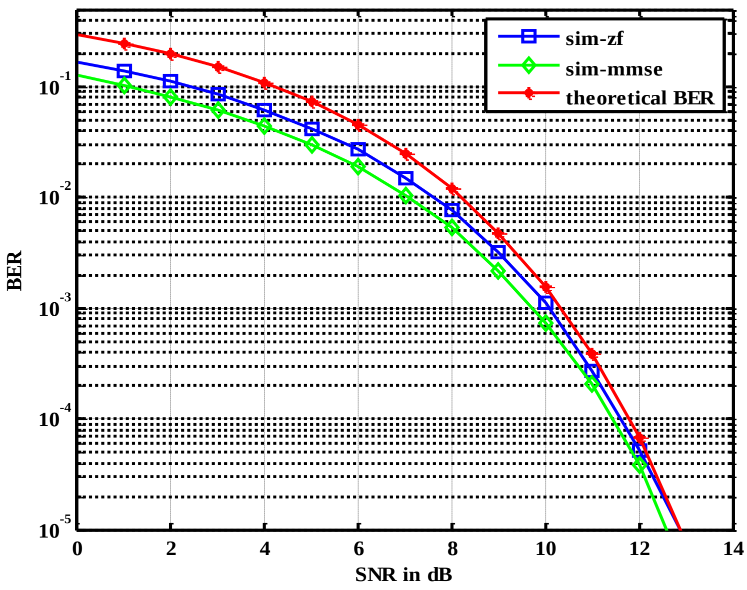


Fig 2.7 (b) SNR vs. BER for 4-QAM modulation (after applying equalization techniques)

We observed from the figure 2.7 (b) though the practical data outperforms the theoretical calculation yet they have no much variation. 4-QAM is bandwidth efficient when compared to BPSK. However states in this modulation are much closer which makes it more inclined to noise reducing the performance in UWAC. Also complex receivers are needed in UWAC in case of 4-QAM modulation. QAM permits higher data rates than normal phase modulated and amplitude modulated patterns in digital transmission applications.

(c) FOR QPSK MODULATION

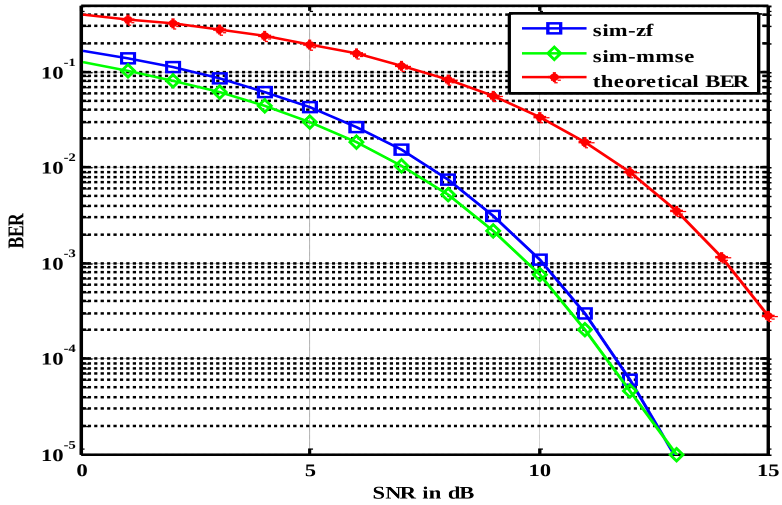


Fig 2.7 (c) SNR vs. BER for QPSK modulation (after applying equalization techniques)

We observed that the quality of signal transmission processing increases from BPSK to QPSK. This is mainly because of its advantages such as immunity to the ambient noise in UWAC, bandwidth efficiency which is almost twice when compared to BPSK. Generally with QPSK, underwater system performs more robust when compared to BPSK [56].

2.6 SUMMARY

In this chapter, various modulation techniques namely BPSK, QPSK and 4-QAM that are applied for a SISO UWAC are studied. The performance in UWAC is mostly impacted by the scattering effects and the multipath with ambient noise. They create ISI and degrade the system performance. To weaken these effects ZF and MMSE equalization techniques are used. Though ZF comes at the cost of increased noise, MMSE moderates all the noise levels. MMSE is a better choice than ZF in terms of BER characteristics and under ambient noise performance.

All the 3 different modulation techniques are individually verified in underwater environment with and without equalization techniques. The reasons behind their performance degradation/enhancement are clearly explained.

B.Pranitha, L.Anjaneyulu, "Analysis of Underwater Acoustic Communication System Using Equalization Technique for ISI Reduction", International Conference on Computational Intelligence and Data Science (ICCIDS 2019), Procedia Computer Science.pp:1128-1138

CHAPTER 3

MULTICARRIER AND CODING TECHNIQUES IN UWAC

This chapter deals with a multicarrier technique by name Orthogonal Frequency Division Multiplexing (OFDM) technique and its application in UWAC. The advantages of OFDM have been used in UWAC to overcome major drawbacks in communicating inside the water. OFDM along with Spatial Diversity techniques and Maximal Ratio Combining (MRC) at the receiver further improve the performance of the system by reducing the havoc in UWAC caused due to multipath effect. Forward Error Correction (FEC) codes also reduce the errors there by increasing the performance of the system. A comparison of OFDM with an extended version of it which is termed as Filter Bank Multicarrier (FBMC) technique is also done.

3.1 INTRODUCTION

UWAC has the disadvantage of excess delay spread which can be defeated using Multi-carrier modulation (MCM) techniques. This has become widespread in UWSNs for two reasons:

(i) The signal is processed with very slight increase of noise/interference in a receiver that is initiated by linear equalization of a single carrier signal.

(ii) Higher immunity to impulse noise is produced by long symbol duration.

In the recent years, MCM in the form of OFDM has become very famous because of its advantages [34]. Signals are transmitted on multiple orthogonal sub-carriers simultaneously thereby performing strongly in tough multi-path environments and achieving realistic spectral efficiency and supportive high data rate transmission [57]. This is a digital multicarrier modulation scheme which uses multiple subcarriers extending the concept of single subcarrier modulation each of them being orthogonal to each other [58]. In this technique, a number of modulated carriers are closely spaced within the same channel. Because of its various advantages such as Immunity to selective fading, Spectrum efficiency, Resilient to ISI and narrow-band effects, Simpler channel equalisation, OFDM finds its applicability in many areas of wireless communications [59] thus leading to its usage in UWAC. OFDM is specifically effective when noise is developed on a vast portion of the bandwidth available. It transmits signals over multiple orthogonal sub-carriers at the same time performing strongly in severe multipath environments and also attaining high spectral efficiency. This is used in UWAC as a substitute to single carrier broadband modulation mainly to achieve high data rate transmission. This is an active technique to overcome the multipath delay spread without any need of complex time-domain equalizers.

Generally guard bands need to be used in any communication system for the signals to be spaced properly, also to reduce overlapping of the signals as shown in Fig 3.1. But because of the orthogonality among the symbols as shown in Fig 3.2, the receiver receives them without any interference. Most common problem in UWAC is the time varying multipath propagation. This is caused by the point that several copies of the transmitted signal reaches the receiver after traveling via different paths, with various attenuations and delays leading to severe ISI. In such cases there is a necessity to use more refined modulation techniques, such as OFDM, to attain a satisfactory communication.

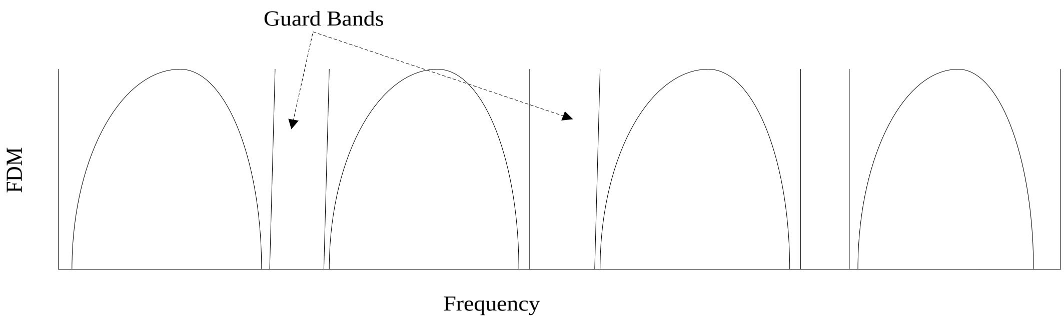


Fig 3.1 Frequency Division Multiplexing

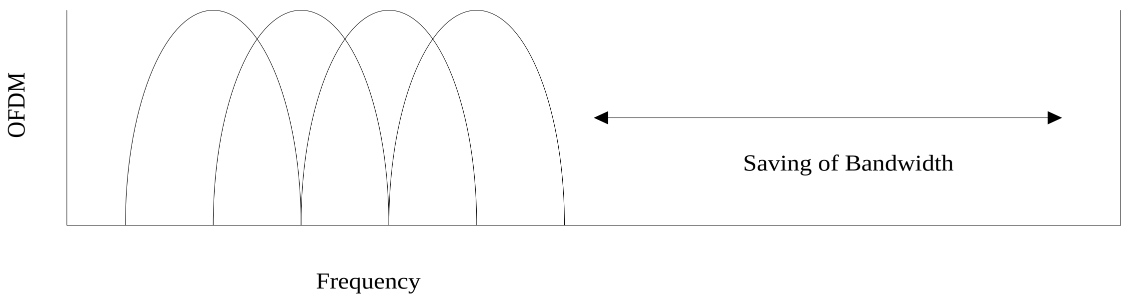


Fig 3.2 Orthogonal Frequency Division Multiplexing

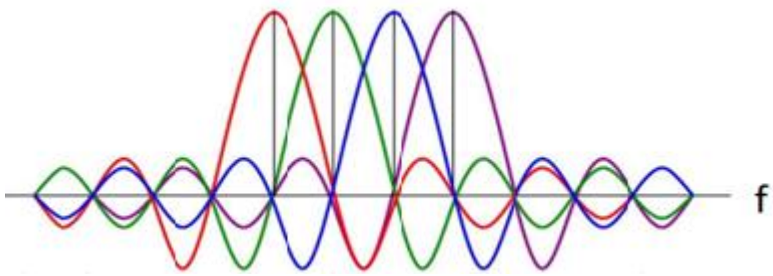
OFDM schemes are simple to instrument than a delay equalizer for multipath channels. Here if the channel's coherence time is short with respect to the equalizer adaptation time, then the delay spread is long when compared to original symbol rate [60]. As discussed in Chapter 1, main issue of UWAC is the interference of signals caused due to multipath and so OFDM finds its suitability here. The advantages of OFDM comprise robustness against multipath fading and high spectral efficiency [61]. OFDM signals that are designed for underwater channels with large Doppler spread are used [62]. In OFDM, the carrier spacing is generally equal to the reciprocal of the symbol period. In OFDM, the subcarrier frequencies are chosen in such a way that they are orthogonal to each other. This removes the cross-talk among the sub-channels, without the necessity of inter-carrier guard bands. Thus the design of both transmitter and receiver becomes simple. Also no separate filter for each sub-channel is required.

The sub carrier spacing should be maintained for orthogonality between them which is $\Delta f = \frac{k}{T_u}$ Hertz, where T_U seconds is the useful duration of the symbol and k is a positive integer, classically equal to 1. This specifies that each carrier frequency undertakes k more complete cycles per symbol period than the preceding carrier. Therefore, the total pass band bandwidth with N subcarriers will be $B \approx N\Delta f$ (Hz).

The main advantages of OFDM are

1. Orthogonality of subcarrier signals which in turn has the following advantages
   a) Transmit signal can be easily generated by an inverse fast Fourier transform (IFFT) block
   b) The transmitted data symbols can be effortlessly separated at the receiver through a fast block
   c) Equalization can be made simple through a scalar gain per subcarrier
   d) Easily adopted to Multiple Input Multiple Output (MIMO) channels
2. The orthogonal subcarriers are closely spaced partitioning the available bandwidth into a maximum of narrow sub bands.
3. Modulation schemes become adaptive for the subcarrier bands to maximize bandwidth efficiency and the rate of transmission.
4. The structure of OFDM symbols simplifies the synchronizations of carrier and symbol.

The orthogonality as shown in picture 3.1 allows high spectral efficiency, with a total symbol rate near the Nyquist rate for the equivalent baseband signal making the whole frequency band available to be used.



Picture 3.1 Orthogonality in OFDM

Irrespective of the channel that is used, basic block diagram or the step wise procedure of OFDM almost remains the same. The simple principle of OFDM is to divide a high rate data stream into a number of lower rate streams that can be transmitted simultaneously over a number of subcarriers. The guard time used in OFDM reduces interference and therefore used for high speed UWAC [63]. Block diagram of OFDM is as shown in Fig 3.3.

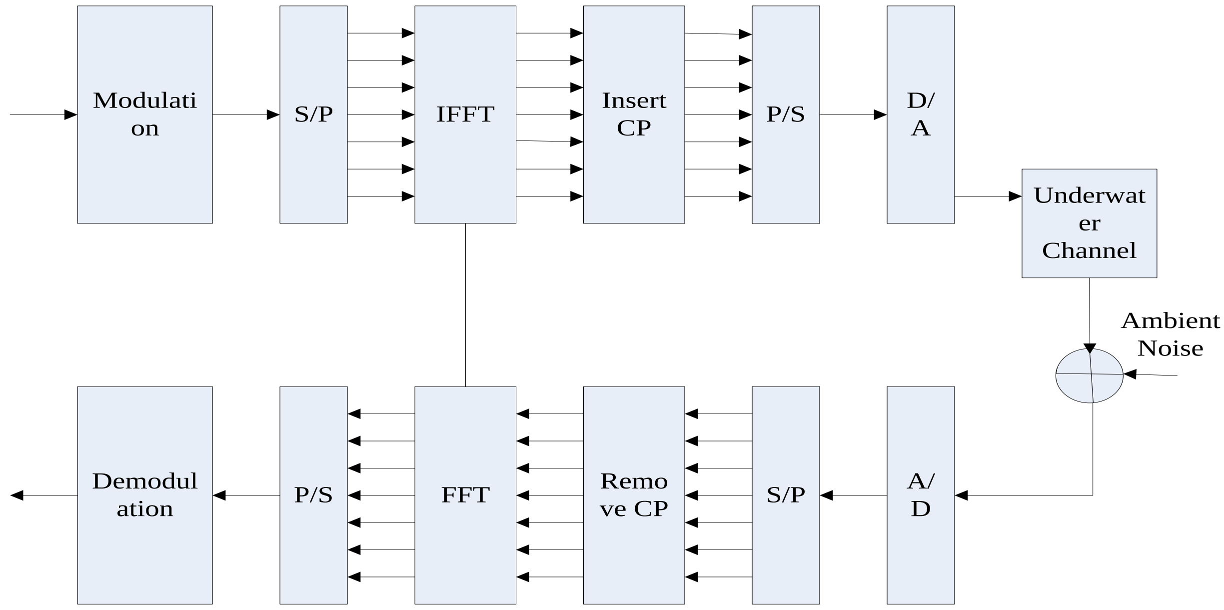


Fig 3.3 Block diagram of OFDM

From Fig 3.3, it is observed that as the input data is modulated it is converted into parallel stream. The whole intention of maintaining parallel data throughout the stream is to avoid interference among them. This technique also helps to collect the data at the receiver without any drawback. Before applying the IFFT each discrete samples represents individual subcarrier in the frequency domain. Then IFFT is applied to convert this signal to the time domain, permitting it to be transmitted. OFDM is computationally effective by using IFFT and FFT techniques to instrument the modulation and demodulation functions separately [20]. Then the data is sent to cyclic prefix. The two main advantages of this particular block are that it provides a guard interval to eliminate ISI, It performs circular convolution because it repeats the last symbol, which makes channel estimation and equalization quite simple. The cyclic prefix (CP) is nothing but the copy of the last portion of the data symbol affixed to the front of the symbol during the guard interval. It provides robustness and reduces ISI in the OFDM system. However, the CP duration adds an extra overhead to the network reducing the spectral efficiency [64]. The entire analog signal is converted to digital samples to pass through underwater channel. At the receiver all the techniques are repeated in an inverse way. In an OFDM system, synchronization at the receiver is one important step that must be performed [65].

At the modulation level, diversity techniques have great advantages. Therefore the performance of OFDM can be significantly better via diversity combining through multiple receivers or linear precoding through the OFDM subcarriers [66]. Here we use OFDM along with spatial diversity technique and Maximum Ratio Combining (MRC) technique at the receiver. This helps the digital communication systems, mostly for underwater use, to achieve high accuracy and reliability in the existence of noise and interference.

Dominant error correcting coding techniques are regularly employed to reduce the BER in the puzzling underwater acoustic channel environments. This technique is the most active and cost-effective [67]. Here, FEC is a kind of error correction which increases simple error detection schemes by allowing the receiver to correct errors immediately after detecting them. Retransmissions and energy consumption are mainly reduced here. Performances of Hamming and Low Density Parity Check (LDPC) codes with UWAC channels are studied by amending the encoding and decoding parameters according to UWAC channels.

3.2 OFDM in UWAC

Recently, MCM in the form of OFDM has been shown practical for UWAC via current algorithms to handle the time variations in the channel. It is used in eliminating the necessity of difficult time domain equalizers that makes it appropriate for real time communications in the acoustic medium. FFT is used in achieving Modulation and Demodulation in OFDM. New algorithms are needed for wideband Doppler compensation as OFDM is sensible to Doppler shift. Hence, after this algorithm, OFDM can accomplish very vigorously and make the transmission of the data as dependable as it is in the wireless networks in the underwater channel. We worked on the combination of FEC algorithms with completely developed OFDM techniques. OFDM is a favourable communication scheme in UWAC because of its resilience against frequency selective channels with long delay spreads. Many current techniques used at RF communications do not work in the complicated UWA channel. However, OFDM has recognized to be best suited in underwater environment because of its advantage such as low complexity design of receivers which deals with particularly dispersive channels [68]. OFDM has recently started working on high bandwidth efficiency over UWA channels [69]. Some sub-carriers are subjected to a deep fading in OFDM UWA communications. Numerical simulations shows that OFDM technique is robust at the frequency selectivity and time selectivity in UWAC [70].

The continuous-time baseband signal exemplary for a particular symbol of the OFDM is [71]

$$s(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j2\pi k f \Delta t} \quad t \in [0, T] \tag{3.1}$$

Here N is the number of subcarriers, X is a vector

$$X = [X_0, X_1 \dots \dots, X_{N-1}]^T \tag{3.2}$$

That denotes the data symbols, T is the duration of the OFDM symbol and

$$f_\Delta = \frac{1}{T} \tag{3.3}$$

is the subcarrier frequency spacing. In this text, a data symbol is renowned from an OFDM symbol clearly unless it is flawless from the context. Note that the pulses used in OFDM, according to (3.1) are

$$h_n(t) = rect\left(\frac{t - T/2}{T}\right) e^{j2\pi \frac{n}{T} t} \quad n = 0,1,2, \dots, N-1 \tag{3.4}$$

Where $rect(t) = \begin{cases} 1 & |t| \leq 1/2 \\ 0 & elsewhere \end{cases}$ (3.5)

The critically-sampled discrete-time signal model is given as

$$s[k] = s(kT_s) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n e^{j2\pi \frac{n}{T} k T_s} \quad k = 0,1, \dots, N-1 \tag{3.6}$$

where the frequency of sampling is $\frac{1}{T_s} = N f_\Delta$ (3.7)

Therefore $s[k]$ can be written as

$$s[k] = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n e^{j\frac{2\pi}{N} nk} \quad k = 0,1, \dots, N-1 \tag{3.8}$$

Simulation parameters that are considered in this work are

Table 3.1 Simulation Parameters

Parameter	Value
Bandwidth	312 Hz
Carrier Frequency	12 KHz
Sampling Frequency	80 KHz
Cyclic Prefix duration	204.8 ms
Symbol duration	819.2 ms
Total Symbol duration	1.024 s

Subcarriers	256
Modulation	QPSK
Carrier Spacing	1.22 Hz

As per the given values in Table 3.1, QPSK mapping is used in our simulation process with 256 subcarriers. By considering the noise and signal power SNR is estimated which is used as a criterion to eliminate packets that are doubted of noise alone. Significant settings for the OFDM modulation scheme are a carrier frequency of 12 kHz, sampling frequency of 80 KHz and a bandwidth of 312 Hz. Narrower carrier spacing of 1.22 Hz reduces the robustness.

3.3 UNDERWATER ACOUSTIC CHANNEL

UWA channels are different from RF channels in many characteristics such as limited bandwidth because of the frequency dependent propagation loss, the lengthy multi-path delays, and the quick signal fluctuations in random ocean media. Inappropriately, no expression for the information has been derived for a general time-varying channel excluding some simple channel models [72]. The ambient noise characteristics need to be taken into consideration while designing UWAC systems if strong and near best performance is looked-for. The underwater channel through with acoustic wave has a high transmission loss, non-uniform sound velocity, multipath propagation, varying Doppler Effect, higher BER and the omnipresent ambient noise contaminate the signal [55]. UWAC channels is mainly characterized by path loss and signal frequency. Path loss depends on both the distance between the transmitter and receiver and the signal frequency. The latter fixes the absorption loss that occurs mainly due to the allocation of acoustic energy into heat. This point infers to the necessity of acoustic bandwidth on the communication distance [73]. Attenuation or path loss that occurs in an underwater acoustic channel over a distance *l* for a signal of frequency *f* is given by

$$A(l,f) = A_0 l^k a(f)^l \tag{3.9}$$

Where A_0 a unit-normalizing is constant, k is the spreading factor, and $a(f)$ is the absorption coefficient. The acoustic path loss in dB is given by

$$10 \frac{log A(l,f)}{A_0} = k.10\, log\, l + l.10\, log\, a(f) \tag{3.10}$$

The first and the second term in the above equation signifies the spreading loss and the absorption loss respectively. *k*=2 for spherical spreading, *k* =1 for cylindrical spreading, and *k* =1.5 for practical spreading.

