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FACULTY OF ELECTRICAL ENGINEERING

DEPARTMENT OF APPLIED ELECTRONICS AND TELECOMMUNICATION

BACHELOR THESIS

Modern Modulation Methods for Underwater Communication

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Thesis Declaration

I certify that this work which is being submitted as a Bachelor Thesis to the Faculty of Electrical Engineering at West Bohemia University in Pilsen is my own work, and the sources of information have been acknowledged. The work was done under the guidance of Ing. Richard Linhart. It is understood that West Bohemia University in Pilsen can use my work under the conditions of § 60 Law č. 121/2000.

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(Date) (Author's Signature)

Abstract

Orthogonal Frequency Division Multiplexing (OFDM) is being considered for communication over wireless (acoustic) underwater channels.

This paper is a study about OFDM modulation for underwater communication system. Study of the theory of OFDM modulation is explained, and a basic simulation was made for the modulator and demodulator structure in MATLAB environment as a study experiment for modern modulation method for underwater communication systems. The symbol-error-ratio (SER) is considered as the main parameter. The simulation is performed as an SNR (signal-to-noise-ratio) versus SER comparison for transmission and reception of modulated signals. OFDM block size is changed in the simulation later to realize the behavior for transmission and reception of modulated signals and to find out how error rate changes based on the size of OFDM block size.

Acknowledgments

I am very grateful to all my teachers at University of West Bohemia in Pilsen, who have taught me the skills for this work. I am very thankful to my guide, Ing. Richart Linhart, who has been very cooperative and understanding. And, I would like to thank the authors who write nice scientific books and articles which are a source of knowledge for many people.

Contents

Introduction

The technique of sending and receiving message below water is called underwater acoustic communication [1]. There are various methods to do underwater acoustic communication. The interest in study and experimental deployment of underwater networks has been growing. [2] In the 4th Generation System, the transmission schemes are based on Orthogonal Frequency Division Multiplexing (OFDM) [3]. The idea behind OFDM modulation is to send the data over different sub-channels which are orthogonal to each other.

The description is divided into three parts in this thesis. First part is the background of underwater communication, best options for underwater communication and reasons of underwater channel as most challenging channels. The second part is the OFDM implementation with basic principle of OFDM. The third part presents the results and discussion regarding the simulation in MATLAB with conclusion.

1
Background - Underwater Communication

There are several ways of sending and receiving message for underwater communication technique and wireless underwater communication is one of them. But what is the best solution for underwater communication? What are the most challenging channels for underwater communication? In this part, we will look for the answers of these questions.

1.1 What is Best Option for Underwater Communication?

For wireless underwater communication, there are several means such as radio waves, optical waves and acoustics.

Radio waves: The only waves, which can propagate any distance in sea water, are radio waves of extra low frequency (30 Hz–300 Hz). However, such low frequencies require high transmission power and large antennas.

Optical waves: There is not too much suffer for attenuation, however when scattered, optical waves are remarkably influenced and because of this reason what can propagate in water is only lasers of extreme intensity.

Acoustics: For wireless underwater communication, it can be said that acoustics is the best key solution. [4]

Having said, underwater acoustic communication is a technique of sending and receiving message below water [1]. To do such communication, there are several ways. Because of factors like time variations of the channel, available bandwidth (small), signal attenuation (strong), multi path propagation, under water communication is difficult – especially for long distances. [4]

In other words, because of accentuated Doppler effect, distance dependent bandwidth, common background noise and frequency dependent attenuation, it can be said that these are the reasons of which makes the underwater channel one of the most challenging channels.

1.2 Reasons of Underwater Channel as Most Challenging Channels

Because of the reasons (such as accentuated Doppler effect, distance dependent bandwidth, common background noise and frequency dependent attenuation) which will be described briefly below, it can be said that these are the reasons of which makes the underwater channel one of the most challenging channels. [4]

Attenuation of Acoustic Propagation

The transmitted signal's energy is not completely transferred to the side of the receiver. For instance, some part of the energy is transferred to heat energy. It can be said that some of the transmitted energy reaches the other sides, not all transmitted energy reaches the receiver.

As seen in the below equation 1, the attenuation in an underwater acoustic channel is described as [5];

$$A(l,f) = A_o l^k a(f)^l \tag{1}$$

In this equation;

- *A* is attenuation, which measures of the energy loss of sound propagation in media
- *l* is distance, *k* is the spreading factor (geometry of propagation),
- *f* is frequency, is the number of occurrences of a repeating event per unit time

- *a(f)* is the absorption coefficient, which determines how far into a material light of a particular wavelength can penetrate before it is absorbed. The major factor which can limit an underwater system's maximal usable frequency is also called the absorption coefficient. [6]

Multipath of Acoustic Propagation

In communications through underwater acoustic links, one of the problems which is very common is the multipath propagation. Reflection or refraction of the acoustic waves can cause underwater multipath.

