OFDM Performance in Multi-Mode Optical Fiber compared with conventional BPSK and QAM modulation

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OFDM Performance in Multi-Mode Optical Fiber compared with conventional BPSK and QAM modulation

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DEDICATION

To my father and mother whose kindness always prays for me.

Also dedicate this to my family and friends.

I am really proud all of them.

Mohammed Ahmed Al-Taae

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First, I would like to thank my university higher management.

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List of Abbreviation

ACI	Adjacent Carrier Interference
ADC	Analog-to-Digital Converter
ADSL	Asymmetric Digital Subcarrier Link
ASK	Amplitude-Shift Keying
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPSK	Binary Phase-Shift Keying
CCDF	Complementary Cumulative Density Function
CD	Chromatic Dispersion
CDF	Cumulative Density Function
COFDM	Coded Orthogonal Frequency Division Multiplexing
CP	Cyclic Prefix
DAB	Digital Audio Broadcasting
DAC	Digital-to-Analog Converter
DFT	Discrete Fourier Transform
DML	Discrete Multitone
DSL	Digital Subcarrier Link
DSP	Digital Signal Processing
DTT	Digital Terrestrial Television
DVB	Digital Video Broadcasting
EMI	Electromagnetic interference
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
FOTS	Fiber Optic transmission System
HDTV	High Definition Television
I	In-phase

ICI	Inter-Carrier Interference
IFFT	Inverse Fast Fourier Transform
IQ	In-phase and Quadrature
ISI	Inter-Symbol Interference
LAN	Local Area Network
LD	Laser Diode
LEDs	Light-Emitting Diodes
MCM	Multi-Carrier Modulation
MMF	Multi-Mode Fiber
MMOF	Multi-Mode Optical Fiber communication system
N.A.	Numerical Aperture
NFFT	Non-uniform Fast Fourier Transform
NRZ	Non-Return to Zero
OFDM	Orthogonal Frequency Division Multiplexing
OOFDM	Optical Orthogonal Frequency Division Multiplexing
PAPR	Peak-to-Average Power Ratio
PSK	Phase-Shift Keying
PSM	Pulse-Shape Modulation
Q	Quadrature
QAM	Quadrature Amplitude Modulation
RFI	Radio Frequency Interference
SMF	Single Mode Fiber
SNR	Signal-to-Noise Ratio
SQNR	Signal-to-quantization noise ratio
WDM	Wavelength-Division Multiplexing
WLAN	Wireless Local Area Network

Abstract

In recent years, Orthogonal Frequency Division Multiplexing (OFDM) system has gained more and more attentions for its great benefit to the optical fiber communication system for improving the transmission performance. The OFDM performance has been reported to be robust not only for long distance of fiber optic but for higher bit rate as well. The OFDM technology has been developed in a wireless communication system, and now is used in Asymmetric Digital Subscriber Line (ADSL), High Definition Television (HDTV), Digital Video Broadcasting (DVB), Digital Audio Broadcasting (DAB), and Wireless Local Area Network (WLAN) and so on.

OFDM is a modulation technique which is now used in most new and emerging broadband wired and wireless communication system. Because it is robust against Inter Symbol Interference (ISI) caused by dispersive channel. Which is the case in Multi-Mode Fiber Optic communication channel (MMOF). The OFDM is special case of Multi-Carrier Modulation (MCM). This technique has been used in optical communication. OFDM is based on the Fast Fourier Transform (FFT).

In this thesis, we study in depth performance of OFDM modulation in Multipath channel (selective fading channel) i.e. MMOF supported by MATLAB extensive simulation. We also study the performance of BPSK and QAM modulation in the same multipath channel. The outcomes of this study and simulation prove that the OFDM modulation performance measured in term of Bit Error Rate (BER) versus Signal-to-Noise Ratio (SNR) is much superior to that of BPSK or QAM modulation in MMOF dispersive or selective fading channel. This make the OFDM system a good choice for Optic Fiber digital communications system.

Keywords: Orthogonal Frequency Division Multiplexing (OFDM) in Multi-Mode Optical Fiber (MMOF), Binary Phase-Shift Keying (BPSK), Quadrature Amplitude Modulation (QAM), Intersymbol Interference (ISI), Cyclic Prefix (CP), Bit Error Rate (BER)

Chapter I: Introduction

Orthogonal Frequency Division Multiplexing (OFDM) belongs to a broader class of Multicarrier modulation (MCM), which is now the basis of many telecommunications standards, including wired and wireless local area networks LANs, digital terrestrial television (DTT) and digital radio broadcasting in much of the world.

OFDM is a method of digital modulation in which a signal is split into several narrowband channels at different frequencies. It efficiently embraces multiple performances for fourth generation system. OFDM is also the basis of most (DSL) standards, though in this context, it is usually called discrete Multitone (DMT) because of some minor peculiarities. **[1]**

The insertion of a Cyclic Prefix (CP) makes OFDM an effective solution to the problem of the Inter-Symbol Interference (ISI) and Inter-Carrier Interference (ICI), caused by the effects of dispersive channel. This become increasingly important as data rates increase to point where, when conversion serial modulation schemes like quadrature amplitude modulation (QAM) or Non-return-to-zero (NRZ) are used, the received signal at any time depend on the rate of multiple transmitted symbol. In this case the complexity of equalization in serial schemes which is used time domain equalization rises rapidly. In contrast, the complexity of OFDM and of systems using serial modulation and frequency domain equalization, scale well as data rates and dispersive increase **[2]**. A second major advantage of transmitters and receivers from analog to digital domain. For instance, while the precise design of analog filter can have a major impact on the performance of the serial modulation system in OFDM any phase variation with frequency can be corrected at little or no cost of the digital parts of the receiver. Despite these important advantages of OFDM, it is only recently that it has been considered for optical communication.

However, OFDM uses the spectrum much more efficiently by spacing the channel much closer together. This is achieved by making all the carriers orthogonal to one another, preventing interference between the closely spaced carriers. Each carrier in an OFDM signal has a very narrow bandwidth (i.e. 1 KHz), thus the resulting symbol rate is low. This results in the signal having a high tolerance to multipath delay spread. One of the main reasons to use OFDM is to increase the robustness against frequency selective fading or narrow band interference **[3]**.

In a single carrier system, a single fade or interferer can cause the entire link to fail, but in multicarrier system, only a small percentage of the subcarriers will be affected. Coded Orthogonal Frequency Division Multiplexing (COFDM) is the same as OFDM except that forward error correction is applied to the signal before transmission. This is to overcome errors in the transmission due to lost carriers from frequency selective fading, channel noise other propagation effects.

I.1 Motivation of this Thesis

Optical Fiber communication system proved to carry a large channel capacity i.e. much higher bit rate. Optical Fiber is competing with satellite communication. And gaining a large segment of communication market.

However, there are a great deal of performance improvement which can be introduced to this technology. For instance there are two major types of optical fiber, namely Multi-Mode Optical Fiber and Single Mode Optical Fiber SMOF. In MMOF communication link a relatively higher optical power can be applied to the optical fiber thus achieving longer communication distance. This comes with the price of higher Inter-Symbol interference because of the multipath mode. OFDM modulation has been reportedly to work well on multipath channel. Inspired by this idea we will study the performance of OFDM on optic fiber communication channel with MMOF.

OFDM system has been known to have excellent performance in multipath and selective channels such as fiber optic communication channel.

In this thesis, we are studding the performance of OFDM modulation in fiber optic channel being a multipath channel. In particular for Multi-Mode Fiber Optic with step index. The effect of cyclic prefix and its length on the performance of OFDM in this communication channel in terms of Bit-Error Rate (BER) is also studied in this work.

I.2 Theoretical Formulation of OFDM

In signal carrier modulation, data serially over one carrier over the channel by modulating the signal carrier at the band rate or ***R*** symbol per second. The data symbol period ***Ts*** is then ***1/R***. In multipath fading channel the data transmit parallel, by converting from serial to parallel, the time dispersion can be significant compared to the symbol period, which is results in Inter Symbol interference (ISI).

The basic idea of multicarrier modulation was introduced and patented in the mid 60's by Chang **[4]**: the available bandwidth W is divided into a number ***Nc*** of subbands, commonly called subcarriers, each of width ***Δf=W/Nc***. The subdivided of Bandwidth is illustrated in **Figure (1)**.