Using the Thorps formula, the absorption coefficient can be expressed empirically where *a(f)* is given in dB/km for *f* in kHz as

$$10\, log a(f) = 0.11 \frac{f^2}{1+f^2} + 44 \frac{f^2}{4100+f^2} + 2.75.10^{-4} f^2 + 0.003 \quad (3.11)$$

This formula is valid for higher order frequencies. And for lower frequencies, the following relation may be used

$$10\, log a(f) = 0.002 + 0.11 \frac{f^2}{1+f^2} + 0.011 f^2 \quad (3.12)$$

A graph is drawn between the absorption coefficient and frequency as shown in fig 3.4

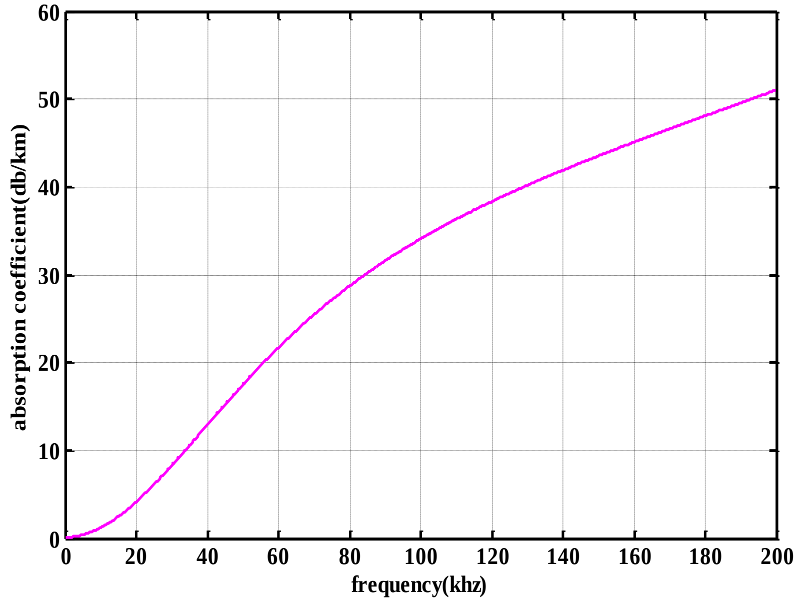


Fig 3.4 Frequency vs. Absorption coefficient in dB/Km

The absorption coefficient is shown in Fig.3.4. It increases swiftly with frequency thereby striking a limit on the maximal usable frequency for an acoustic link over a given distance. Turbulence, shipping, waves, and thermal noise are the four sources that can be used to model the ambient noise in the ocean. While Gaussian statistics and a continuous power spectral density (p.s.d.) are used to describe them. The p.s.d. of the four noise modules in dB re μ Pa per Hz is given by the empirical formulae as a function of frequency in kHz.

$$10\ logN_t(f) = 17 - 30\ log\ f \tag{3.13}$$

$$10\ logN_s(f) = 40 + 20(s - 0.5) + 26\ logf - 60\ log(f + 0.03) \tag{3.14}$$

$$10\ logN_w(f) = 50 + 7.5w^{1/2} + 20\ logf - 40\ log(f + 0.4) \tag{3.15}$$

$$10\ logN_{th}(f) = -15 + 20\ logf \tag{3.16}$$

Turbulence noise has its influence exclusively in the very low frequency region, f<10 Hz. Noise instigated by shipping is very high in the frequency region of 10 Hz -100 Hz. This noise is demonstrated with a shipping activity factor s, whose value generally varies between 0 and 1 for low and high activity, correspondingly. Wind driven waves causes surface motion (w is the speed of wind in m/s) contributes to the noise in the frequency region 100 Hz - 100 kHz (which is predominantly used by the most of the acoustic systems). In conclusion, thermal noise becomes influential for f>100 kHz.

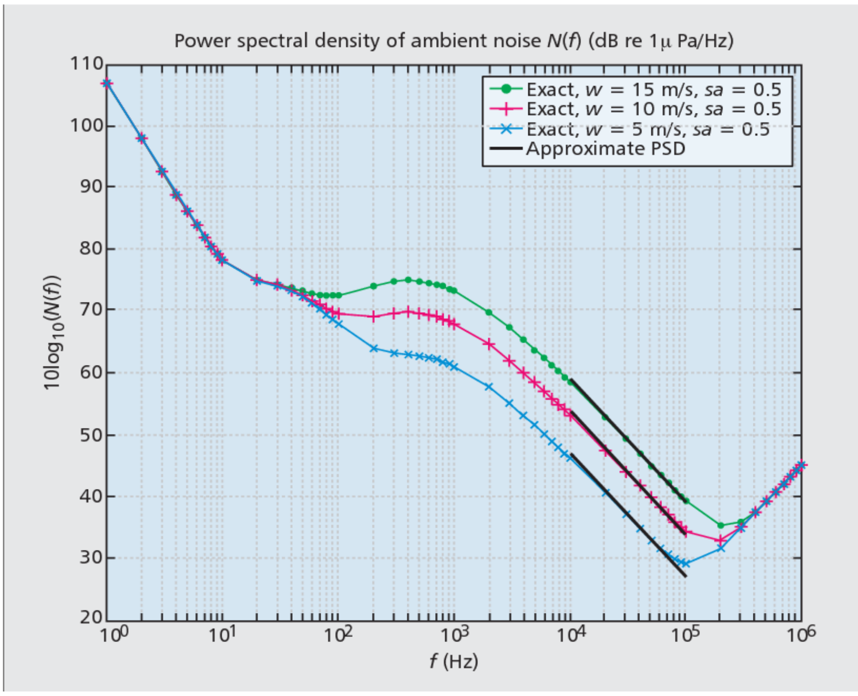
The total p.s.d. of the ambient noise is illustrated in Picture 3.2.

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \tag{3.17}$$

A solid line is represented for the cases of no wind and a dotted line where wind is at a moderate speed of 10 m/s. There is also a case with changing degrees of shipping activity in every case. Useful acoustic BW is limited from below because of the decaying noise with frequency. It is also observed that in a definite range of frequency the noise p.s.d. declines linearly on the logarithmic scale. The following estimate is used then

$$10\ logN(f) \approx N_1 - \eta\ log\ f \tag{3.18}$$

This calculation is shown in the figure (dash-dot) with N_1 =50 dB re µ Pa and η=18 dB/decade.



Picture 3.2 Power spectral density of the ambient noise, *N(f)* [dB re µ Pa].

3.4 DIVERSITY AND COMBINING TECHNIQUE

In many of the scattering environments, antenna diversity is a real, current and widely used technique that reduces the influence of multipath fading. The standard method is to use multiple antennas at the receiver and achieve combining or selection and switching which improves the quality of the received signal. By using the spatial diversity that reduces ISI, the performance of the underwater channel equalizers can be improved as the spatial diversity gain and equalization gain are combined together [74]**.** Underwater channel being very tough, it is very hard to attain high SNR value at the receiver. Transmit diversity and receive diversity techniques prove to be very supportive in multicarrier UWAC [5]. By using MRC over the data from multiple receivers, utilization of spatial diversity will further increase the robustness of the system [75]. Various types of diversity techniques are illustrated in fig 3.5.

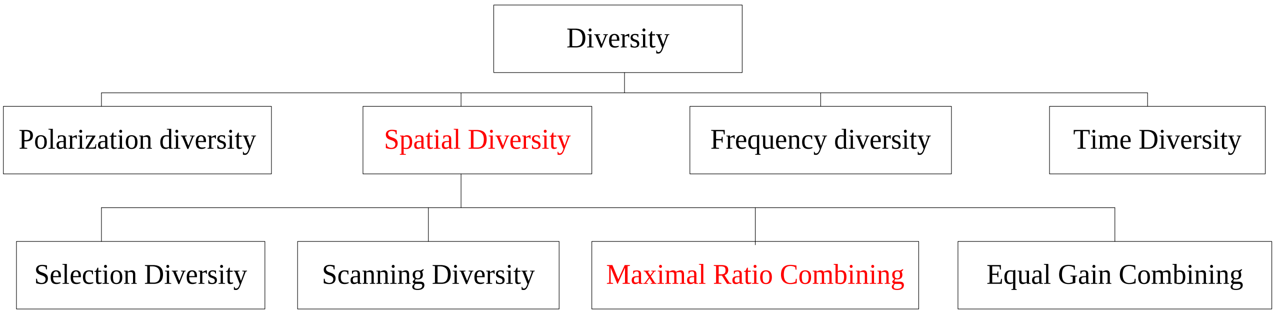


Fig 3.5. Classification of Diversity Techniques

3.4.1 Spatial Diversity Technique:

Diversity compensates the fading channel impairments, and is generally done by using two or more receiving antennas. Spatial Diversity is the most commonly used diversity technique in which multiple antennas are well spaced and related to common receiving system. When one antenna sees a null signal the other antenna sees a peak signal, therefore the receiver will be able to select the antenna with the best signal at any time. Due to the quest for bandwidth efficiency in acoustic systems, the use of space time methods for utilisation of spatial diversity has become a topic of importance for the researchers in the recent years [76]. This technique can be used both in the time domain or in the frequency domain and also at the transmitter or at the receiver. The main use of diversity technique is to overcome the effect of multipath fading in UWC. The useful way to improve the error performance in UWAC is to use spatial diversity. Space-time-coding will make nonstandard conformable modifications mandatory and so it is not appropriate for improving the existing systems. Therefore spatial diversity techniques can be used for standardized systems [77]. The frequency selectivity of the transfer function of the channel can be increased by selecting cyclic delays at the transmitter and receiver antennas. By using multiple antennas system diversity gain is increased to combat channel fading. Multiple individually faded copies of the data symbol is obtained at the receiver by sending the signals that transmit the same information through different paths achieving reliable reception [78]. Spatial diversity is attained by insertion of multiple antennas that is equidistantly placed at the transmitter and/or the receiver. Independent paths are created when the channel gains between different antenna pairs fade more or less individually. Local scattering environment and the carrier frequency are the two factors that are considered for required antenna separation. In LOS environment the separation is of 10's of carrier wavelengths, while it is half to one wavelength in the presence of a multi-path channel

[79]. Sensitivity to fading is concentrated by the spatial diversity provided by multiple spatial paths [80].

This diversity technique requires some sort of post processing to recover the desired message. Among them MRC system provides the greatest resistance to fading.

3.4.2 Maximum Ratio Combining:

Now a day, there are many techniques available to combine the signals from multiple diversity branches. Among them one best way is to use MRC where in each signal branch is multiplied by a weight factor that increases/decreases with the signal amplitude. The main advantage of this combining technique is that the branches with strong signal are amplified and the weak signals are attenuated. Mathematically MRC can be expressed as the diversity combining technique where in the signals from each channel are added and the gain of it is made directly proportional to the signals Root Mean Square (RMS) value and inversely proportional to the mean square noise level in that channel. Here each channel uses different proportionality constants. The other name for MRC is ratio-squared combining and pre detection combining. It is also known to be the optimum combiner for independent AWGN channels [81]. By combining signals from multiple diversity branches the detection performance of the receiver can be improved. The main disadvantage with conventional diversity combining techniques is that it is directly applied to the antenna array elements, requiring a large number of elements to achieve a low BER at low SNR. The complexity of such a receiver is very high and is proportional to the number of antenna elements [82]. By combining or selecting many signals that are passing through different propagation paths, diversity receiving technologies can lessen the influence of propagation distortion. MRC and Selective Combining (SLC) are the methods for incorporating received signals in diversity receivers. MRC is greater than SLC in terms of improving the signal-to-noise ratio (SNR) [83]. The general form of MRC is shown in Fig 3.6.

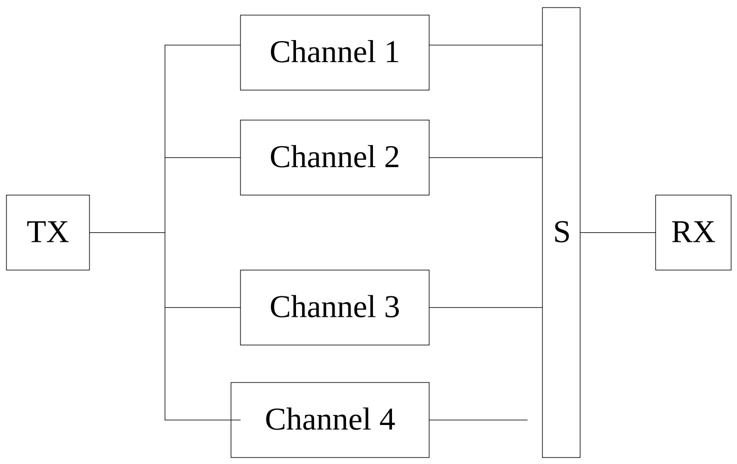


Fig 3.6 Maximum Ratio Combining

The BER performance with MRC diversity is better than without using any diversity technique in UWAC environment. The MRC is the best provider of highest SNR in the combined signal. In common, phases of the complex-valued MRC weights should balance for the phase shifts in the directional signals in which the weight magnitudes and SNR should be proportional to each other [84].

The following are the steps to apply diversity technique for UWAC channel.

Steps followed at the transmitter

Step 1. Generate random data source

Step 2. Apply QPSK Modulation.

Step 3. Convert serial data to parallel data.

Step 4. Apply IFFT technique.

Step 5. Add Cyclic Prefix.

Step 6. Apply Spatial Diversity

Step 7. Convert parallel data to serial data.

Step 8. Pass the information through UWC channel

Steps followed at the receiver

Step 9. Convert Serial to parallel data

Step 10. Remove cyclic prefix

Step 11. Apply FFT

Step 12. Apply MRC

Step 13. Convert parallel data to serial data

Step 14. Demodulate the data.

Step 15. Calculate the number of errors.

Figure 3.7 shows the BER performance with and without diversity

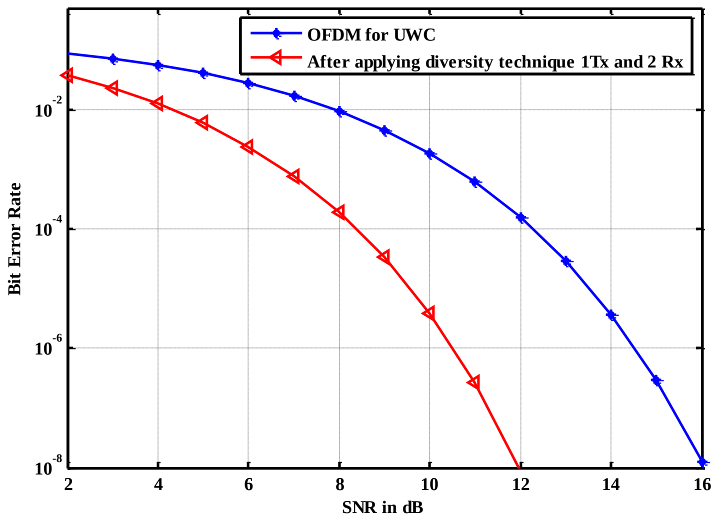


Fig 3.7. BER vs. SNR graph for OFDM and diversity technique.

As we increase the number of receiving antennas at the receiver side the performance increases as shown in Fig 3.8.

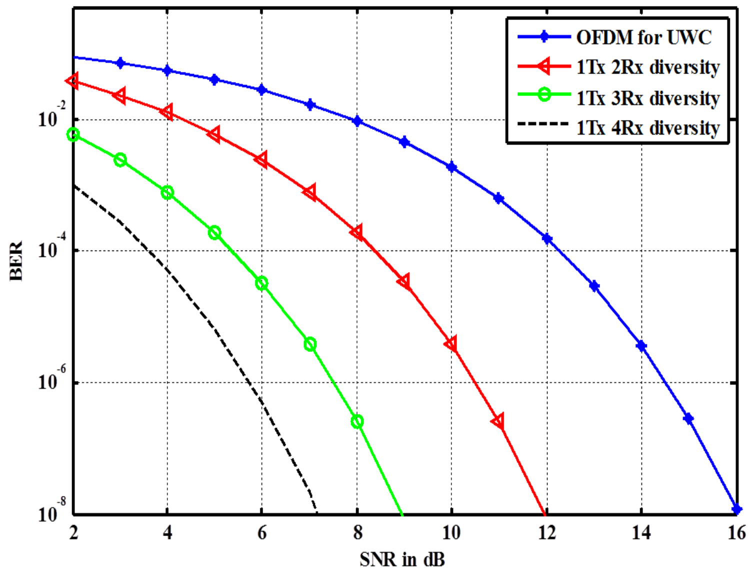


Fig3.8 BER vs. SNR graph for OFDM and diversity technique with increasing number of receiving antennas.

From fig 3.7 and 3.8 it is observed that the BER performance is increased reducing the number of errors when spatial diversity and MRC techniques are applied. Also the increase in the number of receivers makes the communication system more reliable. The performance of the system with this technique is almost reducing the error rate to half of its original value with OFDM.

3.5 FORWARD ERROR CORRECTION

In the received data, the facility of a receiving station to accurate the errors once the transmission is done is Forward Error Correction (FEC). Spectral nulls generally found in frequency selective multipath channels nullify the OFDM carriers located near them which results in loss of the symbols modulated on these carriers. This results in a difficult error rate and a bandwidth loss caused by the necessity to retransmit the symbols that are lost. One better solution for this is the use of FEC technique. The performance of the method that is proposed is quantitatively assessed with the BER of an UWAC OFDM communication system. In addition, for an OFDM with K subcarriers and N users, using FEC coding further improves the performance of the systems due to the resulting frequency diversity and increased reliability of the transmitted data signals. If the BER performance is improved ,then number of receive antennas required can be reduced to design coded massive OFDM systems when compared to un coded systems [85]. This FEC is a digital signal processing technique which increases the data consistency and helps in correcting the errors without any contrary channel to retransmit the data. Extra data bits known as error correction bits need to be added at the transmitter to operate this. In this proposal, Hamming codes and LDPC codes are used for correcting the errors. Their performances have been compared with respect to BER calculation.

There are 2 types of FEC codes:

(i) Block codes

(ii) Convolutional Codes

Block codes are FEC codes that allow a restricted number of errors to be detected and corrected without transmitting the signals again. They can be used to further progress the performance of a communications system mostly when different means of improvement such as increasing transmitter power or using a better modulation scheme are impossible [86].

3.5.1 Hamming Code

In hamming codes, parity bits are further added to blocks of messages bits to build code words or code blocks. Generally in a block encoder, k information bits are encoded into n code bits. For the detection and correction of errors, for k information bits a total of n-k redundant bits are added.

This hamming code is represented as (n, k) code, and the code rate is defined as RC = k/n which is the ratio of information rate and the raw channel rate. For a block containing k bits, then the number of data words is $2e^{k}$. Even if there is one single error while transmitting, i.e., if one data word is converted into another, then it means that an error is found comprising that there is no redundancy. The data word can be encoded into code words that consist of n bits where in the additional n-k bits are derivative of the message bits however not part of the message. The number of possible code word is $2e^{n}$ but only $2e^{k}$ of these will contain data word, and these are transmitted. Therefore, the rest of the code words are redundant, only if they do not add to the message. The n-k bits are denoted as the parity check bits. If errors occurs while transmitting the data, then there is high probability that the allowable code word is converted into one or another of the redundant words and the decoder which is at the receiver is planned to identify the error. There is always the likelihood that sufficient errors occur to convert a transmitted code word into another genuine code word in error.

In this work, k=4 and n=7 are considered by addition of 3 parity bits.

For a (n,k) hamming code,

Message length $n=2^{m-1.}$ (3.19)

Code word length $k=2^{n-m-1}$. (3.20)

Number of parity check bits n-k=m. (3.21)

Minimum distance $d_{min}=3$ (3.22)

Generator matrix : $G=[p;I_k]$ (3.23)

Parity check matrix: $H=[I_{(n-k)};p^T]$ (3.24)

Encoded message : $x=[b;m]$ (3.25)

Where b=mp (3.26)

The matrix $G=(I_k|-A^T)$ is the generator matrix of linear code And $H=(A|I_{n-k})$ is the parity-check matrix.

$HG^T=0$ is the criteria that is to be followed for the structure of generator and parity matrix. To the left hand side H matrix must have nonzero 'n-tuples' and (n-k) identity matrix must be to the right hand side.

Table 3.2 (7, 4) Hamming Code

Bit Position		1	2	3	4	5	6	7
Encoded Data Bits		p1	p2	d1	p4	d2	d3	d4
Parity Bit Coverage	p1	×		×		×		×
	p2		×	×			×	×
	p4				×	×	×	×

In this work a basic (7, 4) hamming code is used.

The visualization of (7, 4) hamming code is tabulated in Table 3.2

G is obtained by the transpose of the LHS of H matrix. Therefore, the code generator matrix G and matrix H are:

$$G=\begin{pmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{pmatrix} \qquad H=\begin{pmatrix} 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 & 1 \end{pmatrix}$$

Finally, non-systematic codes of the matrices can be attained by the following actions

1. Column permutations
2. Elementary row operations

When impractical approach such as increasing the performance and transmitter power of a communication system, is done then block codes are used [86]. Hamming codes include multipath communications, high decoding efficiency and dependability [87]. The performance and energy efficiency of the system can be improved by using Multiple path Forward Error Correction (M-FEC) [88]. Extreme conditions of UWAC, it is impossible to provide low BER without using any of the error correction schemes. The hamming code execution along with OFDM transmitter and receiver is shown in Fig.3.9. The functionality of the hamming code is explained in Fig 3.10.