Propagation Delay of Acoustic Propagation

When comparing the delays in an underwater acoustic communication to open-air, it is known that the delay in an underwater acoustic communication is much higher than open-air. This situation results long propagation delays and then it is needed to correct for the channel distortions. [4]

Doppler Effect of Acoustic Propagation

When transmitter and receiver motions relatively, it causes Doppler effect. The Doppler effect causes a shift in the transmitted signal's frequency. When source speed and the receiver to the medium are lower than the velocity of waves in the medium, the equation 2 can be given as [7];

$$f = (\frac{C+ vr}{C+ vs}) + fo \tag{2}$$

In this equation;

$\boldsymbol{\upsilon_s}$ is the velocity of the source relative to the medium,

$\boldsymbol{\upsilon_r}$ is the velocity of the receiver relative to the medium,

c is the velocity of waves in the medium (the speed of sound underwater)

$\boldsymbol{\upsilon_{r/C}}$ is the frequency shift

2
The OFDM Implementation

In this section, the system implementation has been discussed. The transmitter set-up is explained in detail followed by the receiver algorithms.

2.1 OFDM (Orthogonal Frequency Division Multiplexing) Principle with Basics

OFDM is a modulation technique that splits a wide-band into several orthogonal narrow sub-bands. OFDM modulation sends the data over different sub-channels which are orthogonal to each other. Each sub-channel has a bandwidth less than the coherence bandwidth of the channel which is called flat-fading channel.

With frequency-selective distortion, multi-carrier modulation is a good alternative to single-carrier broadband modulation on channels. During past several years, different type of bandwidth-efficient modulation and detection method has used for underwater acoustic communications. Instead of single carriers, multiple carriers are used. In short, this method is named as Orthogonal Frequency Division Multiplexing (OFDM) [6] [8].

2.1.1 Signal Representation in OFDM

Data is carried on narrow-band sub-carriers in frequency domain in an OFDM modulation. The input data stream is modulated by the modulator. Assume that, the modulated complex data stream is:

$$U(0), U(1), ...U(N-1)$$

where "*N*" is the number of sub-carriers. Each sub-stream passed through S/P converter (i.e. serial-to-parallel) and was transformed into time-domain using IFFT (Inverse Fast Fourier Transform) at the transmitter. The signal after IFFT can be expressed as:

$$u(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} U(k) e^{j2\pi kn/N}, \qquad \{ where, \qquad n = [0, N-1] \tag{3}$$

Each sub-carrier should be orthogonal to the other sub-carriers. The condition for the orthogonality of "*i*th" sub-carrier is shown in the equation (4):

$$\frac{1}{T} \int_0^T U(k) e^{j2\pi (f^{i} f_j) t}\, dt \qquad = \qquad \{ \quad 1, i = j \,; \qquad 0, i \neq j \tag{4}$$

2.1.2 Modulation Using Fast Fourier Transform (FFT)

As OFDM subcarriers' orthogonality expressed, the modulator and demodulator can be implemented. For this case, the FFT algorithm is used on the receiver side and the inverse FFT (IFFT) is used on the transmitter side.

The equation (5) on the transmitter side can be represented as;

$$u(l) = \frac{1}{K} \sum_{k=1}^{K-1} U(k) e^{j2\pi kl/K}, \qquad l = 0, \ldots . K - 1 \tag{5}$$

u(l) is the resulting sampled signal,

k is the frequency component index,

K is the number of frequency components, In order to gain the digital frequency components, inverse equation (6) can be expressed as [9][10];

$$U(k) = \frac{1}{K}\sum_{l=0}^{K-1} u(l)e^{-j2\pi kl/K}, \qquad k = 0, \dots . K-1 \tag{6}$$

2.1.3 The Advantages and Disadvantages of OFDM Modulation

There are advantages and disadvantages of OFDM modulation techniques in wireless systems. Enabling channel equalization in the frequency domain and eliminating the need for potentially complex time-domain equalizers can be counted as the main advantage of OFDM.

In addition to that, high spectral efficiency, robustness against inter-symbol interference and fading caused by the multipath channel, efficient implementation using the FFT - avoiding the need for complex sub-channel filters.

Easy equalization in the frequency domain, simple and effective channel equalization in the frequency domain are the advantages OFDM modulation techniques in wireless systems.

The main disadvantage of OFDM in wireless systems is the sensitivity of the signal to frequency offsets. This causes several synchronization requirements.

The other disadvantages are High Peak to Average Ratio (PAR), with a subsequent difficulty to optimize the transmission power and sensitivity to frequency offsets can be mentioned. [4] [9] [10]

2.2 OFDM Transmitter

As shown in Figure 1 (OFDM Transmitter Block Diagram), the most important parts of the transmitter include the symbol mapping and IFFT.