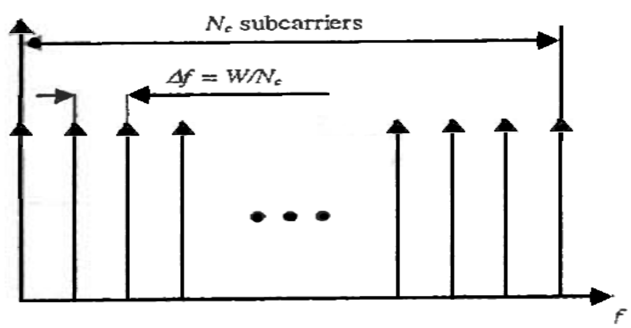


Figure 1: Subdivided of Bandwidth into Nc Sub bands

I.2.1 Orthogonality of OFDM Subcarrier (multicarrier modulation)

OFDM is a special class of MCM, a generic implementation of which is depicted in **Figure (2).** The structure of the complex multiplier (IQ modulator / demodulator), which is commonly used in MCM system, is also shown in the **Figure (2)**. The MCM transmitted signal ***s(t)*** is represented as:

$$s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{N_{sc}} C_{ki} S_k (t - iT_s) \quad \dots\dots\dots (1)$$

$$s_k(t) = \prod(t) e^{j2\pi f_k t} \dots\dots\dots\dots\dots\dots\dots (2)$$

$$\prod(t) = \begin{cases} 1, (0 < t \leq T_s) \\ 0, (t \leq 0, t > T_s) \end{cases} \quad \dots\dots\dots (3)$$

Where C_{ki} is the ***i*th** information symbol at the ***k*th** subcarrier, s_k is the waveform the ***k*th** subcarrier, N_{sc} is the number of subcarriers, f_k is the frequency of the subcarrier, T_s is the symbol period, and **Π(t)** is the pulse shaping function.

The conceptually diagram of a generic multicarrier modulation system was shown in **Figure (2)** **[5]**.

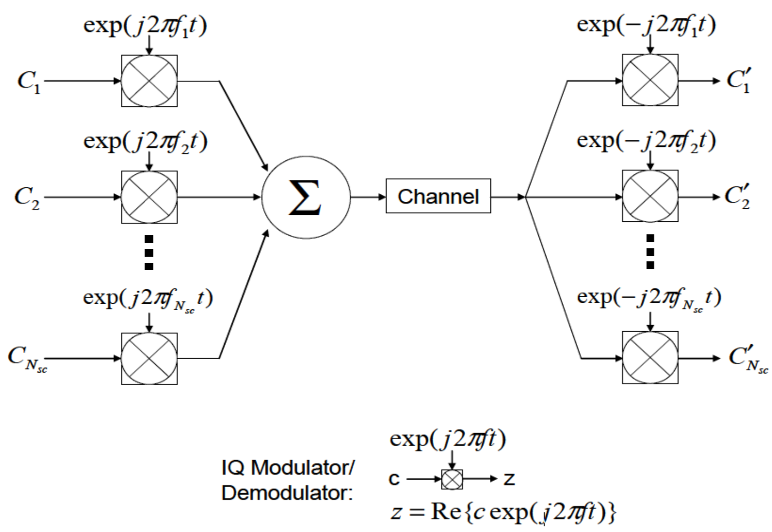


Figure 2: conceptual diagram of a generic multicarrier modulation system

The detected information symbol $\boldsymbol{c'_{ki}}$ at the output is the ***ith*** detected information symbol at the ***kth*** subcarrier, and is given by

$$c'_{ki} = \frac{1}{T_s}\int_0^{T_s} r(t-iT_s)s^*{}_k\,dt = \frac{1}{T_s}\int_0^{T_s} r(t-iT_s)e^{-j2\pi f_k t}\,dt \ldots\ldots (4)$$

Where ***r(t)*** is the received time domain signal, $\boldsymbol{S^*_k}$ is the converse conjugate of $\boldsymbol{S_k}$. Here, the pulse shaping function is equal to 1 because $\boldsymbol{0<t\le T_s}$. The classical MCM uses non-overlapped band limited signals and can be implemented with a bank of large numbers of oscillators and filters at both transmitter and receiver ends. The orthogonality between any two subcarriers is given by:

$$S_{kl} = \frac{1}{T_s}\int_0^{T_s} s_k s^*{}_l\,dt \;=\; \frac{1}{T_s}\int_0^{T_s} \exp(j2\pi(f_k - f_l)t)\;dt \ldots\ldots (5)$$

$$S_{kl} = \exp(j\pi(f_k - f_l)T_s)\frac{\sin(\pi(f_k - f_l)T_s)}{\pi(f_k - f_l)T_s} \dots\dots (6)$$

It can be seen that if the following equation is satisfied,

$$f_s - f_l = m\frac{1}{T_s} \dots\dots (7)$$

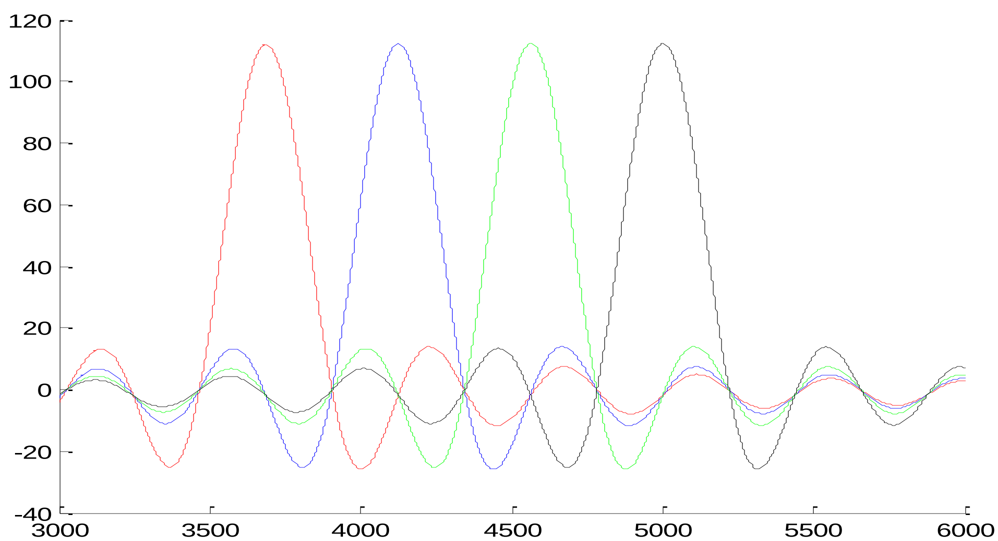


Figure 3: Orthogonality of OFDM Sub-Carriers

As this simulation **Figure (3)** shows that the maximum of *ith* carrier is aligned with zero of (i+1) adjacent carrier.

I.2.2 Saving Bandwidth with OFDM

OFDM is a special case of Frequency Division Multiplexing (FDM). In FDM the data transmitted in one stream and cannot be divided, while in OFDM the data transmitted through many small streams.

As well-known FDM where your bandwidth is divided into multiple subcarrier which are not overlap with each other illustrated in **Figure (4).**

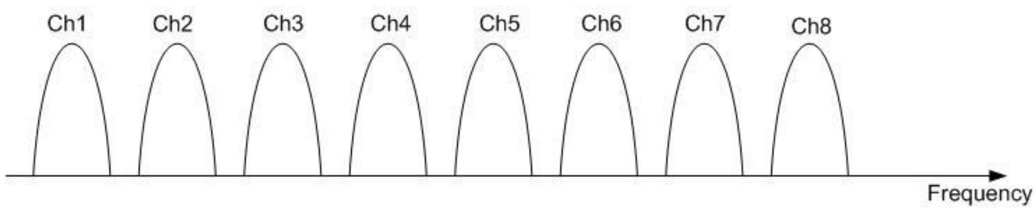


Figure 4: Frequency Division Multiplexing

OFDM is a same FDM technique that is divided bandwidth into many narrow band subcarrier which are allowed overlap and therefore, can be save a bandwidth, but will be more subject to intercarrier interference illustrated in **Figure (5)**.

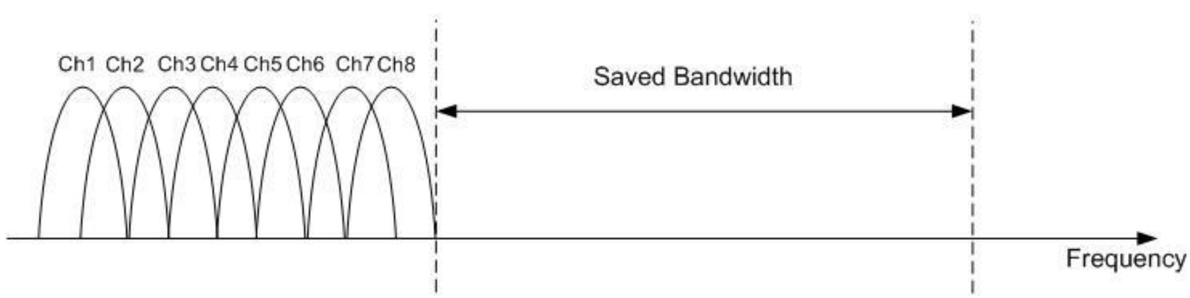


Figure 5: Save bandwidth in Orthogonal Frequency Division Multiplexing

The basic principle of OFDM is to be split a high-rate data stream into a number lower-rate stream and transmitted them over a number of subcarriers.

From this compare we investment the bandwidth in OFDM to support more subcarriers channels compare with FDM. And have the same concept of using parallel data stream, Also in FDM the overlap in the time domain, and in OFDM the overlap in the frequency domain.