BER is calculated after the application of hamming code and is found to be of better-quality than the previous case of using OFDM only.

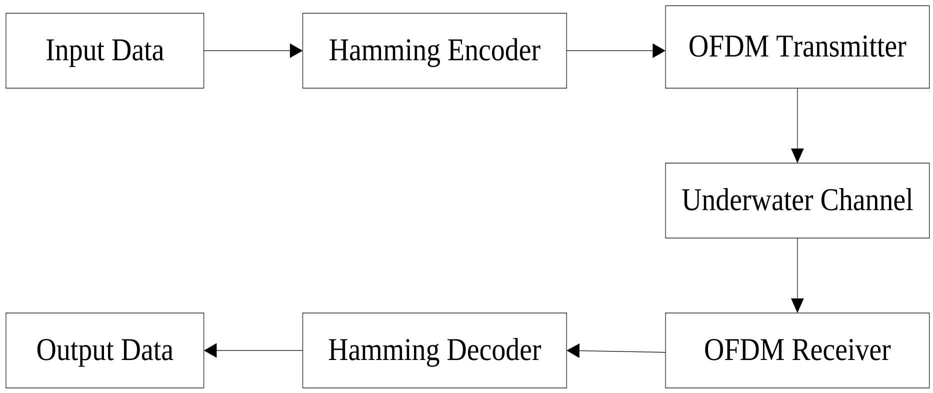


Fig 3.9 Hamming code block diagram

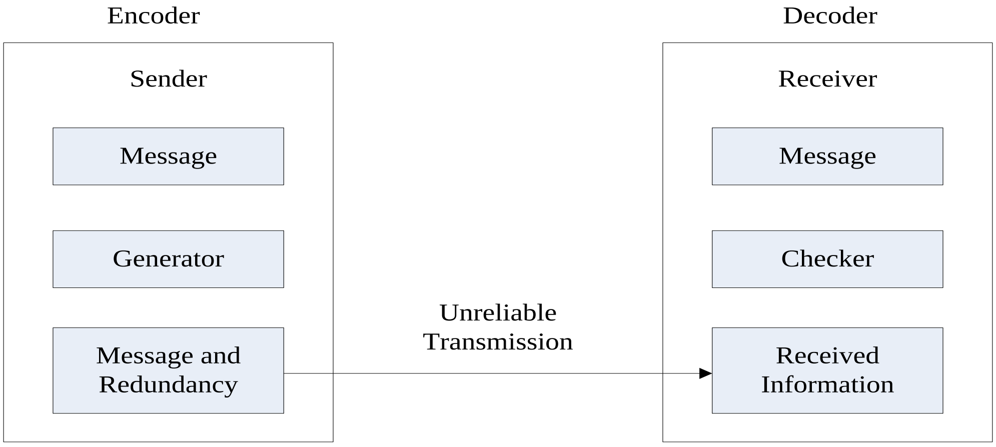


Fig 3.10 Hamming Encoder and Decoder

Fig 3.9 explains how hamming encoder and decoder are applied before and after the OFDM transmitter and receiver for the simulation process. Individual blocks of the encoder and decoder and the process followed at each are clearly explained in Fig 3.10.

3.5.2 Low Density Parity Check (LDPC) Code

LDPC codes are a different type of linear block codes whose parity-check matrix H is very sparse, i.e. this matrix mostly contains zeros. The number of 1s per row of H is known as row weight while that per column is known as column weight. If these row and column weights are constant then it is known as regular LDPC code otherwise irregular LDPC code. LDPC code can also be explained by Tanner graph or distribution polynomials. LDPC codes can be divided into two categories such as random codes, and structured codes considering the method of construction [89]. Due to the excellent performance of LDPC codes in terrestrial radio channel, considerable researches have been done in UWAC system [90]. The main advantage of LDPC codes include reduction of error codes and increasing the transmit performance of underwater digital signal. Experimental results with real data do not have any decoding errors for the rate 1/2 of non-binary LDPC codes whenever the uncoded BER is below 0.1, and it is the same with the simulation results. The un encoded BER can be used as a quick performance meter to measure how likely the decoding will succeed. Research shows that LDPC code system can achieve a better BER on a condition of relative lower SNR [67]. Several efforts have reported applying LDPC codes to the underwater acoustic environment, mostly for OFDM systems [91]. Non binary LDPC performs better when compared to convolutional coding but has the disadvantage of increased decoding time i.e., the complete processing time per OFDM block increases by 30%, but the performance is considerably enhanced [13]. LDPC codes are also a kind of linear block codes just like hamming codes. In this work, a regular (3, 6) LDPC code with a rate of ½ is used [92].

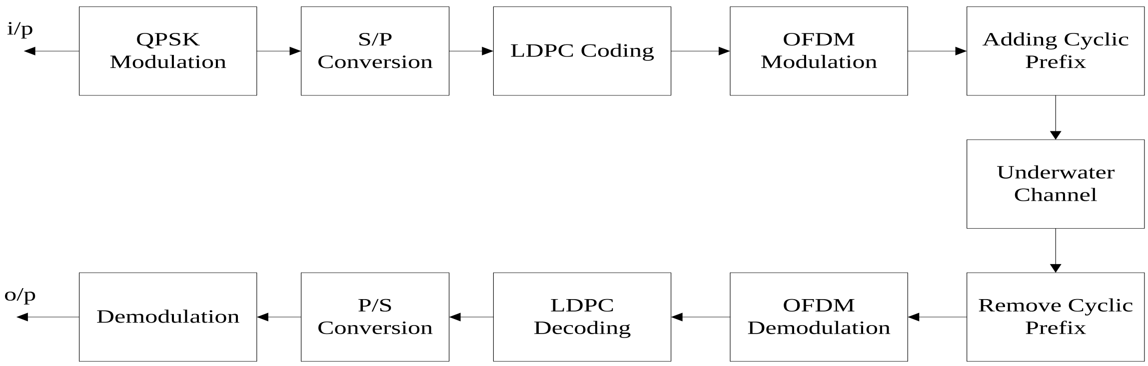


Fig 3.11.OFDM with LDPC coding technique

LDPC codes along with UWAC are as shown in Fig 3.11. The data to be transmitted is LDPC encoded and referred to the OFDM transmitter while the same is decoded at the receiver using LDPC decoder.

In LDPC codes

Generator matrix G: $c=G^T m$

Here $c=[c_1, c_2,\ldots,c_N]^T$-code word

$m=[m_1, m_2,\ldots,m_k]^T$- message word

We define a complete set of parity checks as

$$Hc=0 \tag{3.27}$$

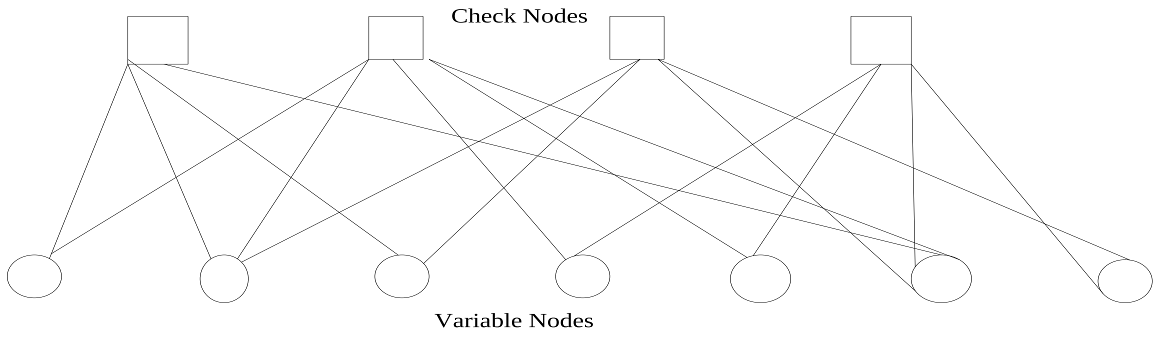


Fig 3.12 LDPC Code

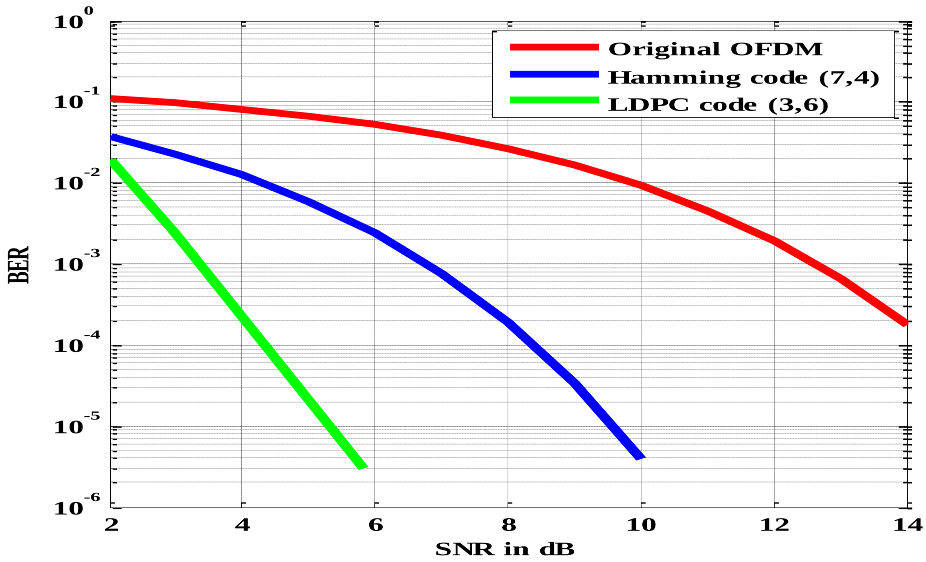


Fig.3.13. SNR vs. BER curves for OFDM and FEC codes in UWCf

Fig 3.13 demonstrations the BER performance of the UWAC system, with and without FEC. It can be observed that the BER performance is improved when block codes are applied to a certain level. LDPC accomplishes better than hamming code for a given SNR. However LDPC works effectively at low SNR values.

3.6 FBMC AND OFDM

OFDM based UWAC system is very complex to the frequency offset because of its wideband nature. This has two major disadvantages where in firstly slight shift result in subcarrier overlapping making the entire signal completely distorted. Secondly the slow speed of sound in water when compared to RF communication which causes oceanic dynamics more leading causing Doppler shifting in the signal in the form of overlapping of the subcarriers. This causes Inter-Carrier Interference (ICI) damaging the orthogonality between the subcarriers. Though OFDM based UWAC has the advantage of increased spectral efficiency, ICI degrades the performance of the system. Therefore UWAC systems based on OFDM regularly need innovative ICI compensation algorithms [11]**.** The main disadvantages of OFDM are

- High PAPR.
- It is more sensitive to carrier frequency offset.
- It requires linear transmitter circuitry, which suffers from reduced power efficiency.
- It suffers efficiency loss caused by cyclic prefix.
- It suffers strong spectral leakage.

Several European projects are launched to overcome the limitations of OFDM and see 5G requirements, such as “mobile and wireless communications enablers for twenty-twenty (2020) information society” (METIS), “flexible air interface for scalable service delivery within wireless communication networks of the 5th generation” (FANTASTIC5G), “enhanced multi-carrier techniques for professional ad-hoc and cell-based communications” (EMPHATIC), and “5th generation non-orthogonal waveforms for asynchronous signalling” (5GNOW). In this project, various modulations are suggested; namely, filter bank multicarrier (FBMC), generalized frequency division multiplexing (GFDM), and universal filtered multi-carrier (UFMC). Of which FBMC seems to be a good technique for 5G systems [96]. In FBMC system, symbols overlap in the time domain while the adjacent subcarriers overlay in the frequency domain. This non-orthogonal modulation does not require Cyclic Prefix (CP) which increases the bandwidth efficiency of FBMC systems [94]. Though having high computational than OFDM, FBMC is experiencing improved interest because of its noteworthy increase in the handling capacity of electronic equipment. To survive with standards constraints and to match time or frequency dispersive channels, the prototype filter of FBMC can be intended with great ease. FBMC can be made as a good candidate for multiple access communications or opportunistic spectrum access by designing subcarriers filters with arbitrarily low secondary lobes. Because of the length of the prototype filter FBMC frames are longer than OFDM frames. However this efficiency loss is compensated by not using CP in FBMC symbols and also by effective frequency localization of FBMC carriers which allow reduced frequency guard band than OFDM. The main advantage of FBMC is the robustness to channel time and frequency spreading because of the well localized waveforms in time and frequency. It also suffers no spectral leakage. The FBMC waveforms use non- rectangular pulse shapes (prototype filters) in which the symbol time duration is expressively larger than OFDM, so that adjacent FBMC symbols overlap in time as shown in Fig 3.14. These prototype filters in FBMC are planned such that interference between overlapping symbols remains low [95].

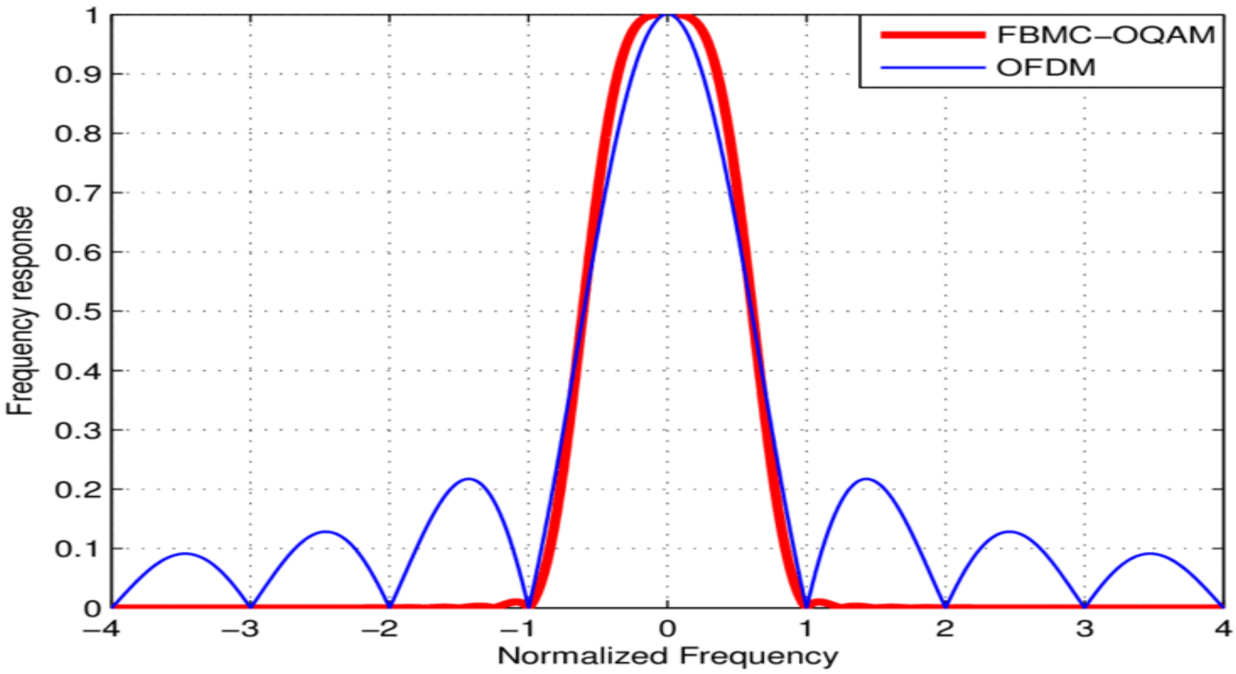


Fig 3.14 OFDM and FBMC Symbol overlapping

FBMC system has to transmit a real symbol every half symbol duration to satisfy the orthogonality requirement. This is known as FBMC/OQAM (offset QAM) system [96]. In FBMC, OQAM is used as the orthogonality of filter is content in real domain. In this technique, real and imaginary parts of QAM symbols are transmitted independently and so FBMC can accomplish high spectral efficiency [97]. Deletion of CP and much smaller side lobe leakage with well-designed prototype filter makes FBMC/OQAM highly spectral efficient than CP-OFDM [98]. Unlike OFDM where orthogonality is mandatory for each and every carriers, FBMC requires only for the neighbouring sub-channels. In OFDM frequency bandwidth is divided into number of carriers, while in FBMC transmission channel related to the given bandwidth is divided into a number of sub-channels. OQAM is used for this purpose where the entire channel bandwidth is divided and the modulation in the sub channels must adjust to the neighbour orthogonality limitation. This grouping of filter banks with OQAM modulation points to maximum bit rate [99]. The main difference is the replacement of the OFDM with a multicarrier system based on filter banks, where the IFFT plus CP_{in} is substituted by the synthesis filter bank (SFB) whereas FFT plus CP_{out} is substituted by the analysis filter bank (AFB). The tabulations for the difference in OFDM and FBMC are shown in Table 3.3 [100].

Table 3.3 Major differences between OFDM and FBMC

Property	OFDM	FBMC

Cyclic Prefix Extension	CP is required sacrificing the Bandwidth	CP is not required conserving the bandwidth
Side lobes	Large and interfering side lobes	Low side lobes
Synchronisation	Multiple access interference (MAI) cancellation to be accomplished at the receiver for correct detection.	MAI is supressed because of Exceptional frequency localisation of the subcarriers
Doppler Effect	Highly delicate to carrier frequency offset	Less delicate
MIMO Systems	High flexibility in adopting MIMO techniques	Low flexibility
Spectrum Sensing	Ruined spectrum sensing performance	High spectrum sensing resolution
Computational Complexity	Low	High

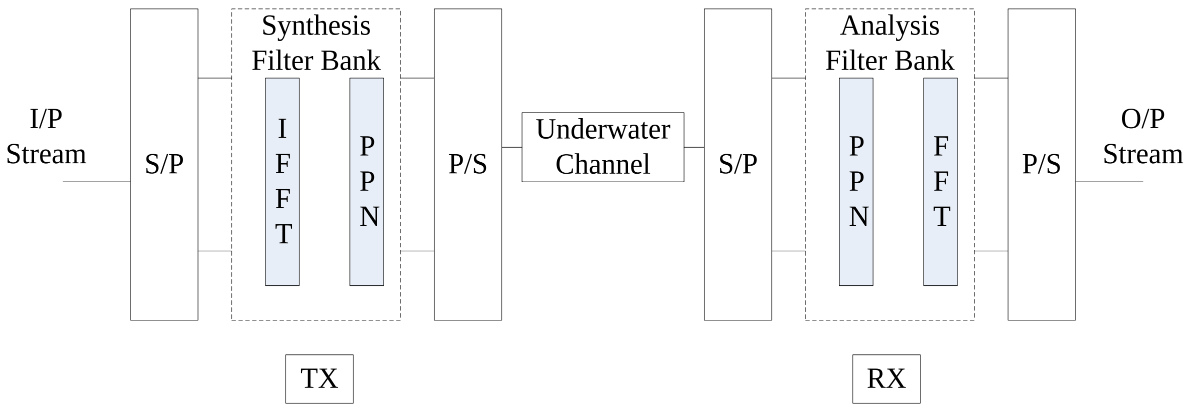


Fig 3.15. Block diagram of FBMC

As depicted in Figure 3.15 the input signal is initially converted from serial form to parallel form before it passes through SFB and then the reverse operation is done after coming out of SFB. Once the signal is passed through the transmitter part it can be observed that in the receiver side, the signal is converted to parallel form by Serial to Parallel (S/P) converter and passed through AFB. At last, once the output signal is attained it is again passed through Parallel to Serial (P/S) converter. Many digital filters are arranged in a parallel manner in a filter bank having digital up samplers and down samplers at the transmitter and the receiver respectively. Time index n denotes the low sampling rate (symbol rate), and m for high sampling rate (channel rate) which are used to highlight the multi-rate character of the system [101]. The prototype filters that are in FBMC are drafted in such a way that the interference between overlying symbols is low.

The transmitted signal in FBMC/OQAM is given by

$$s(t) = \sum_{m=0}^{M-1} \sum_{n=-\infty}^{\infty} a_{m,n} i^{m+n} g(t - n\tau_0) e^{j2\pi f_0 t} \quad (3.28)$$

Where $a_{m,n}$ is the data sent on the m^{th} subcarrier at the n^{th} OQAM symbol. M represents the number of subcarriers, g denotes the prototype function. f_0 denotes the subcarrier spacing which satisfies

$$f_0 = \frac{1}{T_0} = 1/(2\tau_0) \quad (3.29)$$

T_0 is the QAM symbol duration while τ_0 is the symbol duration of OQAM. $g_{m,n}$ represents the shifted version of prototype function expressed as

$$g_{m,n} = g(t - n\tau_0) e^{j2\pi f_0 t} i^{m+n} \quad (3.30)$$

$g_{m,n}$ that is among different subcarriers are completely orthogonal in OFDM and not in FBMC/OQAM because of the interference.

The received signal is given as

$$r(t) = \sum_{m=0}^{M-1} \sum_{n=-\infty}^{\infty} a_{m,n} H_{m,n} g_{m,n}(t) + n(t) \quad (3.31)$$

Where $n(t)$ represents the ambient noise and $H_{m,n}$ are complex valued channel frequency coefficients.

Simulations are done in MATLAB for OFDM and FBMC considering the underwater channel features that are mentioned in Section 3.3. The UWAC channel mainly considered the losses and noise coefficients.