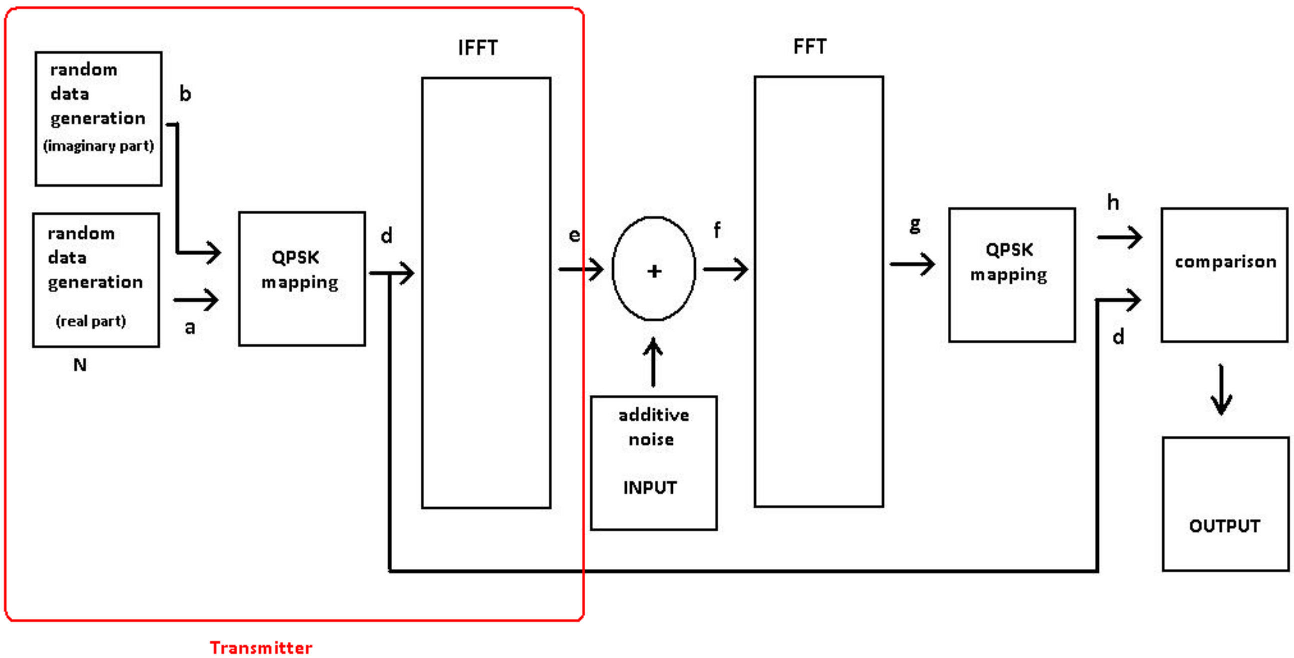

Figure 1: OFDM Transmitter Block Diagram

2.2.1 Random Data Generator

Random data generator is used to generate a serial random data .This data stream models the raw information that going to be transmitted. The serial data is then fed into OFDM transmitter.

2.2.2 Data to symbol Mapper:

This block does modulation of QPSK. The data on each symbol is mapped based on the modulation method used.

2.2.3 Channel model:

Additive white Gaussian Noise (AWGN) is a channel model in which the only impairment to communication is a linear addition of wideband or white noise with a constant spectral density (expressed as watts par hertz of bandwidth) and a Gaussian distribution of amplitude. The model does not account for fading, frequency, selectivity, interference, nonlinearity or dispersion. However, it produces simple and tractable mathematical models which are useful for gaining insight into the underlying behavior of a system before these other phenomena are considered. Wideband Gaussian noise comes from many natural sources, such as the thermal vibrations of atoms in conductors, shot noise, black body radiation from the earth and other warm objects and from celestial sources such as the sun. [11]

2.2.4 Transmitter Implementation

The transmitter implementation is discussed in this section with symbol mapping and noise model.

Symbol Mapping:

Phase shift keying is a digital modulation scheme. It is a suitable modulation and also it conveys data by changing, or modulating, the phase of a reference signal (the carrier wave). Quadrature Phase Shift Keying (QPSK) can be used in particular. To give a brief idea, QPSK uses four points on the constellation diagram that equispaced around a circle. The constellation of a QPSK signal can be seen in the Figure (2) below: [12] [10] [13]

The scaling factor of $\sqrt{E_S/2}$ is for normalizing the average energy of the transmitted symbols to 1, assuming that all the constellation points are equally likely.

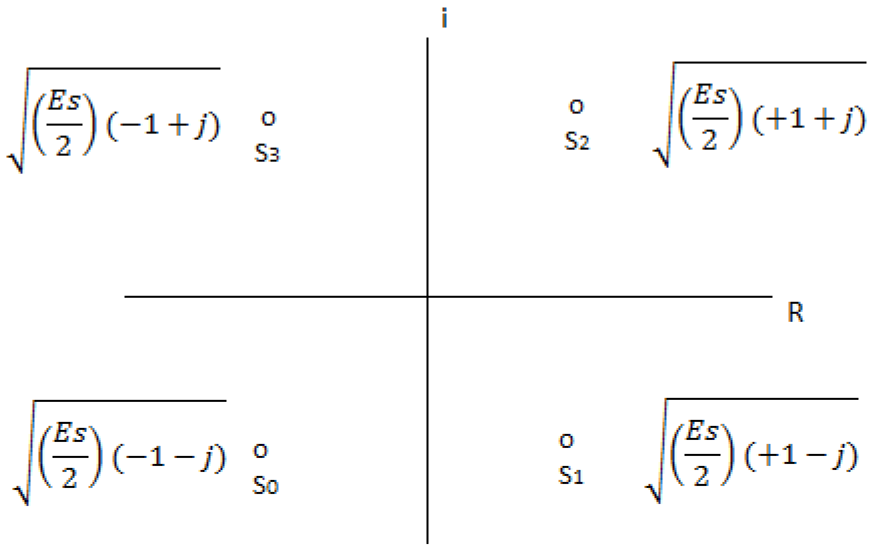

Figure 2: Constellation plot for QPSK (4-QAM) constellation [14]