I.2.3 Channel Delay and Cyclic Prefix (CP)

Cyclic prefix in OFDM in order to combat multipath propagation and also reduces the delay spread or chromatic dispersion relative to symbol time. The cyclic prefix act as the buffer region or the guard interval to protect the OFDM signals from Intersymbol Interference (ISI). To avoid the interference between OFDM symbols and also eliminate ICI illustrate in **Figure (6)**. **[5]**

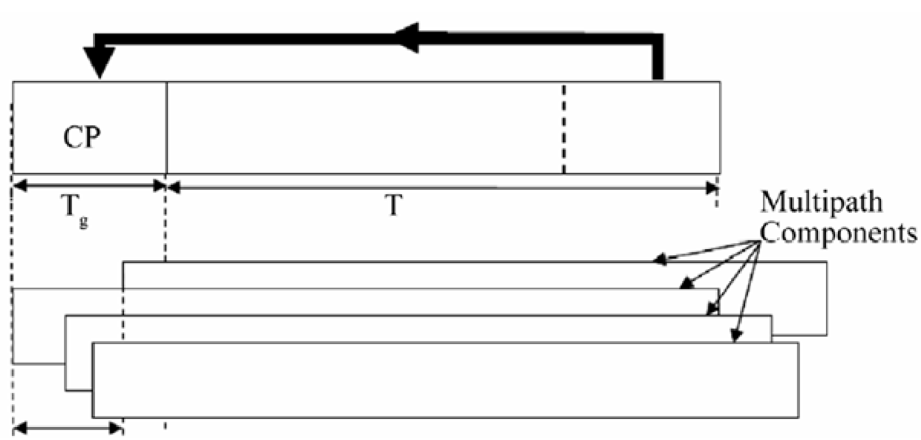


Figure 6: Result of multipath propagation and mitigating effects of CP

Let’s say, without cyclic prefix we transmit the following N values (***N=Nfft=length of FFT/IFFT***) for the single OFDM symbol illustrated in **Figure (7)**.

$$X_0, X_1, X_2, \dots \dots .., X_{N-1} \dots \dots (8)$$

Cyclic prefix of length ***Ncp*** where (***Ncp*** < ***N***), is formed by copying the last ***Ncp*** values from about vector of ***X*** and adding those ***Ncp*** values to the front part of same ***X*** vector. With cyclic prefix length Ncp, (***where Ncp*** < ***N***), the following values constitute a signal OFDM symbol:

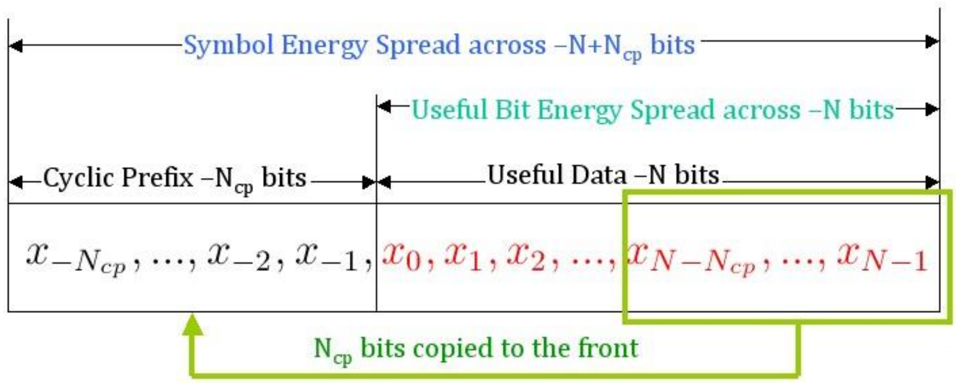


Figure 7: Cyclic Prefix insertion

If T is the duration of the OFDM symbol in seconds, due to the addition of cyclic prefix of length ***Ncp***, the total duration of an OFDM symbol becomes:

$$T_e = T + T_{cp} \dots \dots (9)$$

$$\text{Where} \quad T_{cp} = N_{cp} * {}^{T}\!/_{N} \dots \dots (10)$$

Therefore, the number of samples allocated for cyclic prefix can be calculated as:

$$N_{cp} = T_{cp} * {}^{N}\!/_{T} \dots \dots (11)$$

Where ***N*** is the FFT/IFFT length, ***T*** is the IFFT/FFT period and ***Tcp*** is the duration of cyclic prefix.

Another motivation to add cyclic prefix, convert linear convolution into circular convolution, which eases the process of detecting the received signal by using simple single tap equalizer.

When cyclic prefix of length ***Ncp*** is added to the OFDM symbol, the output of the channel ***r(t)*** is given by circular convolution of channel impulse response ***h(t)*** and the OFDM symbols with cyclic prefix ***x(t)***.

$$r(t) = h(t) * x(t) \dots \dots (12)$$

As we know, for the discrete signals, circular convolution in the time domain translates to multiplication in the frequency domain. Thus, the frequency domain, the above equation translates to:

$$R(f) = H(f)X(f) \dots \dots (13)$$

At the receiver, *R(f)* is the received signal (in Frequency domain) and our goal is estimate the transmitted signal *X(f)* from the received signal *R(f)*. From the above equation, the problem of detection the transmitted signal at the receiver side translate to a simple equalization equation as follows **[6]**:

$$X'(f) = \frac{R(f)}{H(f)} \dots \dots . \dots (14)$$

I.2.4 Peak to average power ratio (PAPR)

The PAPR is one of the drawbacks of the OFDM modulation format. The major problem resides in the power amplifiers in the time domain since many subcarrier components are added via Inverse Fast Fourier Transform (IFFT) operation. As a result, the OFDM systems have high PAPR when compared with single-carrier systems. The high PAPR in OFDM systems as it decreases the signal-to-quantization noise ratio (SQNR) of analog-to-digital converter (ADC) and digital-to-analog converter (DAC) while degrading the efficiency of the power amplifier in the transmitter

[8]. The origin of high PAPR of an OFDM signal can be easily understood from its multicarrier nature. Because the cyclic prefix is an advanced time-shifted copy of a part of the OFDM signal in the observation period, we focus on the waveform inside the observation period **[9]**. The transmitted time domain waveform for one OFDM symbol can be written as:

$$s(t) = \sum_{k-1}^{N_{sc}} c_k\, e^{j2\pi f_k t} \; , f_k = \frac{k-1}{T_s} \ldots\ldots\ldots (15)$$

An OFDM system consists of N subcarriers. The Bandwidth of OFDM symbols is B=Δf * N and symbol time T= 1/Δf * C_k is the complex baseband data modulating the k-th subcarrier for s(t) **[10]**.

The PAPR of the OFDM signal is defined as:

$$PAPR = \frac{\max\{|s(t)^2|\}}{P_{av}} \; , \qquad t \in [0, T_s] \ldots\ldots\ldots (16)$$

Where P_{av} is the average power of the transmitted symbol and the maximum sought over the symbol duration as

$$P_{av} = E\ \{|s(t)^2|\}\ . \ldots\ldots\ldots\ldots (17)$$

Where **E{.}** is the expected value.

$$E\{x\} = \int_{-\infty}^{\infty} x\, f_x(x)\, dx \ldots\ldots\ldots. (18)$$

Where $f_x(x)$ is probability density function as:

$$E\{s(t)\} = \int_{-\infty}^{\infty} s\, f_s(s)\, ds \ldots.. (19)$$

The P_{av} is can be found from time averaging as:

$$P_{av} = \frac{1}{T_s}\int_{-\frac{T_s}{2}}^{\frac{T_s}{2}} s(t)^2\, dt \dots \dots . . (20)$$

The OFDM signal sampled at time instant $t=n\Delta t$ is then expressed as:

$$x(n) = X(n\Delta t), \qquad n = 0, \dots \dots, LN-1 \dots \dots \dots (21)$$

The PAPR is calculated from the digital signal, meaning that the true maximum value of the OOFDM signal may not be included in the sampled points. Therefore, we need to introduce an overlapping factor in order to provide sufficiently accurate results in the measure of it **[11]**. A fourfold oversampling factor (L = 4) is enough to consider the missing peaks. **[12]**

As simulation shows as in **Figure (58)** OFDM system suffers from high PAPR**.**

I.2.5 OFDM Transmitter

At the transmitter block, firstly have an input a stream of D bits. Suppose we have NFFT subcarriers. Then they must transmit D/NFFT =NSYM symbols, where each symbol has NFFT bits. Here we are assuming each signal value in modulation represent one bit, if using 4-QAM each symbol will have 2xNFFT bits, if using 16-QAM each symbol will have 4xNFFT bits, etc. the bits fed into a serial-to-parallel converter and modulated (BPSK/M-QAM/etc.). Also that is possible for different sub-carriers to use different modulation schemes.

To obtain the OFDM communication system, the signal have different stages from the transmitter to the receiver. In **Figure (8)** will descript all the stages for transmitter. Start from a bit sequence, that the first stage divides it in packets of length equal to the number of QAM bits to form a QAM symbol, and then it assigns them to each subcarrier. This process is called Serial-to-Parallel converter.