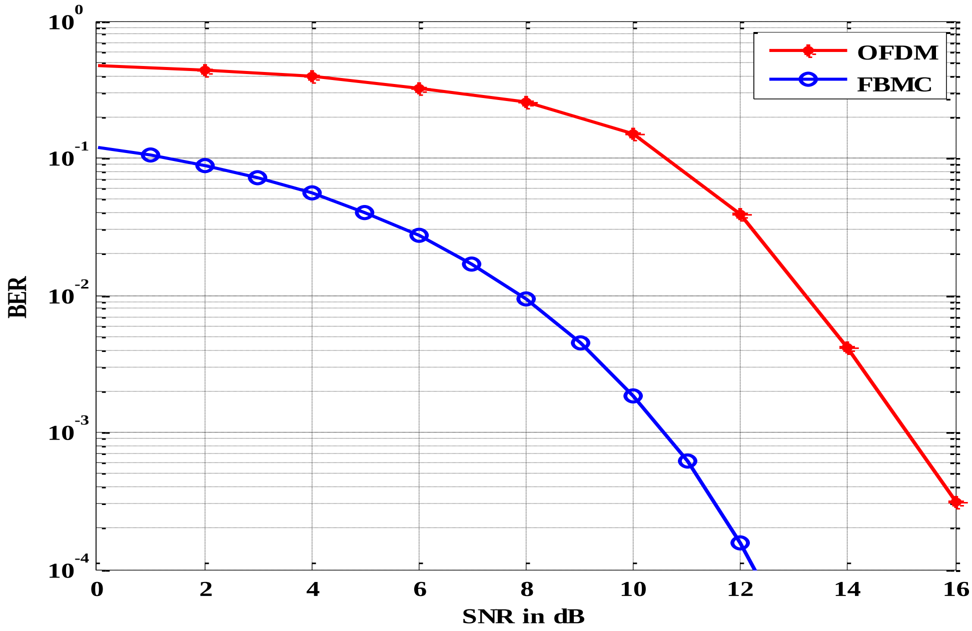


Fig 3.16 SNR vs. BER for OFDM and FBMC

From Fig. 3.16, it is observed that FBMC performs better than the OFDM modulation technique and is observed to be a better technique to reduce ICI. We observed that there is almost a 3 dB difference between OFDM and FBMC in terms of SNR. The well-known restrictions of OFDM such as less spectral efficiency and severe requirements in synchronizing can be outdone by FBMC technique. This technique is less delicate to Doppler Effect and so performs certainly with the improvement of the user mobility. The FBMC technique involves the simplified pulse-shaping filters that delivers a well-contained sub channel both in time and frequency domain reducing the limitations of OFDM. ICI and ISI are the most significant factors that affect the performance of UWAC and this can be reduced by using prototype filters in FBMC.

3.7 SUMMARY

In this chapter, OFDM and its suitability to the UWAC system is clearly studied. The base paper [20] has led to the research of this chapter. Many insights and the work done by them is considered and laid foundation to further explore about OFDM in UWAC and also better ways to further improve the performance of the communication system. Underwater environment which clearly consists of the ambient noise that includes waves, shipping, thermal noise and turbulence is taken into consideration. Factors such as path loss, absorption coefficient and frequency are also considered. Along with the advantages of OFDM, spatial diversity and MRC techniques are also considered which further decreases the number of errors. This is because of the fading channel impairments of the Spatial Diversity technique and the MRC which amplifies the stronger signals. As we increase the number of receiving antennas at the receiver side the performance increases. It is observed that number of errors are reduced when block codes are applied. This is because the reliability of the transmission signals increase as we apply FEC. Restricting to linear block codes, Hamming and LDPC are used to reduce the complexity. LDPC outperforms hamming code for a given SNR. LDPC codes has the advantage of being equipped with very fast (probabilistic) encoding and decoding algorithms, however at a lower SNR and high encoding complexity. A comparison of OFDM and FBMC is made wherein FBMC is an advanced version of OFDM in terms of spectral efficiency, robustness, and spectral protection at the expense of a minor escalation in the complication of UWAC.

- B.Pranitha, L.Anjaneyulu, “BER Performance Evaluation of Underwater Communication System with Spatial Diversity”, Indian Journal of Science and Technology, Vol 9(S1), December 2016.
- B.Pranitha, L.Anjaneyulu, “Performance Evaluation of Underwater Communication System using Block Codes”, Fifth International Conference on Eco-Friendly Computing and Communication Systems (ICECCS 2016) , Dec 8th to 10th 2016, MANIT BHOPAL, IEEE.
- B.Pranitha, L.Anjaneyulu, “Assessment of UWAC System Performance Using FBMC Technique”, Recent Trends in Signal and Image Processing, Advances in Intelligent Systems and Computing 922, (pp53-62).

CHAPTER 4

EQUALIZATION TECHNIQUES IN UWAC FOR MIMO

This chapter deals with Multiple Input and Multiple Output (MIMO) for UWAC. We considered a 2×2 MIMO underwater channel with varying distances and various losses involved in it. Different types of equalization techniques that help in increasing the performance of the system are considered. The accomplishment of a MIMO in UWAC System highlighting both Line of Sight (LOS), i.e. the Rician fading and Non-Line of Sight (NLOS), i.e. the Rayleigh fading signal propagation, is assessed. A comparison of LMS and ZF equalization technique has been observed. Another detection algorithm of MIMO i.e., Vertical Bell Laboratories Layered Space Time (VBLAST) technique is also studied.

4.1 INTRODUCTION

Demand for high data rate in UWAC has been concentrated in recent years to realize effective and fast information transmissions [105]. So there is an immediate requirement to explore and exploit a method for high speed digital UWAC. MIMO is an approach which is developed of multiple transmitter and receiver configuration. These MIMO systems are different from out-dated spatial diversity systems [103].

Advantages of MIMO over Single Input Single Output (SISO)/ Multiple Input Single Output (MISO) are:

1. MIMO increases the system's capacity and the spectral efficiency. The data rate can be improved by spatial multiplexing without consuming more frequency resources increasing the total power at the transmitter.

2. Increased diversity in MIMO reduces the effects of fading.

3. To attain diversity gain, these systems can be implemented in different ways.

To combat fading caused by the channel, MIMO technology is used at the receiving end. At the same time to decrease the spatial correlation of the sub-channels, a decorrelation operation is needed. This will decrease the interference between each sub-channel and progress the transmission rate and BER performance of the system [104].

In this work, fading concepts in MIMO which includes both LOS and NLOS models are considered. The underwater channel which is spatially modulated and passed through a 90m depth from the sea level is considered for simulation in this work. Various parameters such as temperature, salinity, pressure and the losses involved in typical underwater channel are considered. To overcome the draw backs caused due to these parameters in MIMO UWAC, various equalization techniques such as Least Mean Square (LMS), ZF and VBLAST are studied.

A detailed description of the modulation technique, underwater channel model and various equalization techniques and its comparison are considered.

4.2 SPATIAL MODULATION

Spatial modulation (SM) is an additional means of transmission of data which uses antenna indexes in a multiple antenna system. The main intention of SM is to use the active antennas index at any time instant. It depends on whether the modulation scheme is applied at the transmitter or at the receiver. This modulation technique has benefits such as no inter-channel interference (IChI), less complexity in detection and no inter antenna synchronization [105]. However, the gains in MIMO go together with a noteworthy rise in computational complexity and cost of the receiver. One method to get rid of these disadvantages is to use SM. In SM, a group of information bits is plotted into two constellations: a signal constellation that is based on modulation scheme and a spatial constellation which is used to encrypt the index of the transmit antenna. However, at any instant of time, only one transmits antenna is active, while the other transmit antennas radiates zero power. This totally avoids IChI at the receiver and reduces the severe requirement of synchronization between the transmit antennas [106]. Multiple antennas are used by MIMO technology to acquire various gains namely multiplexing and beam forming. Nonetheless, the complexity and cost of the receiver are increased because of these gains. SM is one good approach to overcome the problems mentioned above. In SM, the information bits are mapped into two different constellations: a signal constellation and a spatial constellation. Signal constellation is based on the modulation scheme, while the spatial constellation is used to encode the index of the transmitter. At any point in time, one of the transmitters remains active; while the other transmitter radiates zero power. Thus SM avoids the IChI at the receiver and reduces the high requirement of synchronization among the transmitters. Moreover, unlike the regular MIMO system, RF chains are not required in SM at the transmitter. In this part, we start by giving an introduction to SM–MIMO concept in UWAC. This modulation scheme is applied to the transmitting or receiving antenna to send extra information, and so SM is used to find the index of the active antennas at any time instance. Therefore, the information bits that are to be transmitted are branched into two different parts. In the very first part, it is graphed to a symbol from the signaling constellation. Here the type of modulation used finds the number of bits per symbol. While, from the set of receivers available for transmission or reception, the second part of the information bits regulates the index of the receiver that is selected from a set of receivers that are available for transmitting or receiving the data. Receiver selection in any general MIMO system depends on the state of the channel and the signal strength of the receiver. But it's different in SM-MIMO, where it depends on the incoming user data stream as shown in fig 4.1 [107].

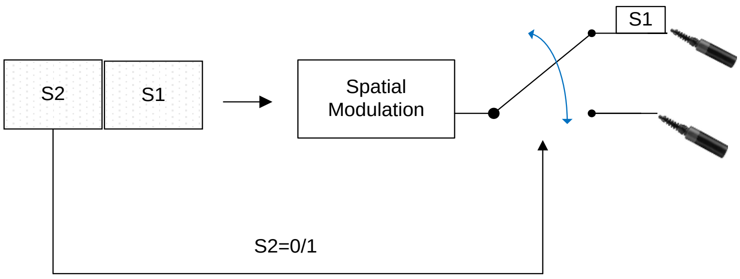


Fig 4.1 Spatial Modulation [23]

The number of transmitters and the receivers are denoted by N_t and N_r respectively. M is the number of entities of the signal constellation. Here we are considering a 4-QAM modulation because of its bandwidth efficient quality and a 2×2 MIMO case. By finding out the index of the active transmitter in SM–MIMO, one symbol S_1 is directly transmitted, and the other symbol S_2 is transmitted indirectly in each channel use. For subjective N_t and M, the rate of SM is

$$R_{SM} = \log_2 M + \log_2 N_t \tag{4.1}$$

Hydrophones are used as the transmitters as shown in Fig 4.1. The disadvantage of using higher order QAM is being more susceptible to noise and data errors as the points are close together. Higher throughput, simpler receiver, and transmitter design and lower transmit power supply are the main advantages of SM-MIMO. But the antenna has to be switched very quickly in this case. Here a basic 4 QAM modulation is used. The received data for the 2×2 MIMO is given by

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \tag{4.2}$$

Here y_1, y_2 are the received data from the two receivers. h_{11}, h_{12}, h_{21}, and h_{22} are the channel coefficients which are explained in Section 4.3, x_1 and x_2 is the transmitted data and n_1, and n_2 is the noise of UWAC.

4.3 MIMO UNDERWATER ACOUSTIC CHANNEL

As the UWA channel environments are composite, the traditional channel models no longer suits for the underwater system condition. In general, MIMO channels can be written as a matrix with M×N components and each element is a CIR with L taps. Therefore at every hydrophone we can assess a set of channels from M transmitters and all these M×N channels can be obtained by iterating the same procedure N times.

If a hydrophone and transducer depth are close to each other, then it receives strong signal from the latter, on the flipside if the depth of hydrophone is much diverse from the depth of a transducer then it receives feeble signal from this transducer.

UWA channels are often time-varying therefore it requires proper Doppler compensation before demodulation [108].

The main reasons for Doppler phenomenon are the relative velocity between transmitter and receiver and the underwater vibrant environment. Though Doppler Effect is present in RF communication, it is particularly evident in the presence of pressure waves, due to the comparatively low speed of the propagation. The effect is much more prominent in UWAC as the buoys and vessels which host transmitter and receiver are rarely at complete rest. Therefore, this disadvantage cannot be ignored and modifying its effect is of supreme importance for an efficient UWAC.

Because of homogeneous nature underwater channel is very complex medium. Due to density and temperature gradients there are many imperfections in the channel. Due to Doppler Effect channel impairments causes. Multipath is the most challenging phenomena of underwater acoustics. Doppler spread in underwater channel is introduced by relative motion between the transmitter and receiver and also by the motion of water. Due to this nature of underwater channel many well-known communication techniques cannot be applied and also it affects the data rate, reliability and distance of underwater communication.

Underwater environments namely ocean, rivers, and water tanks are surrounded by ocean surfaces and sea bottom. Multipath even happens due to scattering from small objects. Additionally, the speed of sound inside the water depends on the temperature, pressure and salinity, and it can change expressively for large depth variations. The changing speed of the sound causes refraction, which can be seen as a bending of the wave. As a result of all these reflections, scattering and refractions, the receiver receives a number of inaccurate replicas of the transmitted signal with diverse delays, amplitudes and phases. Due to the random motion of scatterers and transmitter/receiver displacements, the path delays, amplitudes and phases transforms with time [4].

However, in this work we consider the LOS propagation in 2×2 MIMO wherein the transmitter and receiver are not necessarily in a straight line. This could be in an application where the transmission system is in the middle of the sea. The distance concerning the transmitter and the receiver can be varied and the channel coefficients h_{11}, h_{12}, h_{21}, and h_{22} are calculated correspondingly.

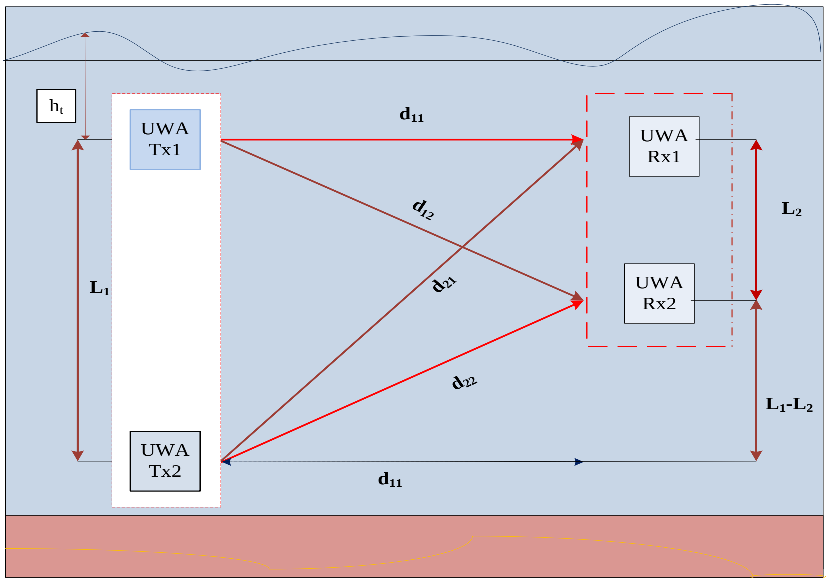


Fig 4.2. MIMO UWA channel

From Fig 4.2, the channel coefficients are calculated using the formula

$$h = \sqrt{\frac{c_R}{1+c_R}} \; A_s(d)A_a(d)e^{j(2\pi f_0 t+\theta_0)} \tag{4.3}$$

Here c_R is the rician factor, $A_s(d)$ is the propagation loss coefficient due to spherical spreading and $A_a(d)$ is the absorption loss. f_0 gives the Doppler frequency and θ_0 represents the phase shift of the LOS component [22]. While evaluating the channel coefficients, all the factors involved in effecting the performance of the system is considered. Doppler Effect is an extra problem in UWAC.

The Doppler frequency f_0 is expressed as

$$f_0 = f_{max}\cos(\alpha_0 - \alpha_v^R) \tag{4.4}$$

where f_{max} represents the maximum Doppler frequency. It is given by

$$f_{max} = v_R f_c / c_s \tag{4.5}$$

Here v_R is the receiver's speed, f_c gives the carrier frequency, and c_s signifies the speed of the sound whose value is usually 1500 m/s. The dynamics α_0 and α_v^R are taken into consideration when there is angle of arrival and angle of departure between the transmitter and the receiver.

The phase shift of the propagating signal is calculated as

$$\theta_{ij} = \frac{d_{ij}}{2\pi} * \lambda \tag{4.6}$$

Here i stands for i^{th} transmitter, and j for the j^{th} receiver.

The wavelength λ is given by

$$\lambda = 1500/f_c \tag{4.7}$$

The loss due to spherical spreading is calculated by using

$$A_s(d) = \frac{1}{d_{ij}} \tag{4.8}$$

Where d is the distance between the transmitter and the receiver.

The absorption loss is calculated as

$$A_a(d) = 10^{\frac{-d\beta}{20000}} \tag{4.9}$$

Eq (4.9) is an empirical formula formulated by Schulkin and Marsh for the absorption loss

The parameter β is given by

$$\beta = 8.68 * 10^3 \left(\frac{S_a f_T f_c^2 A}{f_T^2 + f_c^2} + \frac{B f_c^2}{f_T}\right)(1 - 6.54 * 10^{-4} P) \tag{4.10}$$

Where A and B are constants, S_a stands for salinity, f_c for carrier frequency and f_T is the relaxation frequency which is given by

$$f_T = 21.9 * 10^{6-\left(\frac{1520}{T+273}\right)} \tag{4.11}$$

Here T is the hydrostatic temperature given in (°C); P represents the pressure, which depends on water depth h_t, which is given by

$$P = 1.01(1 + 0.1h_t) \tag{4.12}$$

In Figure 4.2, the two transmitters are positioned at a distance L_1, d_{ij} is the distance between the transmitters i and the receiver j, the two receivers are placed apart at L_2. In the alignment, the transmitters and receivers are in parallel planes and $L_1 > L_2$. For computing the channel coefficients $\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$ using equation (4.2), we consider the distance d_{11}, d_{12}, d_{21}, and d_{22} respectively. Assume that the distances d_{11} and L_1 and L_2 are static, the remaining distances can be calculated. The phase shift of the signal θ_{ij} induced by d_{ij} is also determined for various distances. h_t is the shallow water depth on whom the hydrostatic pressure is dependent. The absorption and spherical loss that is made with respect to d_{ij} is calculated.

The parameters used for MATLAB simulation are presented in Table 4.1.

TABLE 4.1 Simulation Parameters

Symbol	Parameter	Value
N_t	No. of transmitters	2
N_r	No. of receivers	2
N	No. of transmitted bits	10000
m	Order of QAM	4
c_R	Rice factor	0.56
d_{11}	Distance	1m – 100 m
f_c	Carrier frequency	10kHz
T	Temperature	10°C
Sa	Salinity	35 PSU
P	Pressure	11 kg/cm^2
c_s	The speed of the sound	1500 m/s
L_1	Distance between transmitters	5 m
L_2	Distance between receivers	2 m
v_R	The speed of the receiver	9 m/s
h_t	Shallow water depth	90m

4.4 EQUALIZATION TECHNIQUES IN MIMO

Equalization is a method that generates estimates of the transmitted signal by compensating channel effects. There are different approaches for this compensation, such as directly inverting the channel, or minimizing the mean square error (MSE) between the estimated and transmitted symbol. Moreover, equalization can be linear or nonlinear, having a trade-off between complexity and performance. In general, nonlinear equalizers achieve lower BER than linear equalizers, but at the cost of extreme complexity when compared to linear equalizers [52]. However, in underwater acoustic channels which are generally fast time varying, the equalizer's coefficients should be restructured during symbol detection [109].

In this chapter, an investigation is done on various fading techniques for MIMO- UWAC and ZF and MMSE equalization performances are carried out further.

4.5 MIMO FADING

Fading happens when signals traveling along different routes interfere with each other. The unplanned variation of the path amplitude with respect to time which leads to the superposition of many copies of the transmitted signal within an Eigen path is known as fading. In low frequency (i.e. <1 kHz) sound propagation, the fading components, Rayleigh and Rician are related with saturated and partially saturated schemes respectively in which the multipath is completely or partially random. The propagation of acoustic waves requires a medium to transmit data. This medium can be either shallow or deep water. Irrespective of the type of the medium, propagation loss and fading exists. The two types of fading that are considered in this work are Rayleigh and Rician fading. The acoustic multipath propagation in Rayleigh fading model follows an exponential distribution at the received power.

When the Rayleigh fading model is used, the scatterers that are explained in Fig 4.3 are considered. In this type of channel no straight path exists between the transmitter and receiver, but at the receiver, the sum of all the reflected and scattered waves is combined. Here Scattering may be mainly caused due to reflections from the sea surface and the ocean bottom. At the receiver; signals are received in four different ways. They are the direct LOS direction between the transmitter and the receiver, reflected signal from the bottom of the ocean surface and both surface and bottom. However, each receiver receives a number of reflected copies and direct signals from each transmitter. Rough sea surface or the seafloor causes attenuation of the acoustic field in an ocean waveguide. Here attenuation increases with increasing frequency. Ambient noise is considered in Rayleigh fading UWAC channel. Turbulence, Shipping, Waves in the ocean and Thermal noise are the reasons for it.