Noise model: Assuming that the additive noise n follows the Gaussian probability distribution function; [15]

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(x-\mu)^2/2\pi\sigma^2} \quad with \;\; \mu = 0, and\ \sigma^2 = N_0/2$$

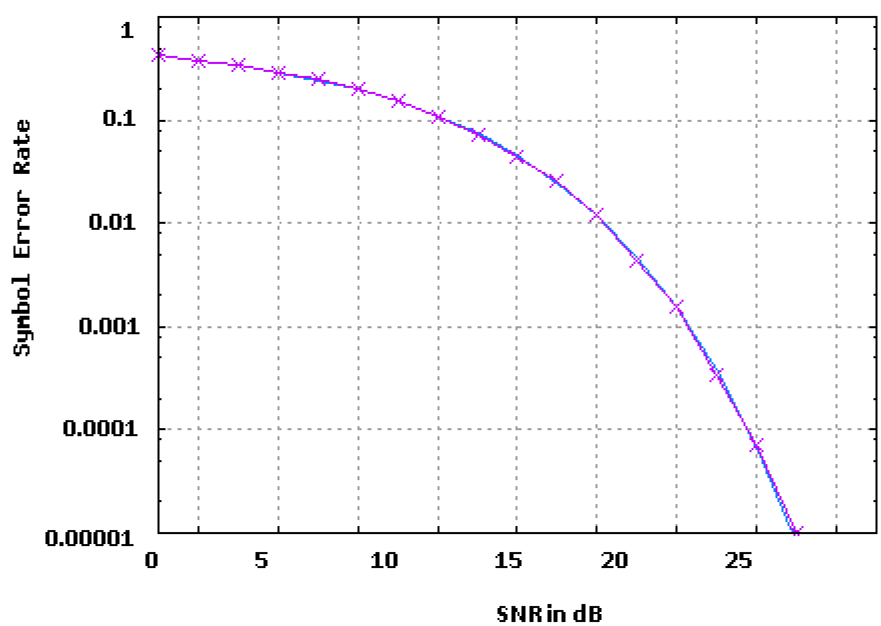

Figure 3: Symbol Error Rate for QPSK modulation [15]

2.3 OFDM Receiver

The most important parts of the transmitter include the FFT and symbol de-mapping.

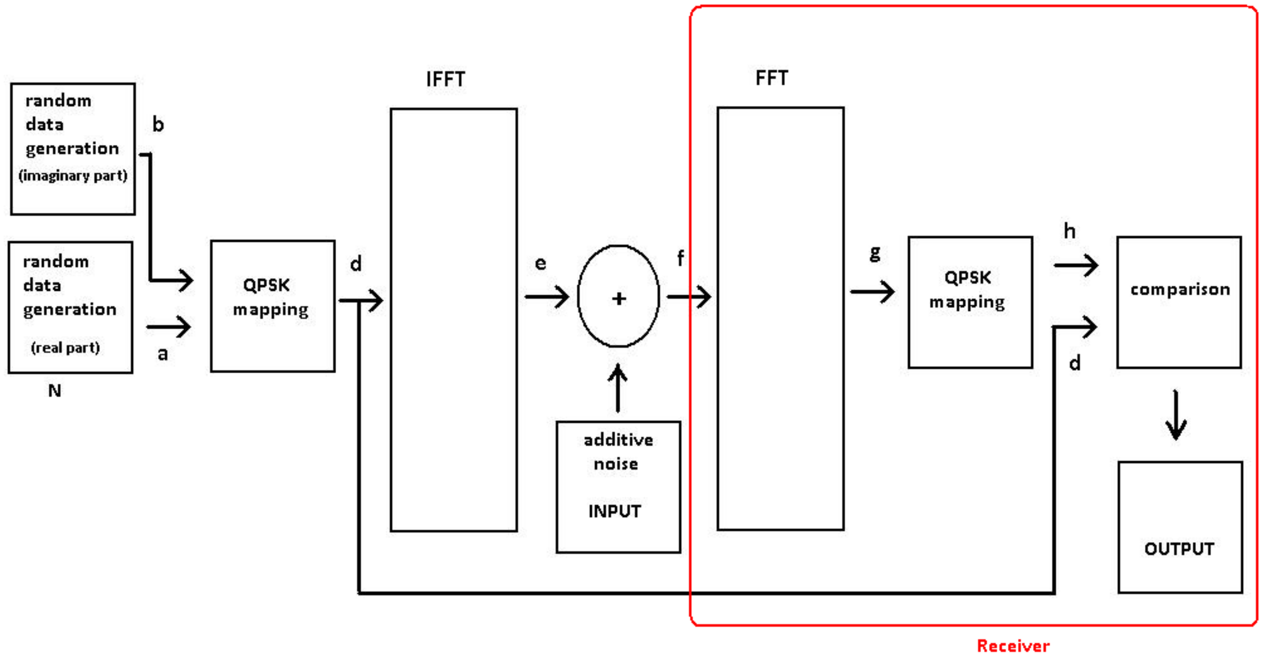

Figure 4: The OFDM receiver block diagram.