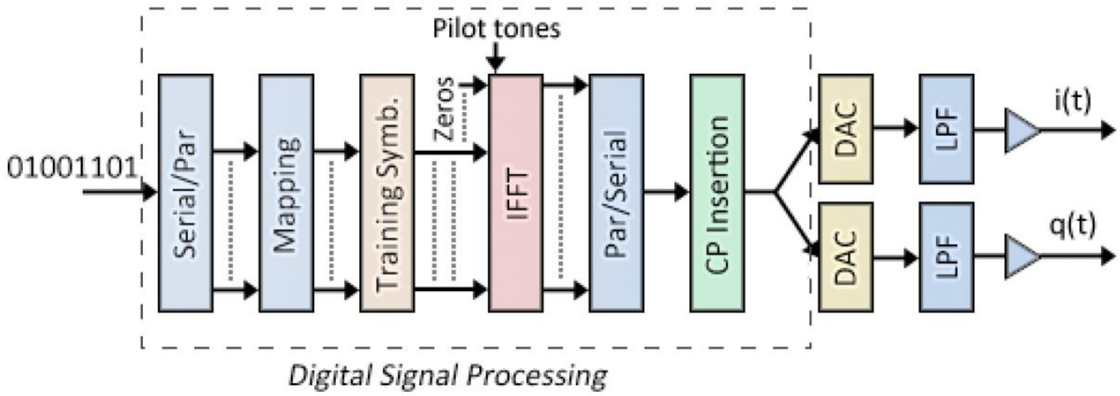


Figure 8: Block Diagram of an OFDM transmitter [13]

The second stage is a reorganization of the subcarriers. After that, a training sequence is added to allow for synchronization and calculate the coefficients of the equalizer.

Before the IFFT stage, an oversampling is applied to make it easier to remove the spectral alias due to non-idea DAC conversion, and at the receiver it will help in synchronization **[14]**. When the oversampling is added the next step is to apply the IFFT algorithm. Then the information of each sub-channel returns to a vector form, applying Parallel-to-Serial, the inverse process which has been applied in the transmitter.

After the Cyclic Prefix (CP) insertion stage, the signal is divided in real part, in-phase I, and in imaginary part, quadrature Q. These two parts have to be converted from digital to analog to be sent over the channel, in this case an optical fiber. In order to further reduce the alias due to imperfect digital-to-analog converter a low pass filtering is used.

I.2.6 OFDM Receivers

In the Receiver block, the block stages are similar to the transmitter stage, but in the reverse way, In **Figure (9)** all stages to receive the signal OFDM from the transmitter.

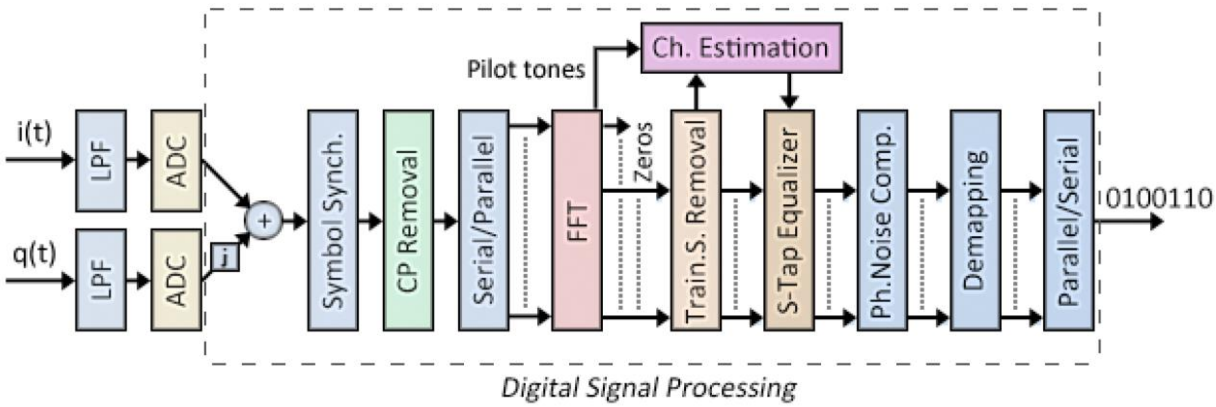


Figure 9: Block Diagram of an OFDM Receiver [13]

After the signal detection, through an antenna or by photodiode the first stage is the filtering process of the in-phase and quadrature components of the received signal, to avoid aliasing problems.

The next stages are the digitalization process of the received signal, which needs two ADC devices, one per each branch. Once the signal is digitalized, the next stage is the synchronization. When the synchronization is completed the CP is removed from the received signal and so the orthogonality is recovered. The resulting signal is parallelized to calculate the FFT. After FFT, the zero padding and the training sequence are extracted. The training sequences are used to estimate the coefficients which are needed to restore the signal in the single-tap equalization block. Consecutively, the phase noise can be compensated, and each subcarrier is demodulated. The finally block is the serialization of the information carried out in each sub-channel to obtain the final bit sequence.

Finally the encoder and decoder of the orthogonal sub-carriers Equation:

Encode: from Frequency-domain samples to Time-domain samples using (IFFT)

$$x(t) = \sum_{k=-N/2}^{N/2-1} X[K] \;\; e^{j2\pi kt/N} \ldots\ldots\ldots (22)$$

Where ***x(t)*** is a Time-domain, and ***X[k]*** is Frequency-domain

Decode: from Time-domain samples to Frequency-domain samples using (FFT)

$$X[K] = \frac{1}{N} \sum_{i=N/2}^{N/2-1} x(t) \;\; e^{-j2\pi ki/N} \ldots\ldots\ldots (23)$$

For Orthogonality of any two bins:

$$\sum_{i=N/2}^{N/2-1} e^{-j2\pi ki/N} \;\; e^{-j2\pi pi/N} = 0 \ldots\ldots\ldots (24)$$

For p ≠ k

Chapter II:

II.1 Background of Optical Fiber Communication

Nowadays, the people widely used a new technology such as High-definition video, web phone, and cloud computing, to support all of them need high speed data transmission. The internet traffic is more increase. And the **Figure (10)** show the internet traffic growth projected to 2014 **[15]**. It is impossible to support this kind of internet traffic growth by the tradition coaxial system. The optical fiber communication system can provide the ability to transmit huge data on long distance, and also optical fiber has an advantage of low loss.

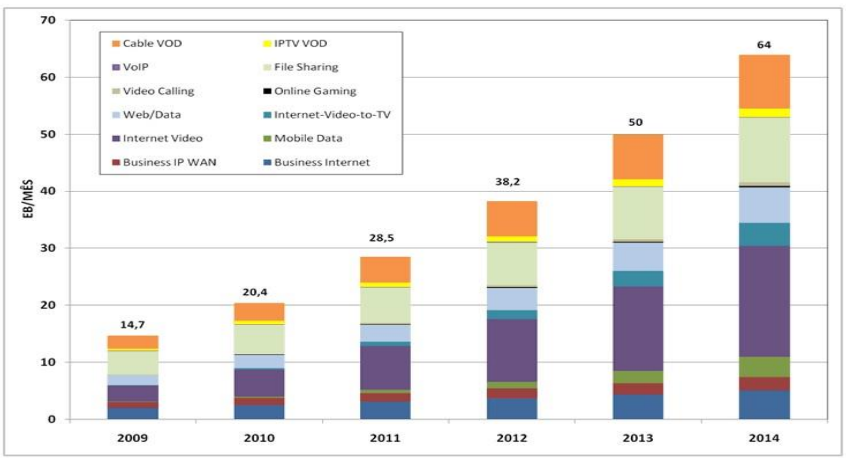


Figure 10: Cisco Forecasts for Internet traffic 64 Exabytes per Month of IP Traffic in 2014

In the later 20th century, electrical-based systems face its obstacle for the limit of capacity and reach. So, the light wave communication systems became the trend for the dramatic increasing data rate. After the invention and realization of the laser, a coherent source for the transmitter was provided **[16]**. In around 1990s, optical coherent communication system enhanced the transmission distance **[17][18]**, but after the invention of the optical amplifier in the 1990s, the optical coherent communication lost its advantage. Massive number of wavelength-division multiplexing (WDM) signals could be transmitted over thousands of kilometers through the optical amplifiers **[19]**.

In 1971, Weistein and Ebert **[20]** used discrete Fourier transform (DFT) and Fast Fourier transform (FFT) to construct and complete multi-carrier transmission system named Orthogonal Frequency Division Multiplexing (OFDM) system. Recently it has been applied for wireless communication.

And it exhibits great performance. And it is also applied to the long-haul optical communication system, and both the coherent detection and direct detection are possible for the optical OFDM system.

II.2 Fiber Optic

The optical transmission system transmits information encoded in optical signal over long distance. The electrical signal in the transmitter at the fiber input is converted to light impulses that are transferred through the fiber optic to the receiver. The optical signal is propagating through the fiber is attenuated less than the electrical signal in the metallic line so it can be sent over long distance without repeaters. And the optical transmitter allows to transmit greater data capacity.