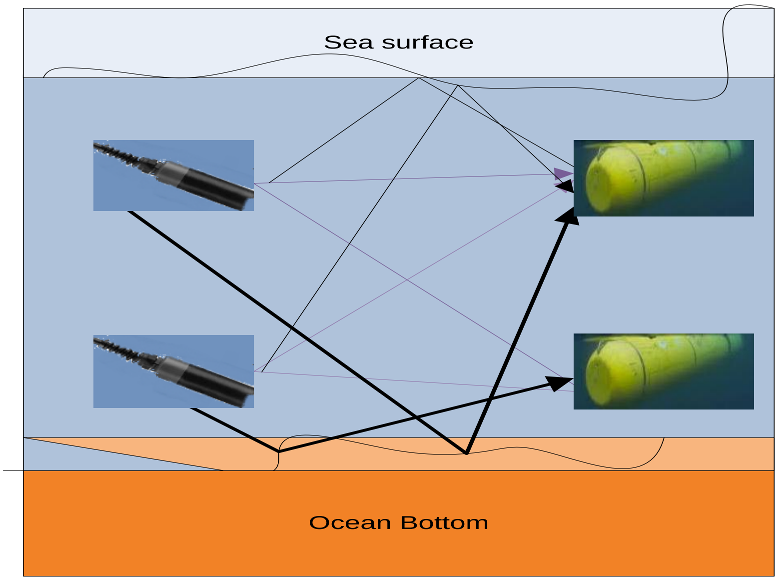


Fig 4.3 Multipath Scattering in UWAC [64]

The power spectral density (PSD) of these noise components as a function of frequency in kHz is expressed as

$$logN_t(f) = 1.7 - 3\log f \quad (4.13)$$

$$logN_s(f) = 4 + 2\left(s - \frac{1}{2}\right) + 2.6\log f - 6\log(f + 0.03) \quad (4.14)$$

$$logN_w(f) = 5 + 0.75w^{1/2} + 2\log f - 4\log(f + 0.4) \quad (4.15)$$

$$logN_{th}(f) = -1.5 + 2logf \quad (4.16)$$

Here the shipping coefficient *s* varies from 0 to 1, for low and high action respectively. *w* is the wind speed that is measured in m/s [67]. The final PSD of the background noise is given by

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \quad (4.17)$$

$N_t(f)$ is the noise due to turbulence, $N_s(f)$ is due to the shipping activity, $N_w(f)$ is caused due to waves and $N_{th}(f)$ is the thermal noise.

Also, point-to-point communications in UWAC is also a major research area that has to be studied. This is known as LOS communications to underwater multicarrier modulation networks. However, in LOS propagation path Rician fading model is adapted. In this LOS propagation path which has a dominant stationary signal component and the random multipath components received at different angles are superimposed on them, the small- scale fading envelope distribution is Rician. Rician fading which is adopted in order to include the effects of LOS conditions of a wireless channel in the relaying link [110]. Here, the gain in amplitude is considered by a Rician distribution [111].

Matlab simulations have been carried out for the channel model that is shown in Section 4.3. 4-QAM Spatial modulation is given at the transmitter which is a cost and complexity efficient, while at the receiver ZF equalization is given to detect the transmitted data. This equalization technique applies the inverse of the channel matrix and detects the transmitted data. For NLOS, i.e., the Rayleigh fading considers the multipath fading involved in UWAC. Even the ambient noise which involves noise caused due to shipping, waves, turbulence, and thermal noise is also considered. While in LOS, i.e., for Rician fading factors such as absorption loss, spherical loss, temperature, pressure, salinity, Doppler frequency, etc. are considered which is shown in Table 4.1.

Simulations are carried out for both LOS and N-LOS UWAC, i.e., for both Rician and Rayleigh Fading Channels with ZF Equalization technique.

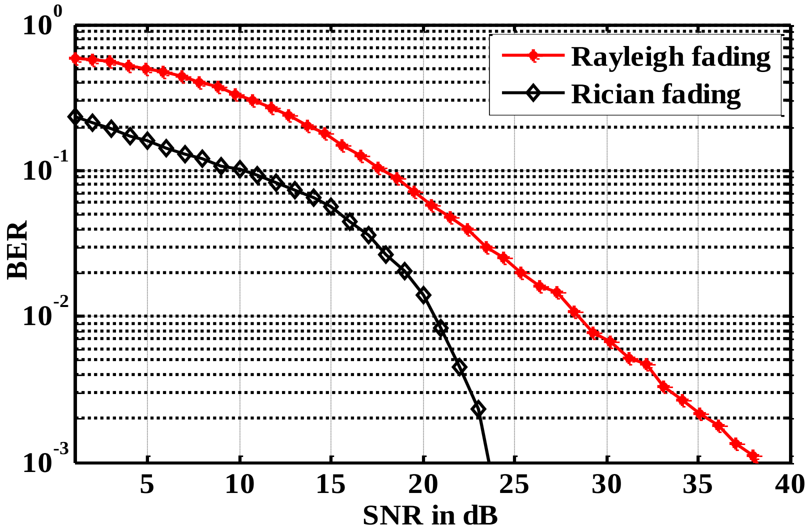


Fig 4.4. SNR vs. BER of Rayleigh and Rician fading UWAC

Fig 4.4 depicts that Rician fading outperforms the Rayleigh fading channel. The SNR to BER values is tabulated as follows in Table 4.2.

TABLE 4.2 BER VALUES FOR RICIAN AND RAYLEIGH FADING CHANNELS

SNR in dB	BER	
	Rician Distribution	Rayleigh distribution
1	0.830409	0.94646
5	0.782244	0.915555

SNR in dB	BER	
	Rician Distribution	Rayleigh distribution
10	0.731129	0.870501
15	0.658818	0.789072
20	0.474383	0.689473
25	0.020281	0.571698
30	0.00	0.447859
35	0.00	0.324006
39	0.00	0.191

From the above-tabulated values, we can observe that the error rate for Rayleigh distribution is very high when compared to Rician distribution. This is because the scattering effects are very less in the LOS component than the N-LOS and also the presence of multipath fading affects the performance of the system. From table 4.2, we notice that the BER values of Rician distribution are zero for SNR values at 30dB. However, the BER values of Rayleigh distribution is 4.48e-01 at the same SNR. For Rician distribution, the distance between the transmitters and the receivers can be varied because of the line of sight propagation. As they are in parallel planes, the channel coefficients can be calculated, and the respective received data can be detected by using the ZF equalizer.

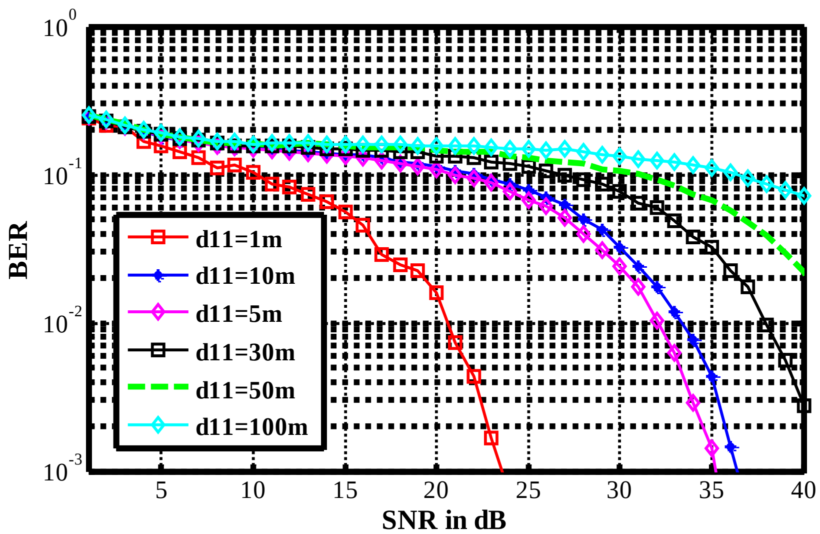


Fig 4.5 SNR vs. BER of ZF equalization with different Tx-Rx distances

From Fig 4.5 we observe that as the distance increases from the transmitter to the receiver increases the error rate increases. In Figure 4.2, as the link distance d_{11} is increased from 1m to 100m. The observation made is that, there is a variation in the geometry of the channel model which introduces larger absorption and spherical losses calculated by using (4.8) and (4.9). Note that there is a simultaneous variation in distance d_{11} and all the other distances linked that are used to calculate various channel coefficients (h_{11}, h_{12}, h_{21}, and h_{22}). Recalculation of the phase shifts of the signals propagating in longer paths are done by using (4.6). It is observed that the BER and the distance are directly proportional to each other.

The main intention of using 4-QAM modulation scheme is its efficiency to use the bandwidth. Generally whenever the requirement of the linearity of the modulation scheme like QAM increases, the power efficiency of the current power amplifiers considerably reduces. So a simple 4-QAM modulation is used in this case of transmission.

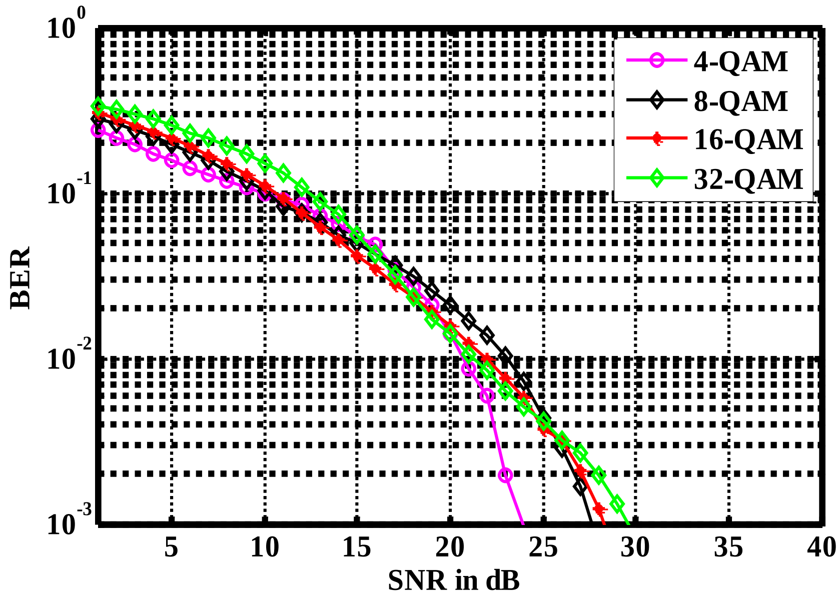


Fig 4.6 SNR vs. BER for different states of QAM

From Fig 4.6 we observe that 4-QAM is the better modulation scheme that can be used for high data rate. However, they are very much affected by noise and interference. This happens at higher SNR, therefore there is a small deterioration in the performance of 4-QAM between 15 to 23 dB of SNR. As SNR decreases errors will increase reducing the throughput. By returning to a lower order modulation scheme the link can be made more trustworthy with few data errors and re-sends. And so 4-QAM is used for better efficiency and reduced complexity.

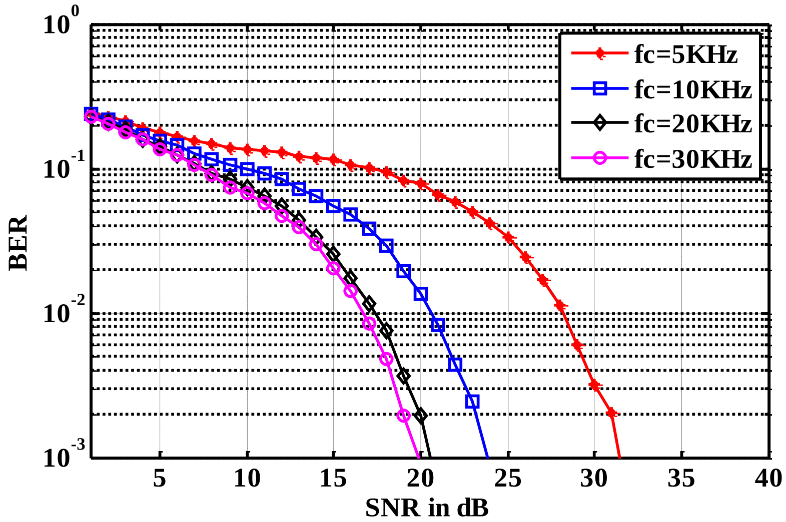


Fig 4.7 SNR vs. BER for different carrier frequencies

Fig 4.7 gives the SNR to BER curve for various carrier frequencies. We observe that the number of errors keeps on decreasing as we increase the carrier frequency value. Carrier frequency and the relative motion between the transmitter and the receiver depend upon the Doppler frequency as explained in (4.5). By optimizing the choice of these basis functions, the Doppler shift is estimated. Doppler Effect plays a vital part in the effective design of high data rate acoustic communication systems.

Apart from the fading concept discussed in MIMO UWAC, there is also work done exclusively on LOS part of MIMO.

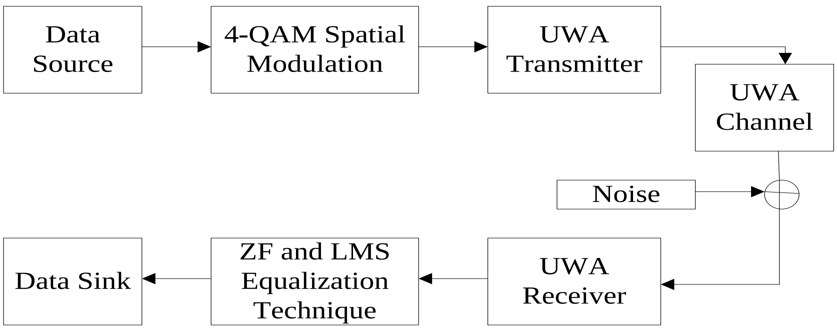


Fig 4.8 Block diagram for UWAC MIMO System

Fig 4.8 represents the schematic diagram of an UWAC system where the unplanned binary data is spatially modulated at the transmitter. Section 4.3 expands the underwater acoustic channel including of the spherical and absorption loss. At the receiver, explained in section 4.6 and 4.7, LMS and ZF equalizers are used to approximate the data, and it is finally recovered.

4.6 LMS TECHNIQUE

Most existing UWAC channels use either the Recursive Least Square (RLS) or Least Mean Square (LMS) algorithm to amend the equalizer coefficient [112]. Decrease in computational complexity can be attained by well-organized LMS algorithms with better-quality tracing properties and by decreasing the number of adaptively adjusted receiver parameters [113]. The total number of coefficients may be very great (more than 100 taps is regularly needed for spatial and temporal processing in medium and long-range shallow water channels). In addition this algorithm is very sensitive to the step-size [114]. To account for time variation of the channel, this approach can be employed to update the equalizer coefficients [115]. Considering LMS and its advantages, it can be used practically for UWAC [116] . The error signal is given by

$$e = d - y \tag{4.18}$$

$$d = w'x \tag{4.19}$$

Here *e* is the error signal, the magnitude of the difference between the actual received signal y(n) and the estimated received signal at time n. *d* stands for the desired signal, *w* represents the weight vector. Filter coefficients are updated by using the formula

$$w(n+1) = w(n) + \mu e x \tag{4.20}$$

Here μ is the adaptive filters step size. The main feature that affects the convergence behaviour and device stability of the LMS algorithm is μ.

In spite of the advantages in computation of LMS algorithm, it has uniform step-size for all equalizer coefficients treating all of the coefficients equally. This fails to exploit the sparsity existing in underwater acoustic channels causing severe noise enhancement [117].

4.7 ZF EQUALIZATION TECHNIQUE FOR MIMO

Error propagation effect is further amplified, particularly in fast time varying MIMO UWA channels, due to the difficult probability of incorrect symbol decision and very long equalizer length.

In this work, the Zero-Forcing (ZF) equalizer is put forward, that is based on channel matrix estimation. The original system is divided into several subsystems allowing data estimation with practicable complexity. The inverse of the channel matrix is calculated and multiplied with the received data to obtain the transmitted data. The estimated/detected data is given by

$$\hat{x} = H^{-1}Y \tag{4.21}$$

$$\hat{x} = H^{-1}(Hx + n) \tag{4.22}$$

$$\hat{x} = x + H^{-1}n \tag{4.23}$$

ZF technique is less complex. The number of receivers should be equal to or greater than number of transmitters in the case of ZF. However, it comes at the cost of increasing the power of noise that leads to degradation in power [14]. When Doppler frequency is small, the received signal quality will be better than when the Doppler frequency is large. Consequently, it will influence the received signal quality. Interference between terminals can be suppressed even further by using ZF equalizer.

ZF and LMS equalizers are used in estimation of the data that is received.

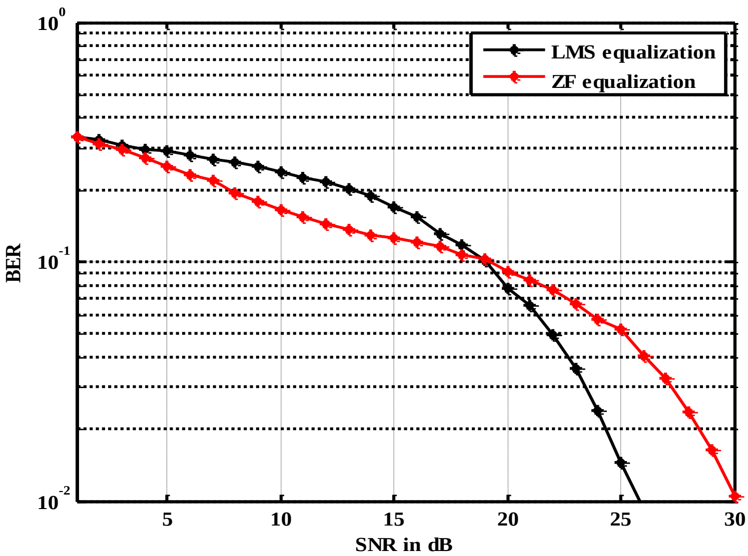


Fig 4.9 BER vs. SNR of UWAC with LMS and ZF equalizer

In Fig 4.9, the presentation of the UWAC system with ZF and LMS equalizations is observed in terms of BER. Low speed of convergence and the performance getting affected by input signal are the disadvantages of LMS algorithm [118]. On the other side, the ZF equalizer does not get influenced by the input signal and the data is recovered by application of inverse of the channel. However, the system needs high SNR to operate, i.e. about 20dB to achieve low BER. ZF equalizer is determined to make best use of the strength of the signal at frequencies that are moderated by noise. At some frequencies where the received signal is weak there ZF equalizer grows very large compensating the magnitude of the signal. Thus we can say that the noise added after the channel is enhanced by a huge factor destroying the overall SNR.

4.8 VBLAST TECHNIQUE FOR MIMO

The problem of enhancing the power of the noise in ZF Equalizer can be overcome by VBLAST to some extent. In this technique, channel coding is given to individual transmitters, relating to the data stream transferred from each transmit antenna. The VBLAST architecture was primarily proposed in [66] wherein at a particular transmitter; each code block is de-multiplexed into different layers. There are two main advantages in VBLAST when compared to the existing technologies.

i. The total channel bandwidth used in the VBLAST system is a small part in additional of the symbol rate.

ii. The entire bandwidth is occupied simultaneously by all the transmitters at a particular time.

The detection is done at the receiver successively where the interference is cancelled. The unknown interferences are nulled by weighting the residual signal vector linearly with a ZF null vector.

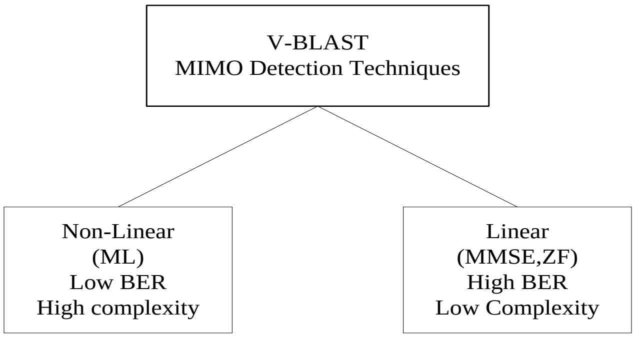


Fig 4.10 Classification of MIMO detection technique [119]

From Fig 4.10 we notice that there are two different types in MIMO detection technique; however, in this case of UWAC, we use the high linear BER and low complexity technique to detect the received data. Though Maximum Likelihood (ML) detection is an optimal technique for VBLAST detection, it is highly complex to implement. ZF filter with ordered successive interference cancellation (OSIC) performs the detection algorithm in VBLAST.

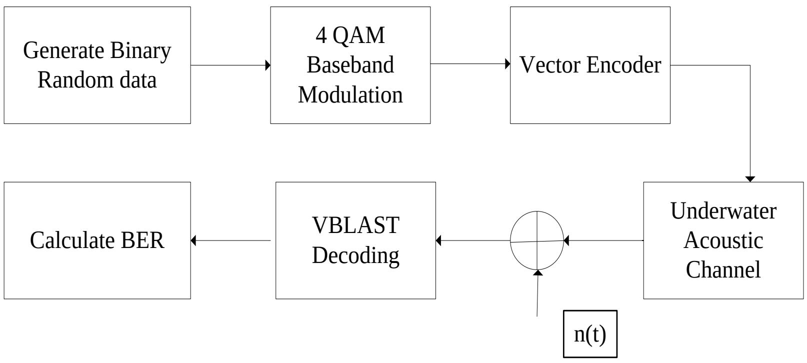


Fig 4.11.VBLAST in UWAC

Fig 4.11 gives the block diagram of the VBLAST algorithm. At the transmitter binary random generator produces the transmitted bits which are modulated using a 4-QAM baseband modulator. The vector encoder plots the symbols to the individual transmitter. Here we are considering the UWAC channel with all the losses involved in it, which is modelled in section 4.3. Two interferences are occurring in this case. They are spatial multi-stream interference and temporal ISI. Since the underwater channel that we are considering is a frequency flat fading LOS MIMO channel, the latter one does not exist. And so equalization for spatial multi-stream interference is done. To overcome this interference VBLAST MIMO concept with SIC at the receiver is proposed. It follows the iteration procedure. After deciding the first signal stream with the detection process, it will be subtracted from the original receiving vector by giving the feedback. This process reduces the ISI on the resulting MIMO layers [21]. The order selection rule of the algorithm prioritizes the sub channel with the smallest noise variance. The algorithm will perform nulling and figures out the decision slice the totalled decision statistic and generates the decision. Then cancellation is performed by decision feedback, and the new pseudo inverse is computed for the next iteration.