Because of the simplicity of channel model, there is no synchronization in receiver and there is no signal delay. In receiver, the transmitted block is directly processed. In addition to that, the frequency characteristic of channel is flat, therefore there is not channel parameters estimation and equalization.

2.3.1 FFT Demodulation

The OFDM blocks have been accomplished at this part. To obtain the raw constellation points, these OFDM blocks are passed through an FFT later. The complementary method to the IFFT modulator is used and before the channel analysis, the FFT FFT algorithm is used to get back the subcarriers' received symbols. [16]

In this case, the applied equation (8) is; [16]

$$U(n) = \frac{1}{K}\sum_{n=0}^{N-1} u(n)e^{-j2\pi kn/N}, \qquad k = 0, \dots . N-1 \tag{8}$$

2.3.2 Signal-to-Noise Ratio (SNR)

The desired signal power ratio to the noise power is defined as signal-to-noise ratio (SNR). The estimation of signal-to-noise ratio signifies the accuracy of the link between the receiver and the transmitter.

Depending on the test, the system parameters are changed. Before that, SNR estimation is used for measuring the channel's quality during system design. For instance; the transmitter adds some complexity to the information bits (more powerful coding) or some redundancy, or increases the spreading rate (for lower data rate transmission) or reduces the modulation level. Variable rates of information transfer can be used to maximize system resource utilization with high quality of user experience instead of fixed information rate for all levels of channel quality. [17] [18].

3

Simulation Results and Discussion

3.1 Coding

Based on the block diagram shown below (Figure 6), this section presents the coding part that is simulated in MATLAB. Each code's duty is explained below for readers to understand the coding. The letters (a, b, c, d, e, f, g, h) in the block diagram below represent in codes.