There are mainly three types of Optical Fibers utilized in Telecommunications intensity. Single Mode Fiber, Step-Index Multi-Mode Fiber, and Gradient-Index Multi-Mode Fiber. Single mode fiber (SMF) stand of glass fiber with a diameter of 8.3 to 10 microns that has one mode of transmission and have a smaller code of high reflective index *n1* surrounded by cladding of low reflective index *n2*, through which one mode will propagate typically 1310 or 1550nm. Carries higher bandwidth than Multimode but required a light source with a narrow spectral width. Step-Index Multi-Mode Fibers and Gradient-Index Multi-Mode fibers are types of Multi-Mode Fibers. Multi-Mode Fibers is a little bit bigger core compare with single mode Fibers, with the most common diameters in the 50-to-100 micron range for the light carry component (in the US the most common size is 62.5um). Light waves are dispersed into multi-path, or modes, as they travel through the cable core typically 850 or 1300nm. Typically the Multimode fiber core diameters are 50, 62.5 and 100 micrometers. In step-index multi-mode fibers the reflective index is constant across the core and higher than of the cladding. Gradient index multi-mode fibers have a variable reflective index in the core, following a decreasing power law with the maximum value at the center of the core.

II.2.1 Principles of Fiber Optic

An optical fiber **Figure (11)** consists of a central glass core of radius surrounded by an outer cladding made of glass with the slightly lower refractive index. The corresponding refractive index distribution (in the transverse direction) is given by:

$$n = n1 \quad for \quad r < \alpha$$

$$n = n2 \quad for \quad r > \alpha \ldots\ldots\ldots\ldots\ldots\ldots\ldots (25)$$

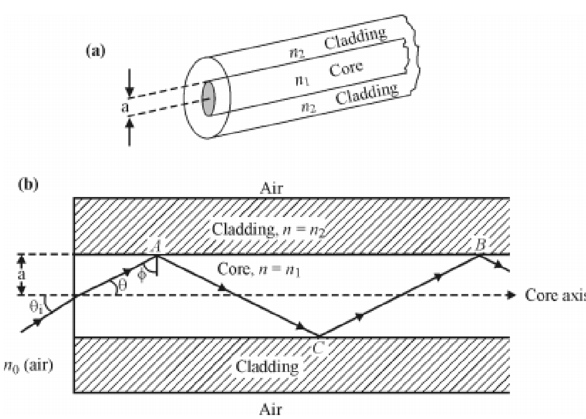


Figure 11: A glass fiber consists of a cylindrical central core surrounded by cladding material. (b) Light ray on the core cladding interface at an angle φ greater than critical angle φc are trapped inside the core

In this figure shows light ray incident on the air-core left interface at an angle θi. Accordance the Snell's law the ray reflects at the angle θ and strikes the core-cladding interface at angle φ. In the drawing shown, the angle φ should be greater than the angle φc that is defined in Equation (25**)**, thus leading to the total internal reflection at A.

The core diameter *d=2a* of a typical telecommunication-grade Multimode fiber is approximately 62.5 µm with an outer cladding diameter of 125um. The cladding index *n2* is approximately 1.45(pure silica), and the core index *n1* around 1.465. The cladding, usually the pure silica while the core is usually silica doped with germanium, which is increasing the reflective index slightly from *n2* to *n1*.

Fiber optic source must operate in the low-loss transmission windows of glass fiber. We have two types of sources, LEDs, source is typically used lower-data rate at the 850nm and 1310nm transmission wavelengths, shorter-distance Multimode systems because of their inherent bandwidth limitations and lower output power. LEDs typically have large numerical apertures (N.A.), which makes light coupling into single-mode fiber difficult due to the fiber small N.A. and core diameter. For this reason LEDs are most used with multimode optical fiber.

Lasers source is primarily used in longer distance at 1310nm and 1550nm transmission wavelengths. Laser source higher data rates are required. Because an LD has much higher output power, then a LEDs, it is capable of transmitting information over long distance. LDs are much narrower spectral width, it can provide high bandwidth communication over long distance, the LDs have smaller N.A. and also more effectively coupled with single-mode fiber.

Multimode fiber is optical fiber which supports multiple transverse guided modes for a given optical frequency and polarization. The number of the modes determined by the waveguide and the refractive index. The quantities are relevant to the radius and Numerical Aperture, which determines combination the V number. For a large number of V values, the number of the modes is proportional to V^2. Multimode particularly of fiber optic are relevant with large core shown in **Figure (12)** in right side **[21]**.

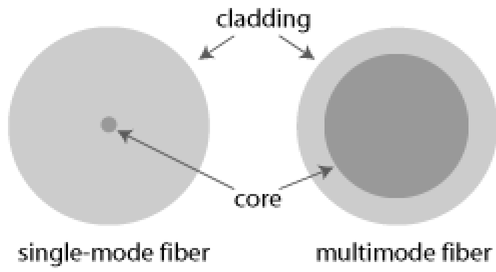


Figure 12: Internal Design for Multimode and Single Mode Fiber

OFDM in optical communication system to support high-speed data rate transmission over both single mode and multimode fiber optic, and it overcomes both linear and non-linear impairments in optical fiber communication **[22]**.

Fiber optic communication systems have many advantages over copper wire-based communication, include long-distance signal transmission, large bandwidth, light weight, and small diameter, nonconductive and security. The low attenuation and superior quality of fiber optic communication systems allow the communication signal to transmit over much longer distances without signal regeneration. Also, it can install in areas with electromagnetic interference (EMI), including radio frequency interference (RFI). Therefor have unlike metallic-based system, the dielectric nature of optical fiber makes it impossible to remotely detect the signal being transmitted within the cable. The only way to do so is by accessing the optical fiber.

II.2.2 Pulse Dispersion

A type of inter-symbol interference (ISI) created when optical pulses overrun each other in a fiber optic transmission system (FOTS). Pulse dispersion is the result of modal dispersion, which is an issue in systems employing Multimode fiber (MMF). Such systems permit optical signals and signal components to propagate along multiple modes, or physical paths, within both the core and the cladding of a fiber. Some light rays take a relatively direct path through the center of the fiber core. Other rays veer towards the edge of the core, where they reflect off the interface between the core and cladding on one side of the fiber, and then the other side of the fiber, and so on as they propagate across the link. Because some paths are more direct than others, and because the time of arrival is directly related to the distance traveled, some portions of the signal arrive before others. As the distance of the circuit increases, the differences in distances traveled by the various portions of each light pulse become greater as the effects of modal dispersion become more pronounced. As the speed of transmission increases, the bit time decreases, and the separation between bits is lost. The overall impact is that the pulses of light tend to smear together as they lose their shape and overrun each other.

II.2.3 Multi-Mode Optical Fiber Dispersion

In addition to power attenuation in optic fiber, the optic fiber induce spreading on the transmitted pulse which is known as pulse dispersion. With the problem of pulse dispersion the transmitted pulse of width τ_0 is received by the end of the optic fiber with prolonged length $\tau = \tau_0 + \delta\tau$, where $\delta\tau$ is the prolonging (spreading) of the transmitted pulse.

The major causes of pulse spreading in optic fiber are basically, firstly, the chromatic dispersion which includes both inter-modal dispersion and material dispersion, secondly the wave guide dispersion.

The reasons for inter-modal dispersion is that the pulse travels so many paths of different, thus it suffers from different delays inside the core, which is resulting in a pulse spreading as the **Figure(13)** depicts.

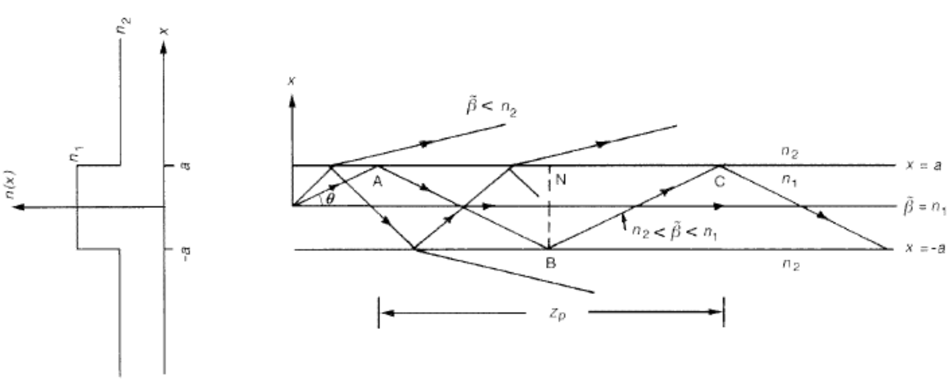


Figure 13: Multi-Mode Optical Fiber Propagation

The value of inter-modal dispersion is given by **[23]**:

$$\delta\tau = \frac{n_1\Delta}{c}L \ldots\ldots\ldots (26)$$

Where: $n_{1\approx 1.5}$ is the refraction index inside the core.

Δ :is the relative refraction index,

$L[m]$:is the fiber length.

For silica fiber optic this pulse spreading is given by **[23]**:

$$\delta\tau = \frac{50ns}{km} \ldots\ldots..(27)$$

The second causes of pulse spreading inside the fiber optic is the material spreading. The refraction index in fact inside the core or inside the cladding is not constant, but depends on wave length (λ).

With practical optic sources such as laser diode or there is inevitable wave length spreading within the transmitted pulse itself, therefore the wavelength component of the transmitted pulse travels at different velocities creating different delaying as a resulting in a spreading in the received pulse at the receiver.