The algorithm of VBLAST/ZF is as follows

Step 1: Initialization

$i=1,\ y_1=y,\ H_1=H$

$G_1=H^{\dagger}$

Step 2: SIC

For $i=1:N_t$

Ordering: $K_i = argmin \left\|(w_i)_j\right\|^2$

$j \notin \{K_1, K_2, \ldots . K_{i-1}\}$

Nulling Vector: $w_{k_i} = (G_i)^{k_i}$

Nulling: $y_{k_i} = (W_i)_{K_i} y_i$

Hard decision: $\hat{x}_{k_i} = Q(y_{k_i})$

SIC: $y_{i+1} = y_i - (H_{k_i})\hat{x}_{k_i}$

Update the channel matrix: $H_{i+1} = H_{\bar{k}_i}$

Calculate the weight matrix: $G_{i+1} = H_{i+1}^{\dagger}$

End

Y is the received vector, *H* is the channel matrix. $H^{\dagger}$ denotes the pseudo-inverse of the matrix *H*. N_t denotes the number of transmitters. $(w_i)_j$ is the jth row of (w_i), *Q(.)* is the quantizer to the nearby constellation point. (H_{k_i}) represents the k_i^{th} column of *H*. $(H)_{\bar{K}_i}$ signifies the matrix obtained by making the columns $k_1, k_2, \ldots, k_i$ as zeros of *H*, and $pinv(H)_{\bar{K}_i}$ denotes the $(H)_{\bar{K}_i}$.

The two main operations that are performed at the detection process are

i. Interference suppression: The received vector is projected onto the perpendicular subspace crossed by the interfering signals. This process reduces the interference followed by normal detection of the first symbol.

ii. Interference cancellation: Subtraction of the received signal and the detected signal is done in this step [120].

VBLAST has an interesting feature wherein no plain orthogonalization of the transmitted signals is forced by the transmitting structure. However, the propagation situation itself exhibits noteworthy multipath. This is done to achieve the signal de-correlation necessary to separate the co-channel signals.

Here we investigated a 2×2 MIMO UWAC channel with the motive to prove that VBLAST along with ZF equalizer proves to perform better than the original ZF equalizer. However, here we considered the realistic underwater channel along with the absorption and spherical loss. The numerical values of the equations that are considered in Section 4.3 are tabulated in Table 4.1. Here, two techniques are considered for detecting the received data. The former one is the ZF equalizer which inverses the channel matrix to get the estimated data. The second one is the VBLAST technique where in it performs a spatial nulling process and employs a ZF nonlinear detection algorithm. This process is combined with symbol cancellation to further improve the system performance. These two techniques are compared in the UWAC channel. In the system, data arrives at the receiver during different time periods, and thus it interferes highly cancelling each other out.

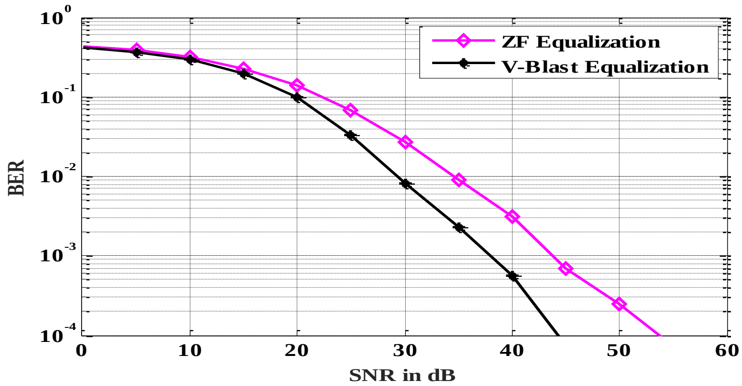


Fig 4.12 SNR vs. BER curve for ZF and VBLAST equalization techniques in UWAC

VBLAST method helps to overcome multipath. This can be done by using the scattering characteristics of the propagation environment which helps to boost up the transmission accuracy by treating the diversity of scattering paths as distinct parallel sub-channels [121]. In fig 4.12, the upper curve shows the performance of the ZF equalization technique while the lower curve shows the VBLAST technique that is observed to be of better performance. To reduce the complexity in simulation the distance between the transmitter and the receiver is considered as 1m. As mentioned in the algorithm, in VBLAST nullifying the weighted terms with cancellation is performed which is better than pure nulling. Hence, the BER performance of the UWAC system is improved by almost 8dB with VBLAST technique when compared to that of a ZF equalization technique.

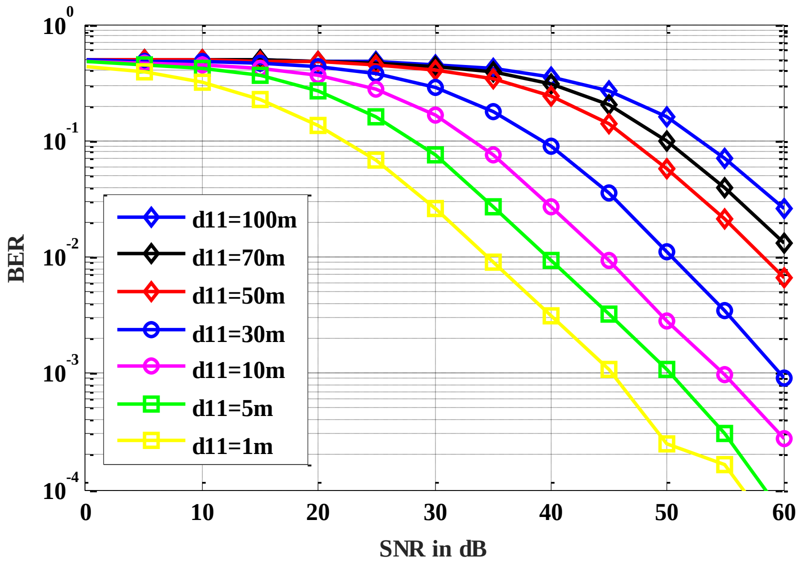


Fig 4.13 SNR vs. BER for ZF Equalization with different Tx-Rx distances

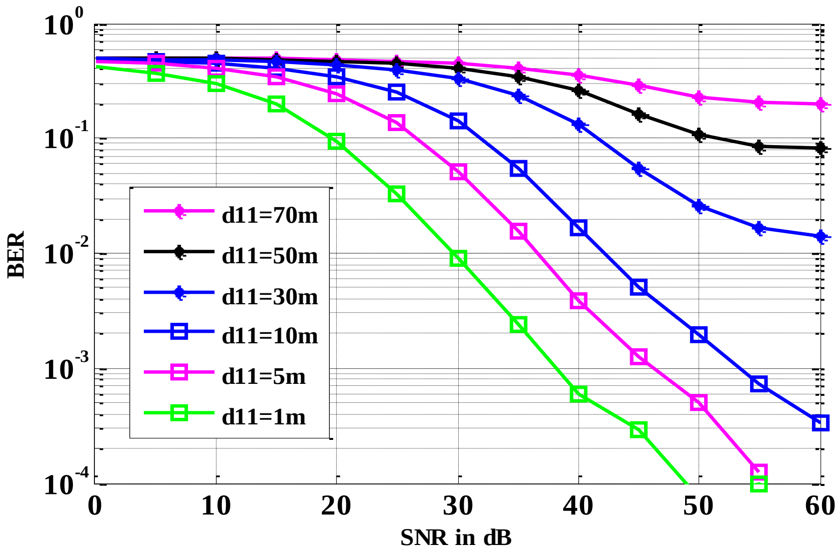


Fig 4.14 SNR to BER for VBLAST with different Tx-Rx distances

We further investigate the ZF and VBLAST performances with varying distances between Tx1 and Rx1. However, VBLAST approach significantly improves spectral efficiencies, and robustness as well as acceptable BER as shown in Fig 4.12, even when we consider the regular ZF equalization technique, we observe that as the distance between the Tx1 and the Rx1 increases the performance of the underwater communication system decreases. It is shown in Fig 4.13. To improve the performance, VBLAST algorithm has been introduced. This is done at lower complex level availing the spatial dimension of highly scattering environment [122]. When we consider the VBLAST algorithm, as the distance varies in the same way of ZF equalizer, it is observed that the performance also varies. From the above two graphs (Fig 4.13 and 4.14) we observe that as the distance is increasing between the Tx1 and Rx1, the BER is also increasing which worsens the performance of the UWAC system. The interferences with extra symbols are cancelled when the initial symbol that is decoded is fed back again and this continues until all the symbols are decoded. However the symbol with largest SNR is decoded first. So in this highly scattering underwater environment a very good spectral efficiency is achieved due to its decision feedback structure [80].

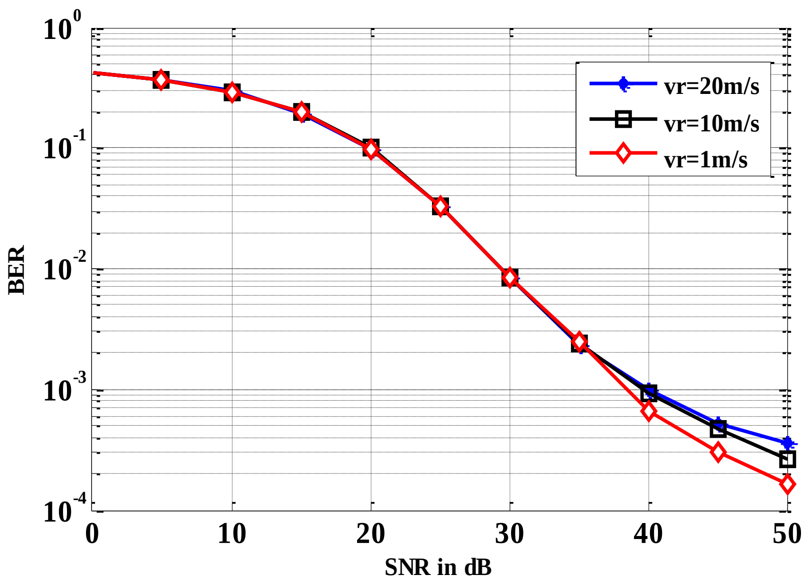


Fig 4.15. SNR to BER curve for VBLAST with different relative motions

Doppler shift is also one of the main characteristic of UWAC. The velocity between the source and the receiver, and the speed of propagation of the signal are the main reasons for the Doppler shift in frequency. Doppler. Though ZF equalizer, that enhances the noise component, does not show much difference concerning the Doppler Effect in our system, the VBLAST system with MIMO explains clearly the effect of Doppler frequency. It is because in the marine environment; acoustic transmission is not easy under the water. The UWA environment is highly resonating which results in many copies of the transmitted signal being received. This is because of the relative motion between the transmitter and the receiver as explained in equation (4.5). This relative delay at the receiver changes with the time. Doppler Effect in UWAC is normally caused by the expansion and shortening of the surface reflected transmission paths and also by the movement of transmitter and receiver (or both). This Doppler Effect poses a great challenge to the decoding of the data at the receiver. This problem actually increases when there is a need for achieving a high data transmission rate [123]. At the receiver, the Doppler Effect shifts the frequency because of the motion between the transmitter and the receiver. From Fig 4.15, we observe that at high SNR, there is a variation in the performance of the UWA system. As the relative motion between the transmitter and the receiver increases the number of errors increases eventually degrading the performance of the system. However, there is no much variation before 35dB. SNR is the parameter to measure the quality of the communication system which is also the same case for UWAC system. Along with the wind and wave action that plays a major role in underwater communications, the reduced SNR value does not contain any increased losses connected with the increase scattering that the wave action generates [124]. At low SNR, the error is subjected by the estimation of the transmitted symbol. While at comparatively higher SNR, the error is subjected by the estimation of the corresponding antenna number [125]. Doppler coefficient approximation modification slowly decreases as the advance of SNR or Doppler factor falls close to zero. The estimate variance of the Doppler coefficient with a higher SNR is a lesser amount [126].

4.9 SUMMARY

This chapter exclusively considered the advantages of MIMO in UWAC and worked on a 2×2 MIMO. All the scattering effects of the undersea channel characteristics are considered in this work. Apart from the MIMO concept, Rayleigh (NLOS) and Rician (LOS) fading criteria is also considered and its performance is observed. Simulation results prove that the LOS component of UWAC outperforms the NLOS component. ZF Equalizer is applied at the receiver. Moreover, in LOS propagation, the performance on varying distances is calculated. Results have been presented for various states of the QAM modulation scheme and also for different carrier frequencies. The shallow water acoustic channel is highly time-varying and does not assuredly follow a Rayleigh distribution. So LOS component is individually verified with the ZF and LMS equalizer that has been applied to assess the transmitted data. BER vs. SNR of UWAC with ZF equalizer with both constant and changing distances are calculated. The simulated results have proved that the performance of the system is better with ZF equalizer than LMS till 20dB SNR is reached. As the value of SNR rises, the noise factor is enriched decreasing the performance of the ZF equalizer compared to LMS equalization technique. ZF equalizer also has a disadvantage of increased noise on multiplication with the inverse of the channel matrix. This disadvantage has been overcome by VBLAST technique which follows the nulling and cancellation procedure. VBLAST algorithm outperforms the ZF equalizer when the realistic underwater channels with the losses involved in it are considered. Effects of distances and Doppler shift are also explained concerning the performance of the UWAC system.

- Pranitha, B. and Anjaneyulu, L., 2019. "Performance Evaluation of a MIMO based Underwater Communication System under Fading Conditions". Engineering, Technology & Applied Science Research, 9(6), pp.4886-4892.
- Pranitha, B., Le Minh, H., Aslam, N., Anjaneyulu, L. and Vangala, S., "BER Performance Investigation of MIMO Underwater Acoustic Communications", 2018 11th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP) (pp. 1-5). IEEE.
- B.Pranitha, L.Anjaneyulu, "Investigation of VBLAST Equalization Technique for Underwater Acoustic Communications", Accepted for publication in International Journal of Electronics and Telecommunications (Vol 66).

CHAPTER 5

ZF EQUALIZATION TECHNIQUE APPLIED TO PRACTICAL CIR OF UWAC

This chapter deals with the channel impulse response (CIR) of underwater channel. A practical experimentation done by Japan Marine Science and Technology Centre (JAMSTEC) on high-speed UWAC, carried out at real sea environment as a time-variant multipath Channel is considered here. ZF equalization technique has been applied at the receiver to further decrease the number of errors and increase the performance of the system. A comparison of both theoretical and practical simulated results is observed.

5.1 INTRODUCTION

Because of expensive sea trials, advances in UWAC are slow. Also because of its peculiar environment, the work that is done for wireless communication cannot be that easy in underwater. However, this channel presents many exceptional challenges for the design of underwater communication systems. Some of these challenges include time varying multipath signals due to reflections caused due to the moving surface waves and rough ocean bottom, which can cause echoes and signal interference. In addition, noise is introduced in water by wind, ships, thermal noise and numerous forms of ocean life, which can disguise a portion of the signal and block the equivalent carried data. In a usual state, the deterministic features depends on the frequency of the sound, ocean surface and bottom acoustic properties, speed of the sound, and transmitter and receiver location. In general, the impulse response defines the response of the system as a function of time (or perhaps as a function of some other independent variable that parameterizes the vibrant behaviour of the system). Due to the fluctuation of amplitudes and phases, Inter Symbol Interference (ISI) is introduced in UWAC. Many of the acoustic communications rely on field experiments for the data. Generally drawback of these experiments is that it is limited only to a specific modulation scheme. Also because of the cost that is involved in conducting an experiment does not allow many algorithms to be tested at once. So this Channel Impulse Response (CIR) database helps the researchers to examine the performance in different algorithms under the convincing ocean conditions without any need to conduct the experiments at sea.

CIR characterizes the multipath and time-varying effect in UWAC. Due to the comparative velocity, Doppler spread occurs which causes amplitude variation in CIR [127]. Since the impulse function comprises all frequencies, the impulse response explains the response of all the frequencies of a linear time-invariant system. It means that the multipath or impulse response of the underwater acoustic channel may be relatively different from one to another [91]. These challenges can cause the UWA signal to fluctuate randomly and as a result it is challenging to select the modulation and error correction. In [128] it was shown that the simulated impulse responses obtained after modelling the parameters of the underwater environment with real measurements were very close to those obtained from the ocean or seawater. In a multipath environment, it is practically natural to envision that an impulse transmitted from transmitter will stretch out to the receiver as a sequence of impulses.

In any experimental setup, acoustic transducers are used to convert either electrical signals into sound or vice versa. Transmitters are known as bases or projectors, while the receivers are known as hydrophones. In general a single transducer acts both as a transmitter and a receiver in acoustic modems. They are exclusively designed for underwater situations and are attached to floating object such as a boat or buoy. Sources or projectors are meant to occupy the frequency bands that are usually thinner than the hydrophone frequency band. Projectors need to be omnidirectional or hemispherical, while hydrophones are supposed to be omnidirectional or directional. A number of omnidirectional hydrophones will form an array. It is probable to select a better receiving direction when the developed signals are properly combined or to use diversity for enhancing system performance. The most used transducers are piezoelectric, magnetostrictive, parametric or finite-amplitude sources and receivers.

In Japan Marine Science and Technology Centre (JAMSTEC), studies have been made on high-speed UWAC for controlling unmanned untethered underwater vehicles or transferring a large amount of data from observation equipment deployed to the sea bottom. The experimentation team proposed a multichannel DFE receiver [129]. The data containing a high-level multipath, which was coming from the angle very near the direct path, was obtained. In this case, they were unable to demodulate a single-channel receiver, but the multichannel receiver provided a good result. So to overcome this drawback of not being able to demodulate a single channel receiver, ZF equalization technique is proposed in this work. All of the simulation process has conditions with respect to the measurement in real condition.

The experimental setup describes the modulation scheme used along with various steps followed at the real time experimentation in section 5.2.

5.2 **EXPERIMENTAL SETUP**

To support higher data rates, a higher bandwidth spectrum needs to be considered. Here we use a 16-QAM modulation for its simple implementation, robust performance and bandwidth efficiency. Rapid data rates and high levels of spectral efficiency for UWAC are caused due to higher order modulations. They are considerably less resistant to noise and interference.

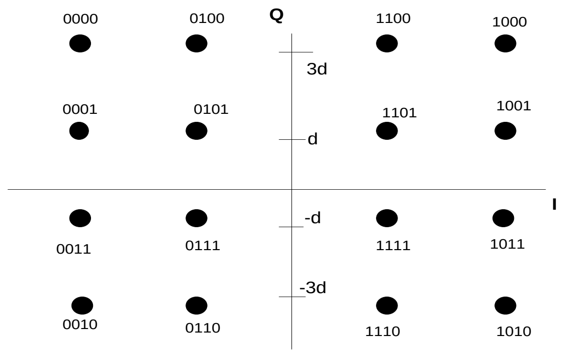


Fig 5.1 16 QAM Constellation diagram

The signal points are arranged as shown in Fig 5.1. The transmitted signal $s(t)$ is expressed as

$$s(t) = \mathrm{a}\sin(\omega t + \theta) + b cos(\omega t + \theta) \qquad (5.1)$$

Here a and b are the amplitude of the I and Q phase components. $\boldsymbol{\omega}$ is the angular frequency and θ is the phase coefficient.

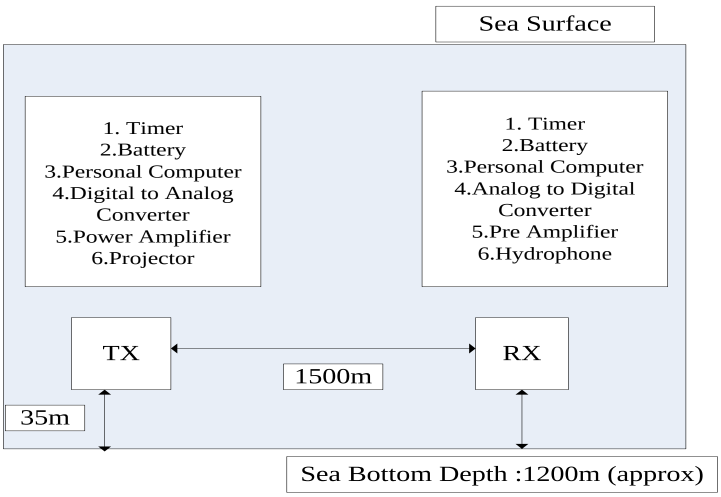


Fig 5.2 Experimental Setup for UWAC [125]

The Sea trial was conducted at approximately 1200m depth in Suruga Bay, Japan as shown in Fig 5.2. The transmitter is composed of a personal computer (PC), a digital-to-analog converter (DAC), a power amplifier, a projector, a timer unit and batteries. The transmitting signal is deposited in a hard disk drive (HDD) on the PC as a binary file, which is a pass-band signal. The receiver also has the same units except that the DAC is replaced by Analog to Digital converter (ADC) and the projector at the TX is replaced by the hydrophone at the receiver. In this sea trial, sampling frequency is 160 kHz. When the DAC received a trigger pulse from the timer unit, it starts to transmit signals through the power amplifier and the projector and receives at the preamplifier and the hydrophone. 20 KHz of the carrier frequency and a bandwidth of 8 KHz are used here. The transmission rate of this 16-QAM is 32kbps (8kbaud). Each packet carries 10,000 symbols each. Both transmitter and receiver are placed 35m above the ocean bottom and are separated by 1500m distance.