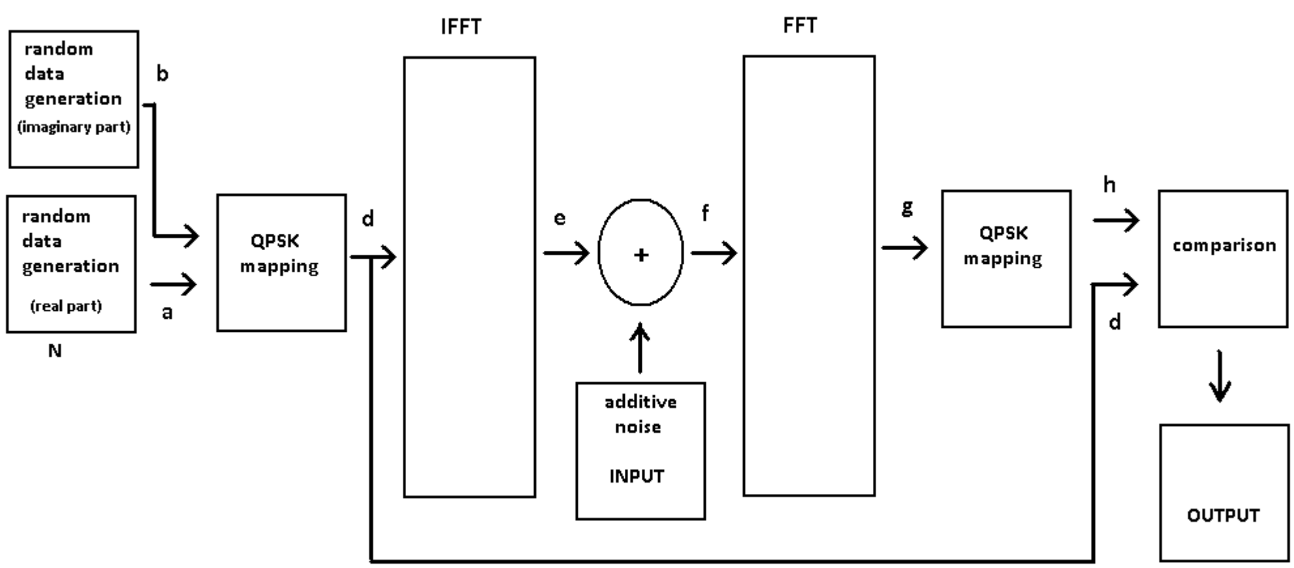

Figure 6: Block Diagram

```
function y=mapping (x)
% it is symbol mapping for QPSK mapping

%x = input signal of data (size 1xN complex)
%y = output signal of data (size 1xN complex)

% in this part, we will do splitting data into real and imaginary part

rex = real (x);
% real part of the signal (splitting data into real part)
% letter a in the block diagram above is representing this part

imx = imag (x);
% imaginary part of the signal (splitting data into imaginary part)
% letter b in the block diagram above is representing this part

rey = quantiz (rex, [0]);
% it is for dividing axis into two parts due to 4 QPSK

imy = quantiz (imx, [0]);
% it is for dividing axis into two parts due to 4 QPSK

rey = ((rey .* 2) -1) .* sqrt (2);
imy = ((imy .* 2) -1) .* sqrt (2);
y = rey + j.*imy;

%Just to summarize shortly what has been done in this part is dividing
complex plain into 4 regions and every region is represented by defined point
which is ideal point (refer Figure 6)


%%%


function error = compare (correct, received)
% in this function, it is comparing correct signal with received signal
```

```
e =(correct ~= received) ;
% this part is when error is not equal to received signal

error = sum (e) ;
% it is sum of errors


%%%

function ser = structure (snr)
% it is the main function

n = 128 ;
% it is the block size of OFDM for this simulation

%snr = 10 ;

m = 10;
% it is averaging

ser = 0 ;

for     ii=1:m

a = rand (1,n);
% it is generating random data into real part of the signal

b = rand (1,n);
% it is generating random data into imaginary part of the signal

a = ((a .* 2) - 1);
% it is making bipolar signal to unipolar signal

b = ((b .* 2) - 1);
% it is making bipolar signal to unipolar signal

c = a + j .* b ;
% it is making complex signal
```

```
d = mapping (c) ;
% it is transmitted signal before IFFT (QPSK mapping)

e = ifft (d,n) ;
% it is OFDM Modulation

f = awgn (e, snr) ;
% it is additive noise which was added here

g = fft( f,n);
% it is OFDM Demodulation

h = mapping (g);
% it is signal after QPSK de-mapping

ser = ser + compare (h,d);
% it is comparing signal h (Signal after QPSK de-mapping) to signal d
%(Transmitted signal before IFFT)

end

ser = ser ./ m;
% it is division in averaging

ser = ser ./ n;
% it is division in by number of subcarriers

%%%

function loop
% This is the looping function. This function is used for looping in the
simulation.

ii=1;

for     snr = 0:5:50
% it is sweeping over snr values
```

```
    SER (ii) = structure (snr);
    SNR (ii) = snr ;
    ii = ii + 1;

end

semilogy (SNR, SER)
% it is y axis values from 0 to 1

xlabel('SNR in dB');
% it is labeling x axis

ylabel('SER');
% it is labeling y axis

% end of coding

%%%
```

3.2 Simulation Results and Discussion

Simulation result of the above MATLAB codes is implemented in the Figure 7 below. The x-axis represents SNR in dB (with range from 0 to 25 db) and the y-axis represents SER [-] (with range from 10^{-3} to 10^{0}).

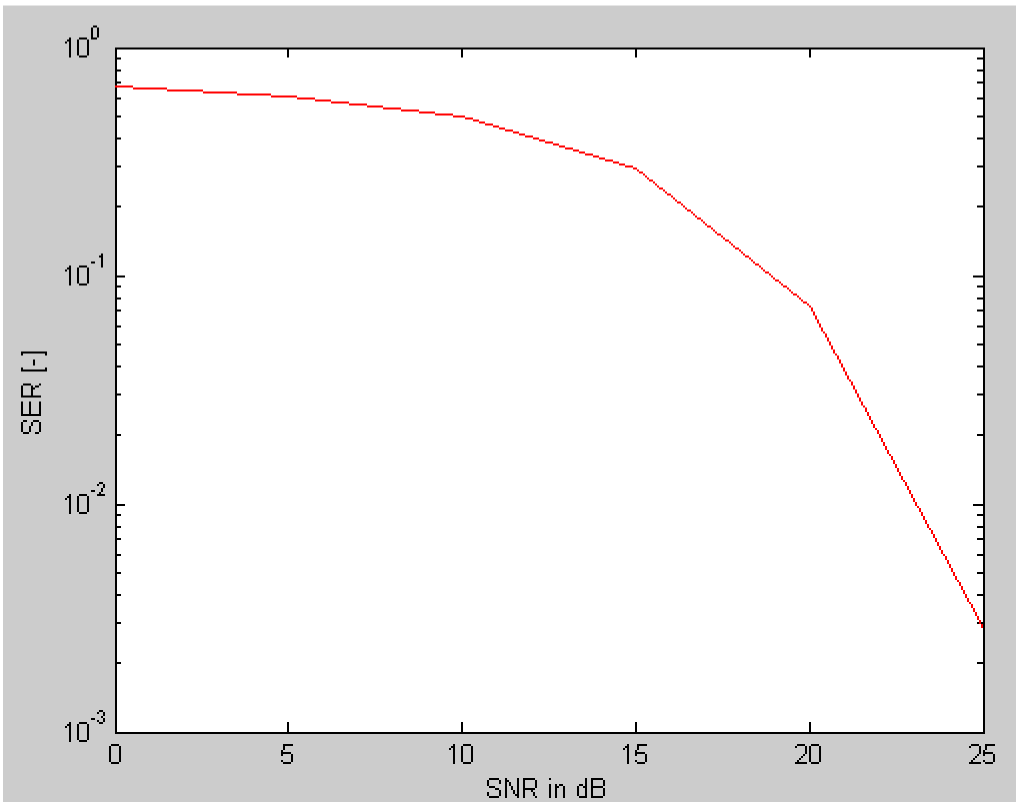

Figure 7: SER vs SNR (when n=128)

In regards to OFDM block size *n*, if errors are zero, then *SER* is zero [$\text{SER} = \frac{error}{n}$]. When all data is wrong, then *SER* will be equal to 1, where 1 represents 100% error.