The pulse spreading due to material effect is given by **[23]**:

$$\delta\tau \approx \frac{z}{\lambda_0 c}\left|\lambda_0^2 \frac{d^2n}{d\lambda_0^2}\right| \delta\lambda_0 \ldots\ldots..(28)$$

Where: z: fiber length m

λ_o: mean wave lengh [m]

$\left|\lambda_0^2 \frac{d^2n}{d\lambda_0^2}\right|$: material dispersion coefficient and it is given by curve

A type of inter-symbol interference (ISI) created when optical pulses overrun each other in a fiber optic transmission system (FOTS). Pulse dispersion is the result of modal dispersion, which is an issue in systems employing Multimode fiber (MMF). Such systems permit optical signals and signal components to propagate along multiple modes, or physical paths, within both the core and the cladding of a fiber. Some light rays take a relatively direct path through the center of the fiber core. Other rays veer towards the edge of the core, where they reflect off the interface between the core and cladding on one side of the fiber, and then the other side of the fiber, and so on as they propagate across the link. Because some paths are more direct than others, and because the time of arrival is directly related to the distance traveled, some portions of the signal arrive before others. As the distance of the circuit increases, the differences in distances traveled by the various portions of each light pulse become greater as the effects of modal dispersion become more pronounced. As the speed of transmission increases, the bit time decreases, and the separation between bits is lost. The overall impact is that the pulses of light tend to smear together as they lose their shape and overrun each other.

II.2.4 Dynamic Range

Dynamic Range **DR** of the system is defined as the difference between two levels of the input signal power namely P_{inoise}, P_{isat} ie. Where P_{isat} is the input power which cusses the output to start saturation, and P_{inoise} is the input power which equal to system noise floor.

$$DR = P_{isat} - P_{inoise} \ldots\ldots\ldots (29)$$

With OFDM modulation we need a fairly large dynamic range to accommodate for the large peak to average power (PAPR) ratio.

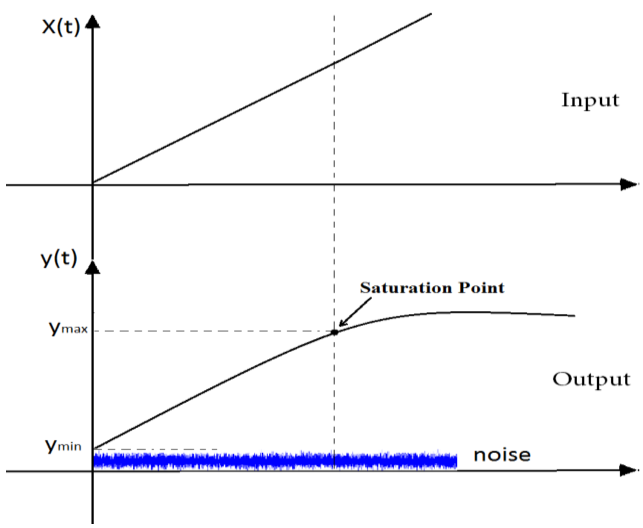


Figure 14: Description Dynamic Range

Chapter III: Digital modulation techniques

III.1 Digital Modulation System

III.1.1 BPSK Modulation

Binary Phase Shift Keying (BPSK) is a simple but significant carrier modulation scheme. The two time-limited energy signal **$s_1(t)$** and **$s_2(t)$** are defined based on a signal basis function **$\varphi_1(t)$** as:

$$s_1(t) = \sqrt{\frac{2E_b}{T_b}}.\cos 2\pi f_c t \;\; \boldsymbol{and} \; s_2(t) = \sqrt{\frac{2E_b}{T_b}}.\cos[2\pi f_c t + \pi] = -\sqrt{\frac{2E_b}{T_b}}.\cos 2\pi f_c t \ldots\ldots (30)$$

The basis function, evidently, is

$$\varphi_1(t) = \sqrt{\frac{2}{T_b}}.\cos(2\pi f_c t) \;\; ; 0 \le t < T_b \ldots\ldots\ldots (31)$$

So, BPSK may be described as a one-dimensional digital carrier modulation scheme. Note that the general form of the basis function is,

$$\varphi_1(t) = \sqrt{\frac{2}{T_b}}.\cos(2\pi f_c t + \varphi) \;\; ; 0 \le t < T_b \ldots (32)$$

Where "φ" indicates an arbitrary but fixed initial phase offset. For convenience, let us set φ=0. As we know, for narrowband transmission, $\boldsymbol{f_c} \gg \frac{\boldsymbol{1}}{\boldsymbol{T_b}}$ That is, there will be multiple cycles of the carrier sinusoid within one bit duration (T_b). For convenience in description let us set, $\boldsymbol{f_c \gg n\, x \frac{1}{T_b}}$ (though this is not a condition to be satisfied theoretically). **[24]**

Now, we see,

$$s_1(t) = \sqrt{E_b}.\varphi_1(t)\ \ \boldsymbol{and}\ \ s_2(t) = -\sqrt{E_b}.\varphi_1(t) \dots\dots\dots (33)$$

The two associated scalar is:

$$s_{11}(t) = \int_0^{T_b} s_1\,(t).\varphi_1(t)dt = +\sqrt{E_b} \quad \boldsymbol{and} \quad s_{21}(t) = \int_0^{T_b} s_2\,(t).\varphi_2(t)dt = -\sqrt{E_b} \dots\dots (34)$$

Figure (15) presents a sketch of the basis function $\varphi_1(t)$ and **Figure (16)** shows the BPSK modulated waveform for a binary sequence. Note the abrupt phase transitions in the modulated waveform when there is a change in the modulating sequence. On every occasion the phase has changed by 180 degree. Also note that, in the diagram, we have chosen to set $\sqrt{\frac{2E_b}{T_b}} = 1$, $i.e. \frac{E_b}{T_b} = \frac{1}{2} = 0.5$, which is the power associated with an unmodulated carrier sinusoid of unit peak amplitude. **[25]**

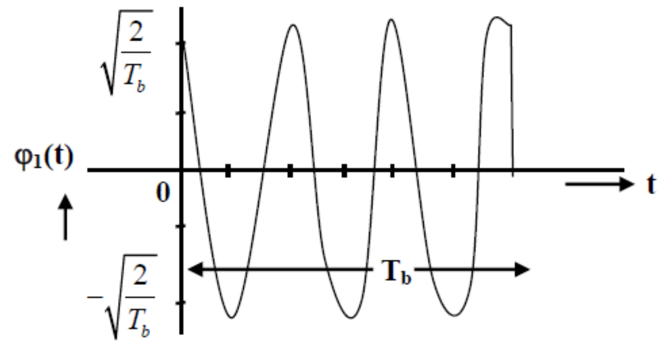


Figure 15: Sketch of the basis function φ1(t) for the BPSK modulation

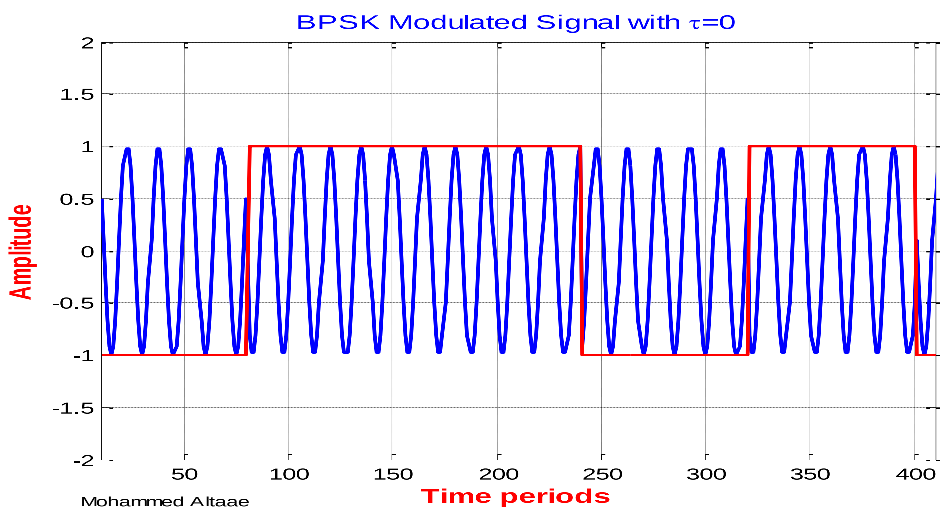


Figure 16: BPSK modulated waveform for the binary sequence 01101. Note that the amplitude has been normalized to ±1, as in a common practice

Figure (17) shows the signal constellation for binary PSK modulation. The two points are equidistant from the origin, signifying that the two signals carry the same energy.

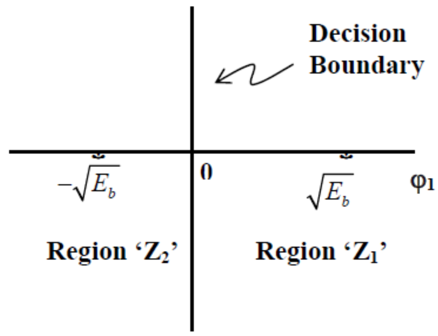


Figure 17: Signal constellation for the BPSK modulation. The diagram also shows the optimum decision boundary followed by a correlation receiver

Figure (18) shows a simple scheme for generating BPSK modulated signal without pulse shaping. A commonly available balanced modulator (such as IC 1496) may be used as the product modulator to actually generate the modulated signal. The basis function $\varphi_1(t)$, shown as the second input to the product modulator, can be generated by an oscillator. Note that the oscillator may work independent of the data clock in general.