5.3 SIMULATION RESULTS

Table 5.1 demonstrates the values of the parameters that are considered in this experimentation. In the impulse response considered for simulation, we reassume flat sea surface and ocean bottom which is approximately of 1200m water depth. Both TX and RX are separated by 1500m distance while it is placed 35m above the sea surface. About 10000 symbols are sent in each packet with a transmission rate of 32kbps. The transmitter and receiver nodes are positioned at 35m above the seafloor. The carrier frequency is 20 KHz and the signal is digitized by a sampling frequency of 160 KHz.

Table 5.1 Numerical Parameters

Parameter	Numerical Value
Carrier Frequency	20KHz
Bandwidth	8KHz
Transmission rate	32kbps
No of symbols in each packet	10000
Distance of TX and RX from the ocean bottom	35m
Distance between TX and RX	1500m
Depth of the water	1200m (approx.)
Sampling frequency	160KHz

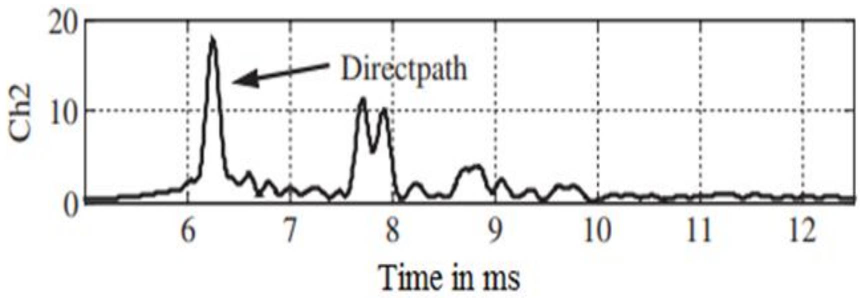


Fig 5.3 Channel Impulse response

The transmitted waveform will reach the receiver via multiple paths. Fig 5.3 demonstrates the impulse response of the acoustic channel categorised by a direct path and a multipath. This multipath propagation alongside with the low underwater sound propagation speed effects the large delay spread. Propagation time between the earliest and latest arrivals could have the duration from tens to hundreds of symbol periods, which decodes into long CIR and severe ISI at the receiver side. Though the experimentation team have considered 5 hydrophones at the receiver, here we consider the 2nd hydrophone which has both direct path and multipath CIR. Fig 5.3 shows a practical CIR estimate of the direct path and the multipath. The x axis represents time in ms while the y axis shows the autocorelated value of the chirp pulse. The CIR obtained by conducting the experiment is taken into account for equalization technique application.

To analyse the data that is received through these impulse pulses, ZF equalizer is used once the data is received. To recover the signal after passing through the channel, the inverse is applied to the received signal. The recovered data at the receiver is calculated as

$$x_{est} = H^{-1}y \tag{5.2}$$

$$\hat{x} = H^{-1}(Hx + n) \tag{5.3}$$

$$\hat{x} = x + H^{-1}n \tag{5.4}$$

Here *x* is the transmitted data, *H* is the impulse response of the channel and *y* is the received data. The term Zero Forcing resembles to bring the ISI to zero in a noise free case. However, this will be effective when ISI is significant compared to noise [130] . Finally, to get the BER, the input data needs to match with the output data.

The CIR (Fig 5.3) that is derived from the experiment is considered for the equalization technique. The sampled data is considered as the channel response and at the receiver the data is collected. At the transmitter 16-QAM is used. Errors are caused due to ISI and multipath in UWAC. ZF Equalizer multiplies the noise term by applying the inverse of the channel [131]. So the ZF Equalizer is applied to the data received from the impulse response and a SNR to BER curve is as shown below.

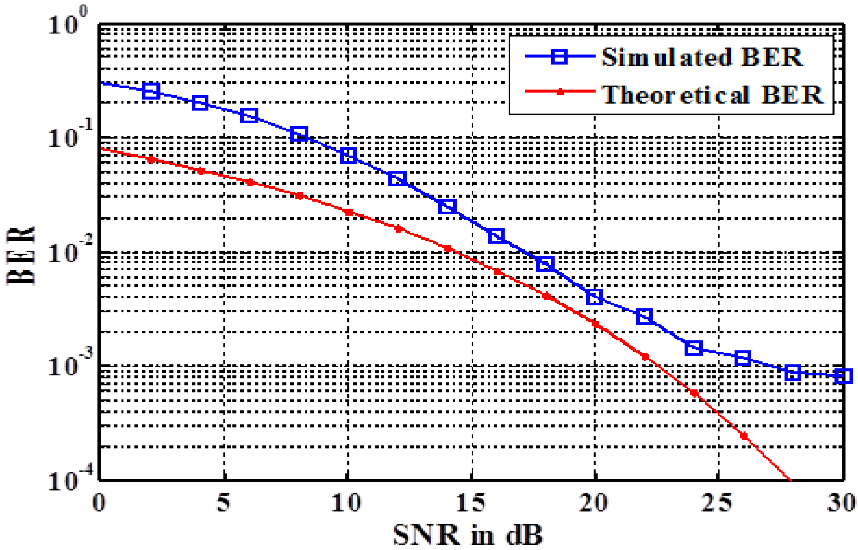


Fig 5.4 SNR vs. BER for ZF Equalization in UWAC

Fig 5.4 shows the SNR to BER curve for ZF equalization of both theoretical and practically calculated values. The theoretical data is taken from the general BER equation while the practical data is taken from the CIR data and the data received is given the ZF Equalization. We observe that there is only slight difference between the theoretical and practical value. This difference is caused by the enhancement of the noise after the application of ZF equalizer. However, it is impossible for a real time experimentation data to exactly match with the theoretical results because of the ocean environment.

5.4 SUMMARY

ZF Equalizer is applied to the CIR data taken from JAMSTEC experimentation on UWAC. The experimentation is carried out in deep sea where the TX and the RX are separated by 1500m. After the application of equalization technique to reduce the effect of ISI, it is observed that the theoretical and practical data almost follow the same path. However, a slight deviation is observed because of the enhancement of noise in ZF Equalization which is its drawback.

B.Pranitha, L.Anjaneyulu, “Channel Impulse Response Evaluation For UWAC With ZF Equalızer”, JESTR (Under Review)

CHAPTER 6

CONCLUSIONS AND FUTURE SCOPE

6.1 CONCLUSIONS

In this research work, various equalization and coding techniques are applied to UWAC system that helped in improving the performance of the system. Various losses in this channel such as absorption and spherical loss, and ambient noise that comprises of noise that is caused due to shipping, waves, turbulence and thermal noise are considered. Key parameters that effect the performance of the system such as temperature, salinity, pressure, Doppler Effect, carrier frequency, relative speed between the transmitter and receiver are also taken into account. BER vs. SNR is used as the figure of merit to specify the system performance.

Studies have been made on various important modulation techniques such as BPSK, QPSK, and 4-QAM for UWAC. It is clear that the scattering effects and the multipath along with the ambient noise underwater affect the performance of the UWAC system. ZF and MMSE equalization methods are used at the receiver to overcome these effects. ZF comes at the cost of escalation of noise but MMSE decreases all noise levels.

In UWAC where bandwidth efficiency is one of the problems can be improved by using OFDM. This technique is used in UWAC because of its advantages such as its effective way in dealing with the multipath propagation delay and high bitrate underwater communications. Also, the main disadvantages in UWAC such as ISI and IChI can be reduced by using OFDM. Applying diversity techniques will additionally increase the performance of UWAC against the fading channel deficiencies. Effects of multipath fading can be overcome by using spatial diversity technique UWAC. Spatial diversity with MRC is found to be a good method to improve the error performance. As we increase the number of receiving antennas in this diversity technique at the receiver side the performance further increases. Linear block codes are used to increase the performance along with the increase in transmitter power. This cannot be achieved without considering any of the error correction schemes. Various FEC are used such as (7, 4) Hamming Coding scheme is a method to improve BER in UWAC. Another coding technique LDPC linear code is also applied. It is found that LDPC outperforms Hamming code in UWAC.

The orthogonality of OFDM is generally destroyed by the Doppler Effect in UWAC which in turn is the result of ICI. To overcome this FBMC technique is used which is another multicarrier modulation technique. So a comparison is made between OFDM and FBMC techniques by considering the losses and noise effects in UWAC. It is observed that FBMC reduces ICI and performs better than OFDM modulation. In SNR we find that there is nearly a 3 dB change between OFDM and FBMC. The disadvantages of OFDM namely less spectral efficiency and harsh synchronization necessities can be compressed by using FBMC technique. FBMC has the advantage of being sensitive to Doppler Effect. The FBMC technique reduces the restrictions in OFDM by including basic pulse-shaping filters which distributes a well-restricted sub channel both in time and frequency domain. These prototype filters in FBMC reduces ICI and ISI when compared to OFDM.

MIMO is considered in UWAC to increase the data rate in undersea channel. The accomplishment of a MIMO in UWAC System highlighting both LOS, i.e. the Rician fading and NLOS, i.e. the Rayleigh fading signal propagation, is assessed. SM technique is used, which helps in increasing the data rate in UWAC. It controls the spatial distribution of the energy caused by a signal in such a way that the single ocean channel sustains multiple parallel communication channels. The utilization of ZF equalizer, which estimates the transmitted data, proves the success of removing ISI. Matlab simulations are done for the UWAC system for values of LOS/NLOS. Because of various scattering effects in NLOS propagation, the error rate is considerably high when compared to that of the LOS propagation. BER values for the corresponding SNR are calculated. Simulation results prove that the LOS component of UWAC outperforms the NLOS component. All the scattering effects of the undersea channel characteristics are considered in this work. Moreover, in LOS propagation, the performance on varying distances is calculated. Results have been presented for various states of the QAM modulation scheme and also for different carrier frequencies. The shallow water acoustic channel is highly time-varying and does not assuredly follow a Rayleigh distribution.

And so we consider the Rician fading individually as a 2×2 MIMO. ZF and LMS equalizers are used to evaluate the transmitted data. BER vs. SNR of UWAC with ZF equalizer with constant and variable distances are determined. Simulation results have verified that the system performs better with ZF equalizer than LMS till $20dB$ SNR. Noise factor is enhanced along with SNR consequently decreasing the performance of the ZF equalizer declines when compared to LMS equalization technique.

The utilization of ZF and VBLAST equalizers that estimates the transmitted data also proved a success of removing ISI. VBLAST method helps to overcome multipath. This can be done by using the scattering features of the propagation environment which helps to boost up the transmission accuracy by treating the diversity of scattering paths as distinct parallel sub-channels. The ISI caused by multipath effect and scattering in UWAC can be decreased by iterative process well-thought-out in VBLAST. A study on distance between the TX and the RX and the Doppler Effect and its impact on the performance of the system is made**.**

The CIR that is taken from a practical deep sea trial is considered. Both the transmitter and receiver are placed at 35m above the surface of the sea. They are separated by 1500m distance. 16 QAM modulation is used because of its efficiency in bandwidth in UWAC. The CIR data considered is sampled and the data is received. To reduce the effects of noise in the receiver and also the ISI, ZF equalization technique is used. Both theoretical and practical values of ZF equalizer are compared. After the application of equalization technique to reduce the effect of ISI, it is observed that the theoretical and practical data only have a slight deviation. This is because of the enhancement of noise in ZF Equalization which is its drawback. However, this enhancement of the noise is observed only after higher value of SNR.

6.2 FUTURE SCOPE OF THE INVESTIGATION

Eventual goals of the future generation UWAC systems are high data rate, performance and best utilization of the bandwidth. There is still a very high scope for this work as much of the ocean bottom is unknown. Also oceanic archaeology needs to find its application of modulation technique in UWAC.

Advances in UWAC are slow because of expensive experimentation setup and the lack of standards. Cost effective methods have to be worked out on for the experiments to be carried in large measure.

Equalization and coding methods that can be improved for higher distance and high signal power transmission are to be examined in advance.

Application of FBMC for MIMO UWA channels is still to be explored. Additional coding and estimation techniques are to be investigated at the receiver with FBMC to match with the present OFDM UWA transceivers.

Many other equalization techniques, which further improve the performance of the underwater system, have to be implemented in this realistic channel, which considers absorption and spherical coefficients. Advanced effort can be done in view of the AOA and AOD if the transmitters and receivers are not in parallel planes. We may get better performance with the increased number of receivers in the VBLAST system instead of an equal number of transmitters and receivers.

In the future, we aim to develop robust long-range communication in the deep sea with higher data rates based on the proposed modem hardware. Real-time detection of undersea environments has to be studied further. Also, MIMO systems that handle more than two transmitters are to be investigated.

References

[1] W. A. Martins, F. M. Costa, and J. N. Gois, “A Survey of Underwater Wireless Communication Technologies,” *J. Commun. Inf. Syst.*, vol. 31, no. January, pp. 242–255, 2016.

[2] J. Diogo and M. Xavier, “Modulation Analysis for an Underwater Communication Channel,” 2012

[3] J. Shu-yao, Y. Fei, C. Ke-yu, C. En, and A. L. Equation, “Application of Stochastic Resonance Technology in Underwater Acoustic Weak Signal Detection,” *IEEE*, no. 2, pp. 2–6, 2016.

[4] M. Chitre, S. Shahabudeen, L. Freitag, and M. Stojanovic, “Recent Advances in Underwater Acoustic Communications and Networking,” in *Oceans 2008*, 2008.

[5] P. Kumar, V. K. Trivedi, and P. Kumar, “Recent trends in multicarrier underwater acoustic communications,” *2015 IEEE Underw. Technol. UT 2015*, 2015.

[6] D. Wen, W. Cai, and Y. Pan, “Design of underwater optical communication system,” *Ocean. 2016 - Shanghai*, pp. 1–4, 2016.

[7] C. M. G. Gussen, P. S. R. Diniz, M. L. R. Campos, W. A. Martins, F. M. Costa, and J. N. Gois, “A Survey of Underwater Wireless Communication Technologies,” vol. 31, no. 1, pp. 242–255, 2016.

[8] H. M. Roudsari, J. F. Bousquet, and G. McIntyre, “Channel model for wideband time-varying underwater acoustic systems,” *Ocean. 2017 - Aberdeen*, vol. 2017-Octob, pp. 1–7, 2017.

[9] Akyildiz, I., P. Wang and Zhi Sun. “Realizing underwater communication through magnetic induction.” IEEE Communications Magazine 53 (2015): 42-48.

[10] Y. Y. Al-aboosi, M. S. Ahmed, N. Shahida, M. Shah, N. Hisham, and H. Khamis, “Study Of Absorption Loss Effects On Acoustic Wave Propagation In Shallow Water Using Different,” vol. 12, no. 22, pp. 6474–6478, 2017.

[11] B. Kelley and K. Naishadham, “RF multicarrier signaling and antenna systems for low SNR broadband underwater communications,” *IEEE Radio Wirel. Symp. RWS*, pp. 340–342, 2013.

[12] Y. Bai and P. J. Bouvet, “Orthogonal chirp division multiplexing for underwater acoustic communication,” *Sensors (Switzerland)*, vol. 18, no. 11, pp. 1–13, 2018.

[13] L. Wan, “Underwater Acoustic OFDM : Algorithm Design , DSP Implementation , and Field Performance,” 2014.

[14] Manjiti and Ravikant Kaushik, “MIMO-OFDM and IDMA Scheme in Underwater Communication,” *Ijitr*, vol. 4, no. 3, pp. 2971–2976, 2016.

[15] P. Kumar and P. Kumar, “DCT Based OFDM for Underwater Acoustic Communication,” in *2012 1st International Conference on Recent Advances in Information Technology (RAIT)*, 2012, pp. 170–176.

[16] S. Mine, “Performance analysis of zero forcing and minimum mean square error equalizers on multiple input multiple output system on a spinning vehicle,” 2014.

[17] S. Roy, T. M. Duman, V. McDonald, and J. G. Proakis, “High-rate communication for underwater acoustic channels using multiple transmitters and space - Time coding: Receiver structures and experimental results,” *IEEE J. Ocean. Eng.*, vol. 32, no. 3, pp. 663–688, 2007.

[18] Milica Stojanovic, “Underwater Acoustic Communication,” *Encycl. Electr. Electron. Eng.*, pp. 1–30.

[19] M. Stojanovic and J. Preisig, “Underwater Acoustic Communication Channels: Propagation Models and Statistical Characterization,” *IEEE Commun. Mag.*, vol. 47, no. 1, pp. 84–89, 2009.

[20] K. Chithra *et al.*, “Underwater communication implementation with OFDM,” *Indian J. Geo-Marine Sci.*, vol. 44, no. 2, pp. 259–266, 2015.

[21] H. D. Trung and N. Van Duc, “An analysis of MIMO-OFDM for underwater communications,” *Int. Congr. Ultra Mod. Telecommun. Control Syst. Work.*, 2011.

[22] M. Naderi, M. Patzold, and A. G. Zajic, “A geometry-based channel model for shallow underwater acoustic channels under rough surface and bottom scattering conditions,” *2014 IEEE 5th Int. Conf. Commun. Electron. IEEE ICCE 2014*, pp. 112–117, 2014.

[23] M. J. Bocus, A. Doufexi, and D. Agrafiotis, “Performance Evaluation of Filterbank Multicarrier Systems in an Underwater Acoustic Channel,” in *2016 IEEE 27th Annual IEEE*

International Symposium on Personal, Indoor and Mobile Radio Communications - (PIMRC): Fundamentals and PHY, 2016.

[24] S. Narayanan, M. J. Chaudhry, A. Stavridis, M. Di Renzo, F. Graziosi, and H. Haas, “Multi-user spatial modulation MIMO,” *IEEE Wirel. Commun. Netw. Conf. WCNC*, vol. 1, no. 3, pp. 671–676, 2014.

[25] I. Nelson, K. S. Vishvaksenan, and V. Rajendran, “Performance of Turbo Coded MIMO-OFDM System for Underwater Communications,” in *International Conference on Communication and Signal Processing, April 3-5, 2014, India*, 2014, pp. 1735–1739.

[26] Etter, P.C. (2018). Underwater Acoustic Modeling and Simulation (5th ed.). CRC Press. https://doi.org/10.1201/9781315166346

[27] R. Khan, Q. Gang, A. Ismail, and K. Mehboob, “Investigation of Channel Modeling and Simulation of OFDM Based Communication Near Northern Regions of Arabian Sea,” *Res. J. Appl. Sci. Eng. Technol.*, vol. 5, no. 4, pp. 1169–1182, 2013.

[28] S. M. Santhanam, “Study and analysis of various Modulation Techniques for Underwater Communication,” no. June, 2017.

[29] A. Herald and V. C, “Comparison of Modulation Techniques for Underwater Optical Wireless Communication at Mallipattinam , Tamil Nadu,” *2016 Int. Conf. Emerg. Trends Eng. Technol. Sci.*, pp. 1–5, 2015.

[30] S. Sendra, J. Lloret, J. M. Jimenez, and K. Z. Ghafoor, “Underwater Ad Hoc Wireless Communication for Video Delivery,” *Wirel. Pers. Commun.*, vol. 96, no. 4, pp. 5123–5144, 2017.

[31] Y. Wang, H. Zhang, Z. Sang, L. Xu, C. Cao, and T. A. Gulliver, “Modulation Classification of Underwater Communication with Deep Learning Network,” *Hindawi*, vol. 2019, no. Dl, 2019.

[32] U. Katare, “Comparative Analysis of ZF and MMSE Receiver for Multicode MC-CDMA Downlink Channels,” vol. 3, no. 4, pp. 180–185, 2014.

[33] M. Divya, “Bit Error Rate Performance of BPSK Modulation and OFDM-BPSK with Rayleigh Multipath Channel,” no. 4, pp. 623–626, 2013.

[34] “UWA Communication using MIMO OFDM 1,” vol. 10, no. 3, pp. 346–352, 2017.

[35] J. Lloret, S. Sendra, M. Ardid, and J. J. P. C. Rodrigues, “Underwater wireless sensor communications in the 2.4 GHz ISM frequency band,” *Sensors*, vol. 12, no. 4, pp. 4237–4264, 2012.

[36] H. C. Song and W. S. Hodgkiss, “Efficient use of bandwidth for underwater acoustic communication,” *J. Acoust. Soc. Am.*, vol. 134, no. 2, pp. 905–908, 2013.

[37] B. Priyalakshmi and K. Mahalakshmi, “Analysis of suitable modulation techniques for underwater wireless optical communication,” *J. Adv. Res. Dyn. Control Syst.*, vol. 10, no. 13, pp. 2538–2544, 2018.

[38] Version 2, ECE IIT Kharagpur, Lesson 27, Performance of BPSK and QPSK in AWGN Channel *Module 5, Carrier Modulation, Lecture Notes.*

[39] N. Voudoukis, “Performance Analysis, Characteristics, and Simulation of Digital QAM,” *Eur. J. Electr. Eng. Comput. Sci.*, vol. 1, no. 1, 2017.

[40] K. Krishnan, S. Gauni, C. T. Manimegalai, and V. Malsawmdawngliana, “Ambient noise analysis in underwater wireless communication using laser diode,” *Opt. Laser Technol.*, vol. 114, no. February, pp. 135–139, 2019.

[41] C. Polprasert, J. A. Ritcey, and M. Stojanovic, “Capacity of OFDM Systems Over Fading Underwater Acoustic Channels,” vol. 36, no. 4, pp. 514–524, 2011.

[42] K. Saraswathi, K. A. Netravathi, and S. Ravishankar, “A Study on channel modeling of underwater acoustic communication,” vol. 3, no. 1, pp. 143–147, 2014.

[43] A. C. Singer, J. K. Nelson, and S. S. Kozat, “Signal Processing for Underwater Acoustic Communications,” *IEEE Commun. Mag.*, vol. 47, no. 1, pp. 90–96, 2009.