When *SNR* is zero, it is shown that *SER* is very close to 1. Once SNR is increased from 5dB to 10dB, then from 10dB to 15dB, and then again from 15dB to 20dB and so on (until after SNR>25db where SER = 0), SER values decreases. In order words, when *SNR* increases in dB, error and *SER* is decreasing.

Having said that SER (Symbol error rate) is the ratio of symbol errors to total symbols sent (i.e. Number of symbols received in error/Number of symbols sent). SNR is the signal-to-noise ratio (i.e. it is the average power of signal relative to the average power of noise). Large value of SER indicates low quality of communication (as more errors are encountered). While large value of SNR indicates better communication (as the signal will be getting stronger when compared to the noise and therefore it will be affected to a small extend). As seen in the Figure 7 above, when SER increases (number of symbols received in error is greater than number of symbols sent), we can realize that SNR is indicates worse communication because the signal is getting weaker compared to the noise. And when SER decreases (number of symbols received in error is getting smaller than number of symbols sent), we can realize that SNR is indicates better communication because the signal is getting stronger compared to the noise. This means that according to the Figure 7, the demonstrated simulation result of SER versus SNR is very close in terms of comparison to the theoretical result (see Figure 3: Symbol Error Rate for QPSK modulation). Which means this simulation result supports this claim.

As shown in the Figure 8 below, OFDM block size *n* is 128 - illustrated with red. When OFDM block size *n* is increased to 256 (illustrated with blue) and then changed to 512 (illustrated with green), *SER* increases as well as error does increase.

For the given values;

In case of OFDM block size n=128, SNR in dB is 25 when SER is zero;

In case of OFDM block size n=256, SNR in dB is 29 when SER is zero;

In case of OFDM block size n=512, SNR in dB is 31 when SER is zero.

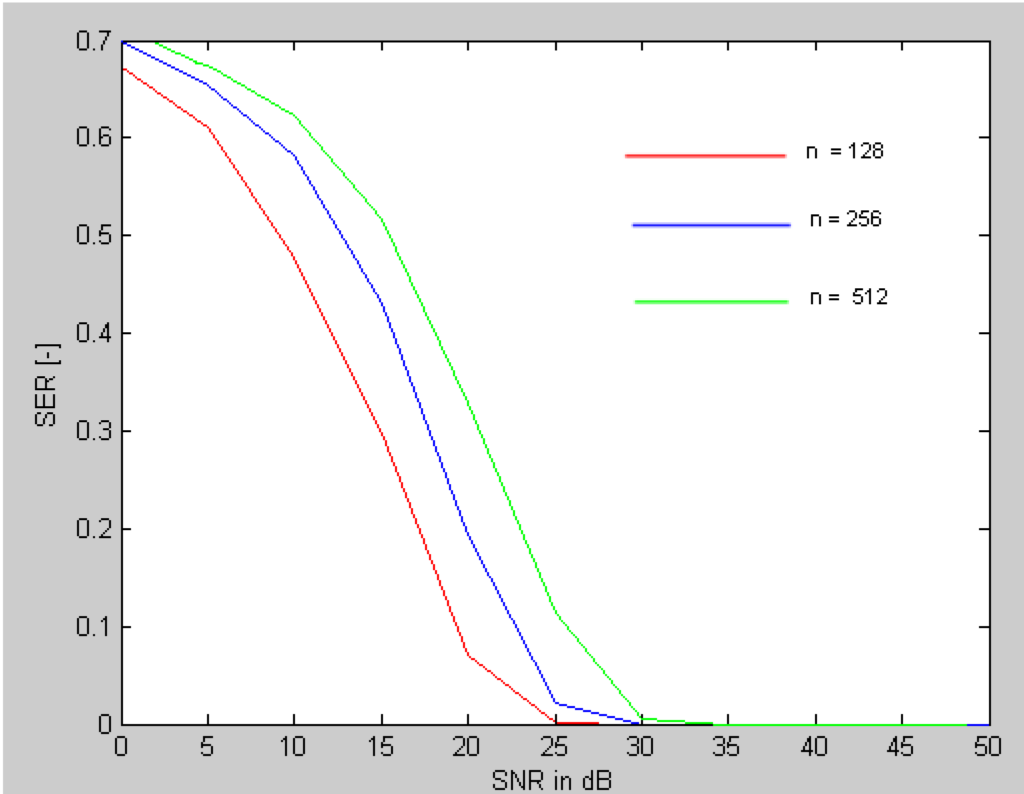

Figure 8: SER vs SNR (when n= 128, n=256, n=512)

As seen above, when subcarriers *n* increases, error increases – and in relation to that *SER* increases.