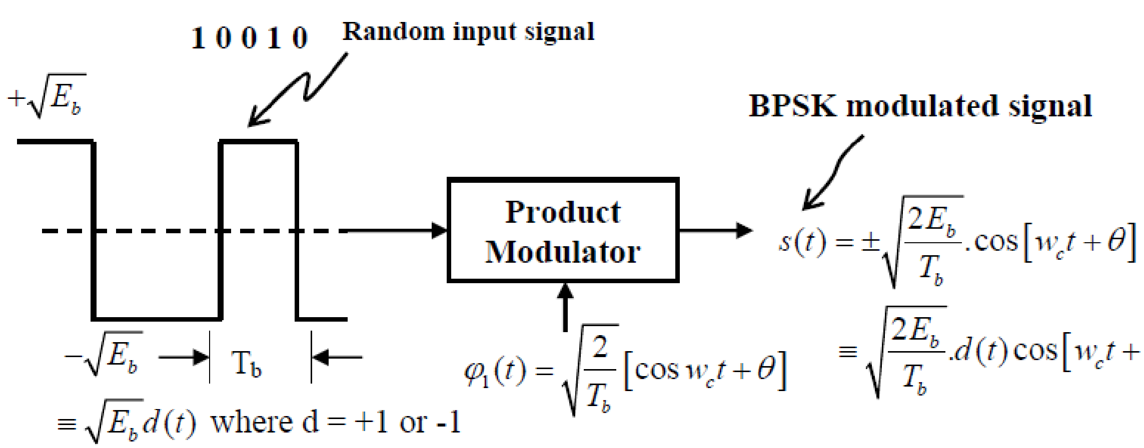


Figure 18: A simple scheme for generating a BPSK modulated signal. No pulse-shaping filter has been used

Figure (19) presents a scheme for coherent demodulation of BPSK modulated signal following the concept of optimum correlation receiver. The input signal **r(t)** to the demodulator is assumed to be centered at an intermediate frequency (IF). This real narrowband signal consists of the desired modulated signal **s(t)** and narrowband Gaussian noise **w(t)**. As is obvious, the correlation detector consists of the product modulator, shown as an encircled multiplier, and the integrator. The vector receiver is a simple binary decision device, such as a comparator. For simplicity, we assumed that the basis function phase reference is perfectly known at the demodulator and hence the $\boldsymbol{\varphi_1(t)}$, shown as an input to the product demodulator, is phase-synchronized to that of the modulator. Now it is straightforward to note that the signal at (A) in **Figure (19)** is:

$$r_A = [s(t) + w(t)].\sqrt{\frac{2}{T_b}}.\cos(w_c t + \theta) \ldots\ldots\ldots (35)$$

The signal at (B) is:

$$r_1 = \sqrt{\frac{2}{T_b}}\int_0^{T_b}\left[d(t).\sqrt{\frac{2E_b}{T_b}}.\cos(w_c t + \theta) + w(t)\right]\cos(w_c t + \theta)dt$$

$$= \sqrt{E_b}.d(t) + \sqrt{\frac{2}{T_b}}\int_0^{T_b} w(t).\cos(w_c t + \theta)dt \quad \ldots\ldots\ldots (36)$$

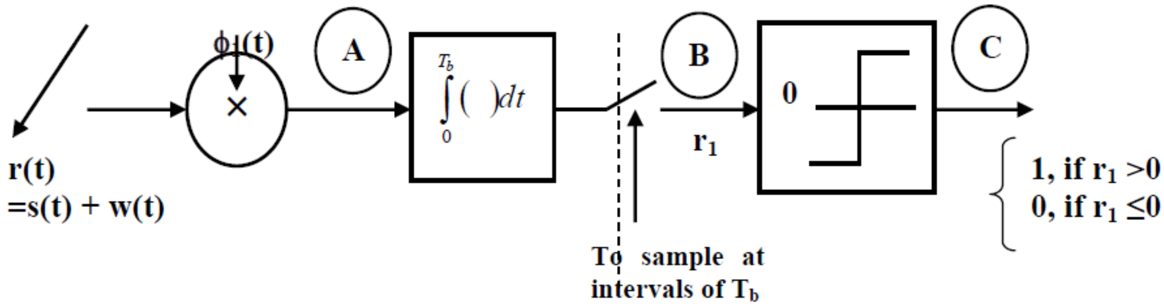


Figure 19: A scheme for coherent demodulation of BPSK modulated signal following the concept of optimum correlation receiver

Note that the first term in the above expression is the desired term while the second term represents the effect of additive noise. We have discussed about similar noise component earlier in Module #4 and we know that this term is a Gaussian distributed random variable with zero mean. Its variance is proportional to the noise power spectral density. It should be easy to follow that, if d(t) = +1 and the second term in Equation (36) (i.e. the noise sample voltage) is not less than -1.0, the threshold detector will properly decide the received signal as a logic '1'. Similarly, if d(t) = -1 and the noise sample voltage is not greater than +1.0, the comparator will properly decide the received signal as a logic '0'. These observations are based on 'positive binary logic'.

III.1.2 QAM Modulation

Quadrature Amplitude Modulation (QAM) is one of form, modulation which is widely used for modulation data signal onto carrier used for radio communication, because it offers advantages over other forms of data modulation such as PSK, although many forms of data modulation operate alongside each other.

QAM is signal in which two wave carriers usually sinusoids, are shifted in phase by 90 degrees are modulated and the results consist of both amplitude and phase variations. In view of the fact that both amplitude and phase variations are present it may also be considered as a mixture of amplitude and phase modulation. And used the phase and amplitude of the carrier signal to encode data. QAM finds widespread use in current and emerging wireless standards, including Wi-Fi, Digital Video Broadcast (DVB), WiMAX, IEEE 802.11n etc.**[26]**

QAM it is sometimes viewed as a combination of ASK and PSM modulation, a more fundamental way of viewing QAM through is that it encodes data by varying amplitude of two carrier. Single that is in-quadrature (phase difference between 90 degrees). Hence the name “quadrature-amplitude modulation”. **[27]**

As we have seen, a modulated carrier signal can be expressed in term of it’s IQ components as:

$$\mathrm{s(t)} = I\cos(2\pi f_c t) - Q\sin(2\pi f_c t) \ldots\ldots\ldots (37)$$

$$\boldsymbol{where}\ \ I = R\cos(\varphi)\ \ \boldsymbol{and}\ \ Q = R\sin(\varphi)$$

Where I is In-phase, Q is quadrature–phase components respectively. Thus, we can change the amplitude () and phase () of a carrier signal by varying I and Q values.

QAM is both a digital modulation and analog modulation scheme. The analog versions of QAM are typically used to allow multiple analog signal to be carried on a single carrier. In digital QAM case, a finite number of at least two phases and at least two amplitudes are used. QAM is used extensively as a modulation scheme for digital telecommunication system. **[28]**

When using QAM, the constellation points are normally arranged in a square grid, with equal vertical and horizontal spacing and as a result the most common forms of QAM use a constellation with the number of points equal to power 2 i.e. 2,4,8,16 illustrate in **Figure (20)**. **[24]**

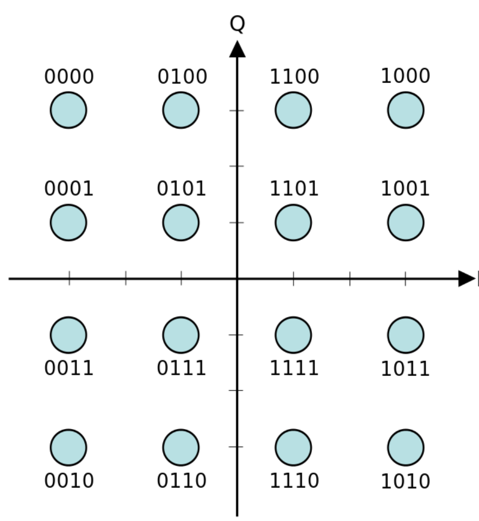


Figure 20: Constellation diagram for rectangular 16-QAM

Figure (21) the structure of QAM transmitter with carrier frequency f_0 and the frequency response of the transmitter's filter H_t. The first flow of bits to be transmitted is split into two equal parts, this process generates two independent signals to be transmitted. They are encoded separately just like they were in an (ASK) modulator. Then one channel "in-phase" is multiplied by cosine, while the other channel "Quadrature" is multiplied by a sine. By this way there phase of 90 degree between them.