[44] J. Diogo and M. Xavier, “Modulation Analysis for an Underwater Communication Channel,” no. October, 2012.

[45] A. Sehgal, D. Cernea, and A. Birk, “Modeling Underwater Acoustic Communications for Multi-Robot Missions in a Robotics Simulator,” *Ocean. IEEE SYDNEY*, pp. 1–6.

[46] J. Poncela, M. C. Aguayo, and P. Otero, “Wireless underwater communications,” *Wirel. Pers. Commun.*, vol. 64, no. 3, pp. 547–560, 2012.

[47] Y. Kularia, S. Kohli, and P. P. Bhattacharya, “Analysis of Acoustic Channel Characteristics for Underwater Wireless Sensor Networks,” *Int. J. Comput. Sci. Inf. Technol. Control Eng.*,

vol. 3, no. 12, pp. 11–24, 2016.

[48] A. Kulkarni and K. Kosbar, “Performance analysis of zero forcing and minimum mean square error equalizers on multiple input multiple output system on a spinning vehicle,” *Proc. Int. Telemetering Conf.*, vol. 50, pp. 457–466, 2014.

[49] M. Stojanovic, “On the Relationship Between Capacity and Distance in an Underwater Acoustic Communication Channel ∗,” 2007.

[50] F. C. Vilar, “IMPLEMENTATION OF ZERO FORCING AND MMSE EQUALIZATION TECHNIQUES IN OFDM,” 2014.

[51] L. Sun, M. Wang, G. Zhang, H. Li, and L. Huang, “Filtered Multitone Modulation Underwater Acoustic Communications Using Low-Complexity Channel-Estimation-Based MMSE Turbo Equalization,” *MDPI*, vol. 19, pp. 1–19, 2019.

[52] N. S. Kumar and K. R. S. Kumar, “Performance Analysis And Comparison Of M X N Zero Forcing And MMSE Equalizer Based Receiver For Mimo Wireless Channel,” vol. 33, no. 3, pp. 335–340, 2011.

[53] A. Kulkarni, “Performance Analysis Of Zero Forcing And Minimum Mean Square Error Equalizers On Multiple Input Multiple Output System On A Spinning Vehicle,” 2014.

[54] V. M. Pinho, R. S. Chaves, and M. L. R. Campos, “On Equalization Performance in Underwater Acoustic Communication,” no. July, 2018.

[55] D. R, M. Panicker, H. S, and H. Muhammed, “Reliable Approaches for OFDM Based UWAC,” *Ijirst.Org*, vol. 3, no. 10, pp. 128–134, 2017.

[56] W. Duan and Y. R. Zheng, “Experimental Evaluation of Turbo Receivers in Single-Input Single-Output Underwater Acoustic Channels,” pp. 1–6, 2016.

[57] P. Kumar and P. Kumar, “Performance evaluation of DFT-spread OFDM and DCT-spread OFDM for underwater acoustic communication,” *IEEE Veh. Technol. Conf.*, pp. 0–4, 2012.

[58] S. Mahajan, P. Kumar, N. Mahajan, and A. Suman, “Reduction of Peak to Average Power Ratio and Bit Error Rate Ratio in OWDM and OFDM,” *Int. J. Eng. Res. Technol.*, vol. 3, no. 2, pp. 123–125, 2014.

[59] M. Bhardwaj, “A Review on OFDM: Concept, Scope & its Applications,” *IOSR J. Mech. Civ. Eng.*, vol. 1, no. 1, pp. 07–11, 2012.

[60] R. F. Ormondroyd, “A robust underwater acoustic communication system using OFDM-MIMO,” *Ocean. 2007 - Eur.*, pp. 1–6, 2007.

[61] T. Strohmer and S. Beaver, “Optimal OFDM design for time-frequency dispersive channels,” *IEEE Trans. Commun.*, vol. 51, no. 7, pp. 1111–1122, 2003.

[62] Z. Wang *et al.*, “Frequency-Domain Oversampling for Zero-Padded OFDM in Underwater Acoustic Communications,” *IEEE J. Ocean. Eng.*, vol. 37, no. 1, pp. 14–24, 2011.

[63] J. Han, S. Kim, K. Kim, S. Chun, and K. Son, “Design of OFDM System for High Speed Underwater Communication,” in *2009 International Conference on Computational Science and Engineering*, 2009, pp. 988–992.

[64] A. Aminjavaheri, A. Farhang, A. Rezazadehreyhani, L. E. Doyle, and B. Farhang-boroujeny, “OFDM without CP in Massive MIMO,” vol. 2, pp. 1–14.

[65] T. M. Schmidl and D. C. Cox, “Robust Frequency and Timing Synchronization for OFDM,” *IEEE Trans. Commun.*, vol. 45, no. 12, pp. 1613–1621, 1997.

[66] J. Huang, S. Zhou, and P. Willett, “Nonbinary LDPC Coding for Multicarrier Underwater Acoustic Communication,” vol. 26, no. 9, pp. 1684–1696, 2008.

[67] H. Esmaiel and D. Jiang, “Review Article: Multicarrier Communication for Underwater Acoustic Channel,” *Int. J. Commun. Netw. Syst. Sci.*, vol. 06, no. 08, pp. 361–376, 2013.

[68] R. Khan, Q. Gang, A. Ismail, and K. Mehboob, “Investigation of Channel Modeling and Simulation of OFDM Based Communication Near Northern Regions of Arabian Sea,” *Res. J. Appl. Sci. Eng. Technol.*, vol. 5, no. 4, pp. 1169–1182, 2013.

[69] Y. hai Zhou, F. Tong, and G. qiang Zhang, “Distributed Compressed Sensing Estimation Of Underwater Acoustic OFDM Channel,” *Appl. Acoust.*, vol. 117, pp. 160–166, 2017.

[70] F. De Rango, F. Veltri, and P. Fazio, “A Multipath Fading Channel Model For Underwater Shallow Acoustic Communications,” *IEEE Int. Conf. Commun.*, pp. 3811–3815, 2012.

[71] S. Afrasiabi-Gorgani, “An Introduction to OFDM-OQAM,” no. July, 2017.

[72] X. Huang, “Capacity Criterion-Based Power Loading For Underwater Acoustic OFDM System With Limited Feedback,” *Proc. - 2010 IEEE Int. Conf. Wirel. Commun. Netw. Inf. Secur. WCNIS 2010*, pp. 54–58, 2010.

[73] M. Stojanovic, “On The Relationship Between Capacity And Distance In An Underwater

Acoustic Communication Channel,” *ACM SIGMOBILE Mob. Comput. Commun. Rev.*, vol. 11, no. 4, p. 34, 2007.

[74] S. I. Siddiqui and H. Dong, “Blind Deconvolution Based Equalizer For Underwater Acoustic Communications,” *Appl. Acoust.*, vol. 149, pp. 114–122, 2019.

[75] M. Chitre, S. Shahabudeen, and M. Stojanovic, “Underwater Acoustic Communications and Networking: Recent Advances and Future Challenges,” *Mar. Technol. Soc. J.*, vol. 42, no. 1, pp. 103–116, 2015.

[76] G. Qiao, Z. Babar, L. Ma, S. Liu, and J. Wu, “MIMO-OFDM Underwater Acoustic Communication Systems—A Review,” *Phys. Commun.*, vol. 23, pp. 56–64, 2017.

[77] S. K. Armin Dammann, “TransmitReceive-Antenna Diversity Techniques for OFDM Systems,” vol. 13, no. 5, pp. 531–538, 2002.

[78] C. Zhang, F. X. Ge, L. Dai, and H. L. Zhu, “MIMO Underwater Acoustic Communications By Using A Quasi-Orthogonal Group Space-Time Architecture,” *Int. Conf. Signal Process. Proceedings, ICSP*, pp. 483–486, 2017.

[79] R. Zakaria, “Transmitter And Receiver Design For Inherent Interference Cancellation In MIMO Filter-Bank Based Multicarrier Systems,” 2012.

[80] S. KumarChourasia and R. Pandey, “Extensive Survey on MIMO Technology using V-BLAST Detection Technique,” *Int. J. Comput. Appl.*, vol. 98, no. 5, pp. 38–42, 2014.

[81] D. Malik and D. Batra, “Comparison of Various Detection Algorithms In A MIMO Wireless Communication Receiver,” *Int. J. Electron. Comput. Sci. Eng.*, vol. 5, no. 6, pp. 1–8, 2012.

[82] J. Li, L. Liao, and Y. V. Zakharov, “Space-time cluster combining for UWA communications,” *Ocean. 2016 - Shanghai*, pp. 1–6, 2016.

[83] R. Ishimoto, S. Yoshizawa, H. Tanimoto, and T. Saito, “Evaluation Of Diversity Combining Methods For Underwater Acoustic OFDM Communication,” *2014 Int. Symp. Intell. Signal Process. Commun. Syst. ISPACS 2014*, pp. 13–16, 2014.

[84] J. Li and Y. V. Zakharov, “Efficient Use of Space-Time Clustering for Underwater Acoustic Communications,” *IEEE J. Ocean. Eng.*, pp. 1–11, 2017.

[85] A. J. Al-Askery, C. C. Tsimenidis, S. Boussakta, and J. A. Chambers, “Performance

Analysis Of Coded Massive MIMO-OFDM Systems Using Effective Matrix Inversion," *IEEE Trans. Commun.*, vol. 65, no. 12, pp. 5244–5256, 2017.

[86] Y. Labrador, M. Karimi, and D. Pan, "Modulation and Error Correction in the Underwater Acoustic Communication Channel," *IJCSNS Int. J. Comput. Sci. Netw. Secur.*, vol. 9, no. 7, pp. 123–130, 2009.

[87] J. Xu, T. Zhang, and Z. Dong, "On Forward Error Correction With Hamming Code For Multi-Path Communications," *2012 Int. Conf. Wirel. Commun. Signal Process. WCSP 2012*, pp. 1–5, 2012.

[88] S. Suganthi and S. Sathya, "Segment based Reliable Multipath Communication in Underwater Sensor Networks," *IJCSNS Int. J. Comput. Sci. Netw. Secur.*, vol. 15, no. 1, pp. 127–131, 2015.

[89] W. Han, J. Huang, and M. Jiang, "Performance Analysis Of Underwater Digital Speech Communication System Based On LDPC Codes," *2009 4th IEEE Conf. Ind. Electron. Appl. ICIEA 2009*, pp. 567–570, 2009.

[90] X. Xu, Y. Chen, L. Zhang, and W. Feng, "Comparison Of The Performance Of LDPC Codes Over Different Underwater Acoustic Channels," *Int. Conf. Commun. Technol. Proceedings, ICCT*, no. 3, pp. 155–158, 2010.

[91] S. Liu and A. Song, "Optimization of LDPC Codes over the Underwater Acoustic Channel," vol. 2016, 2016.

[92] L. Yuxiang, L. Guolong, Z. Guangpu, and F. Jin, "The Application Of LDPC Code In Underwater Acoustic Wireless Communications," *Proc. - 5th Int. Conf. Wirel. Commun. Netw. Mob. Comput. WiCOM 2009*, vol. 2, pp. 9–11, 2009.

[93] W. Khrouf, M. Siala, and F. Abdelkefi, "How Much FBMC / OQAM Is Better than FBMC / QAM ? A Tentative Response Using the POPS Paradigm," vol. 2018, 2018.

[94] N. Cassiau, D. Kténas, and J. Doré, "Time And Frequency Synchronization For Comp With FBMC," 2013.

[95] V. Mol, A. A. Zaidi, X. Chen, T. J. Oechtering, and R. Baldemair, "A Comparison of OFDM , QAM-FBMC , and OQAM-FBMC Waveforms Subject to Phase Noise," vol. 0, no. 3, 2017.

[96] L. Zhang, P. Xiao, A. Zafar, A. Ul Quddus, and R. Tafazolli, "FBMC System: An Insight Into Doubly Dispersive Channel Impact," *IEEE Trans. Veh. Technol.*, vol. 66, no. 5, pp. 3942–3956, 2017.

[97] S. Jo and J. S. Seo, "Tx Scenario Analysis Of FBMC Based LDM System," *ICT Express*, vol. 1, no. 3, pp. 138–142, 2015.

[98] X. He, Z. Zhao, and H. Zhang, "A Pilot-Aided Channel Estimation Method For FBMC / OQAM Communications System," no. 1, pp. 175–180, 2012.

[99] M. Bellanger, "FBMC Physical Layer: A Primer," *PHYDYAS, January*, pp. 1–31, 2010.

[100]P. Kansal and A. K. Shankhwar, "FBMC vs OFDM Waveform Contenders for 5G Wireless Communication System," *Wirel. Eng. Technol.*, vol. 8, pp. 59–70, 2017.

[101]B. Farhang-boroujeny, "Filter Bank Multicarrier Modulation : A Waveform Candidate for 5G and Beyond," vol. 2014, 2014.

[102]X. Han, J. Yin, B. Liu, and L. Guo, "MIMO Underwater Acoustic Communication in Shallow Water with Ice Cover," *China Ocean Eng.*, vol. 33, no. 2, pp. 237–244, 2019.

[103]Y. Goswami and D. K. K. Naik, "Comparative survey on Underwater and Terrestrial Communication Data rates," *Int. J. Comput. Math. Sci.*, vol. 7, no. 3, pp. 161–168, 2018.

[104] Y. Li, H. Qiu, X. Chen, J. Fu, M. Musa, and X. Li, "Spatial Correlation Analysis Of Imaging MIMO For Underwater Visible Light Communication," *Opt. Commun.*, vol. 443, no. February, pp. 221–229, 2019.

[105] C. R. Kumar and R. K. Jeyachitra, "Dual-Mode Generalized Spatial Modulation MIMO for Visible Light Communications," *IEEE Commun. Lett.*, vol. 22, no. 2, pp. 280–283, 2018.

[106] K. Sankhe, S. Chaudhari, and G. R. Murthy, "Distributed Spatial Modulation With Dynamic Frequency Allocation," *Phys. Commun.*, vol. 23, pp. 65–75, 2017.

[107] K. M. Humadi, A. I. Sulyman, and A. Alsanie, "Spatial Modulation Concept for Massive Multiuser MIMO Systems," vol. 2014, 2014.

[108] Q. Lu, X. Hu, D. Wang, and S. Zhou, "Parallel Combinatory Multicarrier Modulation In Underwater Acoustic Communications," vol. 11, pp. 1331–1337, 2017.

[109] W. Duan and Y. R. Zheng, "Soft Direct-Adaptive Turbo Equalization for MIMO Underwater Acoustic Communications," *MTS*, pp. 1–6, 2017.

[110] N. Kapucu, M. Bilim, and I. Develi, “Average Symbol Error Rate And Outage Probability Of DS-CDMA Systems With AF Relaying Over Asymmetric Fading Channels,” *Phys. Commun.*, vol. 23, pp. 76–83, 2017.

[111] K.Vidhya and K. S. Kumar, “Ber Performance of AWGN , Rayleigh and Rician Channel,” *IJARCCE*, vol. 2, no. 5, pp. 2058–2067, 2013.

[112] W. Duan and Y. R. Zheng, “Soft Direct-Adaptive Turbo Equalization for MIMO Underwater Acoustic Communications,” *Ocean. 2015 - MTS/IEEE Washingt.*, 2016.

[113] M. Stojanovic, L. Freitag, and M. Johnson, “Channel-Estimation-Based Adaptive Equalization Of Underwater Acoustic Signals,” *Ocean. Conf. Rec.*, vol. 2, no. 1, pp. 590–595, 1999.

[114] *Underwater Acoustic Digital Signal Processing and Communication Systems*. 2002.

[115] A. C. Singer, J. K. Nelson, S. S. Kozat, A. C.Singer, J. K. Nelson, and S. S.Kozat, “Signal Processing for Underwater Acoustic Communications,” *IEEE Commun. Mag.*, vol. 47, no. January, pp. 90–96, 2009.

[116] F. Tong, B. Benson, Y. Li, and R. Kastner, “Channel Equalization Based on Data Reuse LMS Algorithm for Shallow Water Acoustic Communication,” *2010 IEEE Int. Conf. Sens. Networks, Ubiquitous, Trust. Comput.*, pp. 95–98, 2010.

[117] Q. Meng, J. Huang, J. Han, C. He, and C. Ma, “An Improved Direct Adaptive Multichannel Turbo Equalization Scheme For Underwater Communications,” *Progr. B. - Ocean. 2012 MTS/IEEE Yeosu Living Ocean Coast - Divers. Resour. Sustain. Act.*, pp. 4–8, 2012.

[118] S. R. Patel, S. R. Panchal, and H. Mewada, “Comparative Study of LMS & RLS Algorithms for Adaptive Filter Design with FPGA,” *Prog. Sci. Eng. Res. J.*, vol. 02, no. Jan-Feb, pp. 185–192, 2014.

[119] Mohit Thakur, R.K., Walia, Harjit Singh, 2015. MIMO Technology using V-BLAST Equalization Techniques – Literature Survey. *International Journal of Advanced Research in Computer and Communication Engineering*, *4*(5).

[120] D. V. Ha, N. Van Duc, and M. Patzold, “SINR Analysis Of OFDM Systems Using A Geometry-Based Underwater Acoustic Channel Model,” *IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC*, vol. 2015-Decem, pp. 683–687, 2015.

[121] N. D. Gohar and Z. Rafique, "VBLAST : A Space-Division Multiplexing Technique Providing A Spectral Efficiency Necessary For High Data Rate Wireless Networks," pp. 238–248.

[122] P. K. Barmashe and P. R. Nema, "Performance Evaluation of VBLAST MIMO System using BPSK," vol. 1, no. 3, pp. 64–67.

[123] M. Caley and A. Duncan, "Multi-Path Doppler And Delay Spreading In A Shallow Marine Environment."

[124] Gunilla Burrowes and Jamil Y. Khan, "Short-Range Underwater Acoustic Communication Networks," *intech*, pp. 173–198, 2011.

[125] R. Mesleh and H. Haas, "Impact Of Channel Imperfections On Spatial Modulation OFDM," in *The 18th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'07)*, 2007.

[126] X. Zhang, X. Han, J. Yin, and X. L. Sheng, "Study On Doppler Effects Estimate In Underwater Acoustic Communication," *Proc. Meet. Acoust.*, vol. 19, no. 2013, pp. 1–7, 2013.

[127] I. P. A. I. Kusuma and M. Z. B. Margareta, "Analysis of Channels Impulse Response Due to Transducer Movements in Underwater Acoustic Communication," in *IOP Conference Series: Materials Science and Engineering*, 2019, vol. 462, no. 1.

[128] Z. George, "A Novel Matlab-Based Underwater Acoustic Channel Simulator," *J. Commun. Comput.*, vol. 10, pp. 1131–1138, 2013.

[129] H. Ochi, Y. Watanabe, and T. Shimura, "Experiments On Acoustic Communication With Quadrature Amplitude Modulation In Multipath Environment," *Japanese J. Appl. Physics, Part 1 Regul. Pap. Short Notes Rev. Pap.*, vol. 43, no. 5 B, pp. 3140–3145, 2004.

[130] F. C. Vilar, "Author : Ferran Conillera Vilar Implementation Of Zero Forcing And Mmse Equalization Techniques In," 2014.

[131] P. Sharma, "Performance Analysis of Zero-Forcing Equalizer for ISI Reduction In Wireless Channels," *Int. J. Eng. Res. …*, vol. 1, no. 8, pp. 1–6, 2012.

List of Publications out of Research Work

[1] B.Pranitha, Dr.L.Anjaneyulu, "Research Trends in Underwater Communications-A Technical Survey", Presented in IEEE International Conference on Communication and Signal Processing (ICCSP) held from 6 to 8 of April 2016 in Chennai, India, Published in IEEE Xplore, 978-1- 5090-0395-2/16/$31.00©2016 IEEE.

[2] B.Pranitha, Dr.L.Anjaneyulu, "Performance Evaluation of Underwater Communication System using Block codes", Presented in Fifth International Conference on Eco-Friendly Computing and th th Communication Systems (ICECCS 2016) held on 8 and 9 of December 2016, Published in IEEE Xplore, 978-1-5090-2541-1/16/$31.00©2016 IEEE.

[3] Pranitha, B., Le Minh, H., Aslam, N., Anjaneyulu, L. and Vangala, S., 2018, July. BER Performance Investigation of MIMO Underwater Acoustic Communications. In 2018 11th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP) (pp. 1-5). IEEE.

[4] Pranitha, B. and Anjaneyulu, L., 2016. BER Performance Evaluation of Underwater Communication System with Spatial Diversity. Indian Journal of Science and technology, Vol 9 (s1).

[5] Pranitha, B. and Anjaneyulu, L., 2019. Assessment of UWAC System Performance Using FBMC Technique. In Recent Trends in Signal and Image Processing (pp. 53-62). Springer, Singapore.

[6] Pranitha, B. and Anjaneyulu, L., 2020. Analysis of Underwater Acoustic Communication System Using Equalization Technique for ISI Reduction. Procedia Computer Science, 167, pp.1128-1138.

[7] Boddu, P., Anjaneyulu, L., Le Minh, H., Aslam, N. and Kumar, S.V., 2020. Investigation of VBLAST Equalization Technique for Underwater Acoustic Communications. International Journal of Electronics and Telecommunications, 66(2), pp.331-337.

[8] Pranitha, B. and Anjaneyulu, L., 2019. Performance Evaluation of a MIMO based Underwater Communication System under Fading Conditions. Eng. Technol. Appl. Sci. Res, 9(6), pp.4886-4892.

[9] B.Pranitha, L.Anjaneyulu, "Channel Impulse Response Evaluation For UWAC With ZF Equalızer, JESTR(Under Review)

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