As seen in the Figure 9 below, when we assume that – for instance- SER value is 0,4 [-], here there are the SNR values in dB such as;

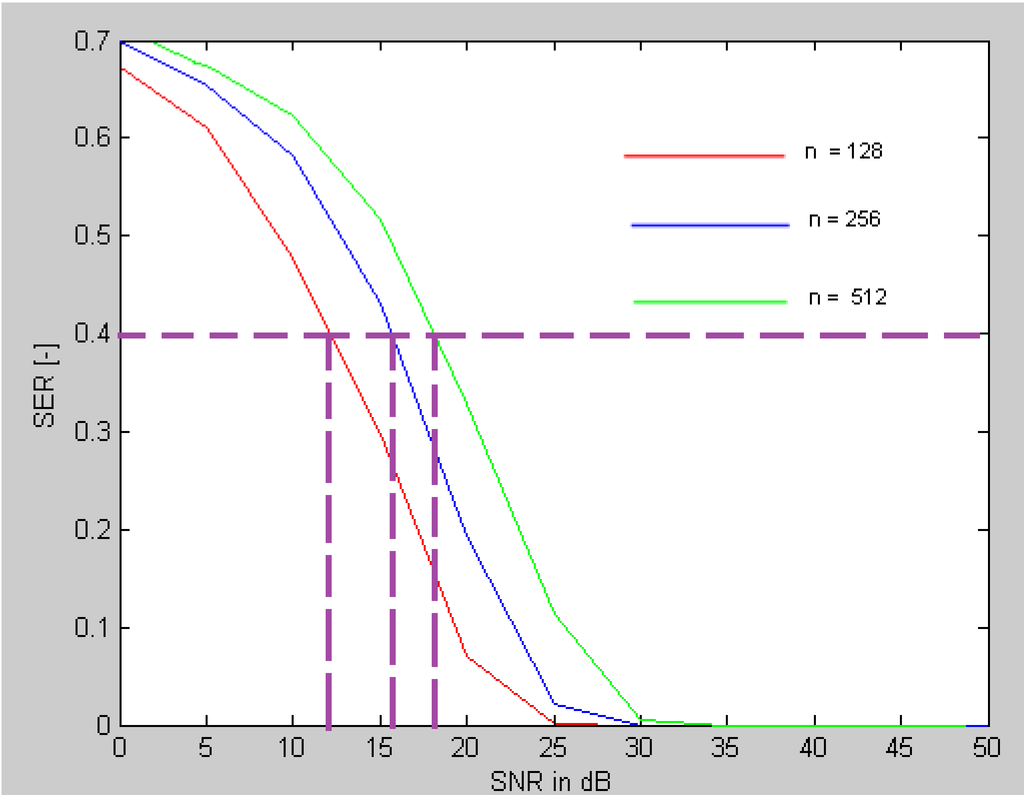

Figure 9: SNR values at point SER 0,4 [-] for (n= 128, n=256, n=512)

In case of OFDM block size n=128, SNR is 12dB at point where SER is 0,4 [-]

In case of OFDM block size n=256, SNR is 16dB at point where SER is 0,4 [-]

In case of OFDM block size n=512, SNR is 18dB at point where SER is 0,4 [-]

In other words, symbol error rate remains the same at the same point when there are more subcarriers, we need better signals because bandwidth is bigger in this simulation example.

Conclusion

A study experiment, as well as a study about OFDM modulation for underwater communication system, is made in this paper in regards to modern modulation method for underwater communication systems. The modulator and demodulator structure is shown and a study experiment made for modern modulation method for underwater communication systems. The symbol-error-ratio (SER) is considered as the main parameter. The simulation is performed as an SNR vs SER comparison for transmission and reception of modulated signals.

Large value of SER indicates low quality of communication as more errors are encountered. While large value of SNR indicates better communication as the signal gets stronger when compared to the noise. As a result of the first simulation part, it was shown that the demonstrated simulation result of SER versus SNR is very close in terms of comparison to the theoretical result (shown in Figure 3: Symbol Error Rate for QPSK modulation).

As a result of the second simulation when OFDM block size subcarriers n increases, error increases and SER increases. In order to have (SER=0), SNR should be increased. In other words, the more sub-carriers, the more power is to spend. Therefore, there is a higher SNR values needed in order to keep the same quality. We can also say that the smaller the subcarriers, the less the error is. It is found out that data increases, length of symbol gets bigger in time domain (more data, longer).

In addition, some parts of this paper may not be full-filled completely according to the task that was given for this project, For instance, a basic simulation was made rather than a complex one due to accessibility of materials, lack of MATLAB knowledge. However, in my future work, these sides will be rapidly improved and also test of some physical properties of some channel model will be examined as a good continuation of this work – hopefully as a master thesis.

Abbreviations

AWGN : Additive white Gaussian Noise

FFT : Fast Fourier Transform

IFFT : Inverse Fast Fourier Transform

OFDM: Orthogonal Frequency Division Multiplexing

SER: Symbol Error Rate

SNR: Signal-to-Noise Ratio

PSK: Phase Shift Keying

QAM : Quadrature Amplitude Modulation

QPSK: Quadrature Phase Shift Keying

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