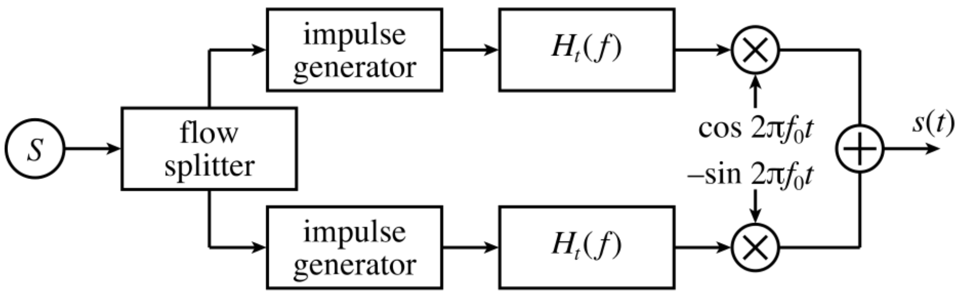


Figure 21: Diagram of a QAM transmitter

They are simply added one to the other and sent through the real channel. The sent signal can be expressed in the form:

$$s(t) = \sum_{n=-\infty}^{\infty} [v_c(n)^*. h_t(t - nT_s)\cos(2\pi f_0 t) - v_s(n)^*. h_t(t - nT_s)\sin(2\pi f_0 t)] \ldots\ldots (38)$$

Where $\mathbf{v_c}^*$ and $\mathbf{v_s}^*$ are voltages applied in response to the $\mathbf{n^{th}}$ symbol to the cosine and sine waves respectively.

Figure (22) the receiver is inverse process of the transmitter with the receive filter's frequency response H_r. the multiplying by a cosine or sine and by Low-pass filter it is possible to extract the component in phase or quadrature.

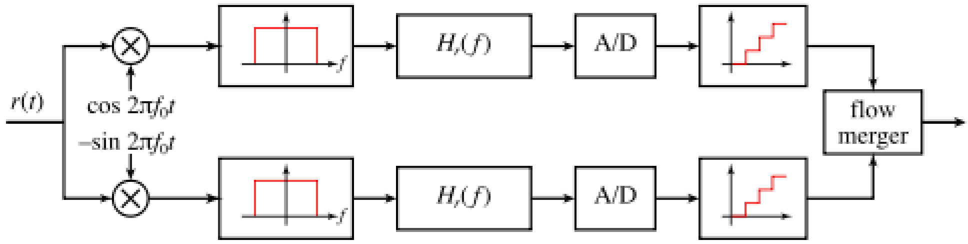


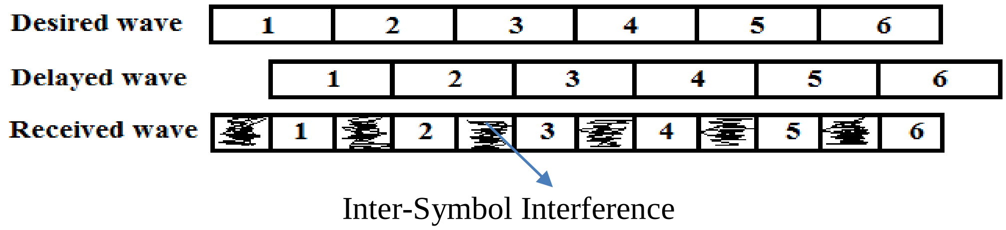
Figure 22: Diagram of QAM demodulator

There is an unknown phase delay between the transmitter and receiver that must be compensated by synchronization of receivers by sine and cosine functions illustrate in **Figure (22)**.

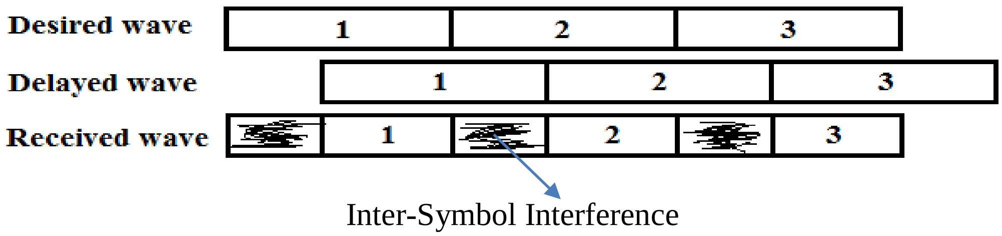
III.1.3 OFDM Modulation

The primary problem confronting modulation is interference caused by delayed waves in the channel in large cities, when there are many high risk structures. When planning a new digital broadcast system, devising countermeasures to reduce the effects delayed waves is extending the symbol length **Figure (23)** that is called Inter-Symbol Interference (ISI) by the cutting the degree of overlap between adjacent symbols **[29]**.

The information sequence is divided into a number of frequencies branches (i.e. FDM) for transmission to limit the problem of frequency selective fading, also using multicarrier scheme, means divided the bandwidth frequency into a narrow band frequencies.



(a) Short symbol length



(b) Long symbol length

Figure 23: Symbol Length Effect on Delay wave interference

The OFDM System is implemented through the FFT, we shall describe an OFDM system in which QAM is used to transmission data on each of the subcarriers and the FFT algorithm implementation will be used in modulator and demodulator system.

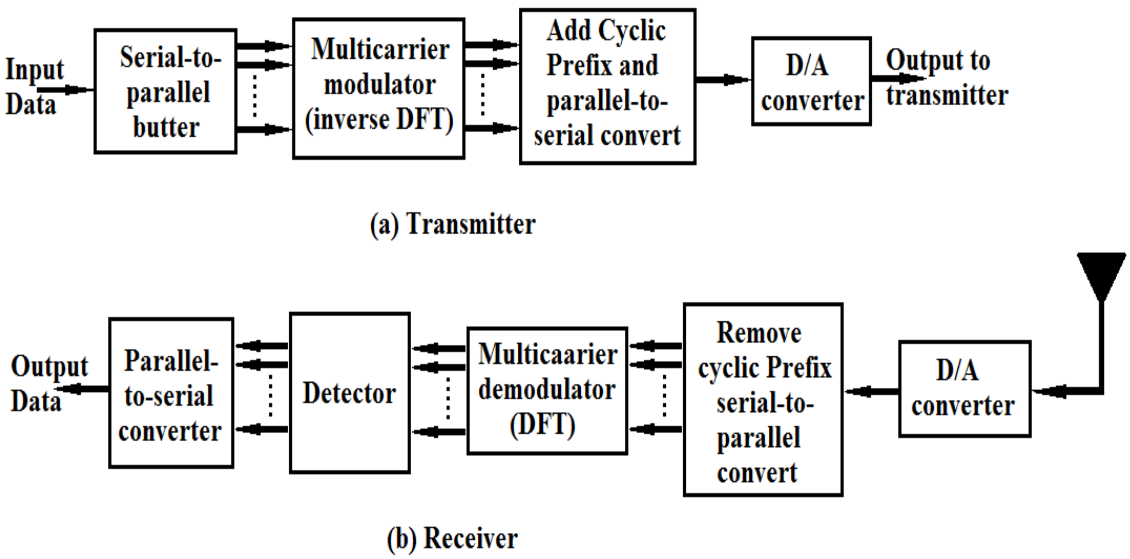


Figure 24: Bloch diagram of OFDM modulation and demodulation system

In OFDM carrier, all orthogonal carrier waves are used in the symbol period T, we can use sinusoidal waveform which has integer number of periods in the T see in **Figure (25)**.

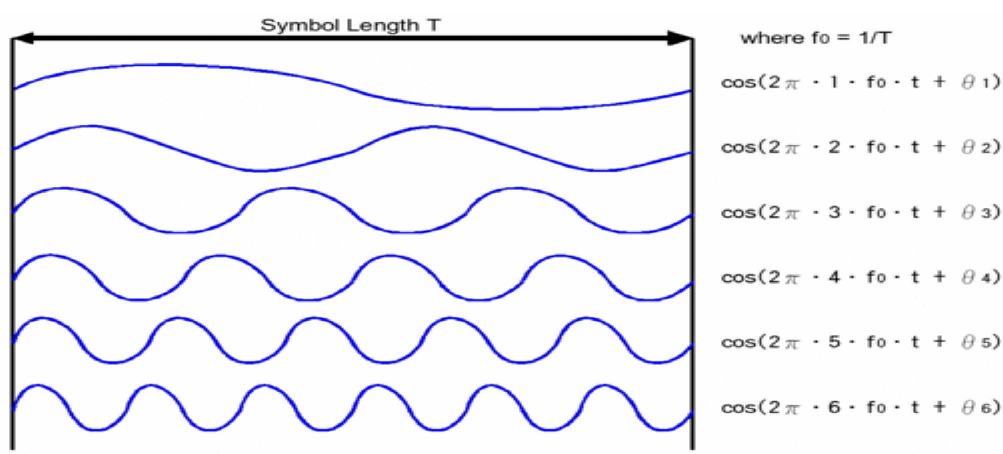


Figure 25: OFDM subcarrier

In OFDM, subcarriers overlap. They are orthogonal because the peak of one subcarrier occurs when other subcarriers are at zero. This is achieved by realizing all the subcarriers together using

Inverse Fast Fourier Transform (IFFT). The demodulator at the receiver parallel channels from an FFT block. Note that each subcarrier can still be modulated independently. This orthogonality is represented in **Figure (26) [30]**.

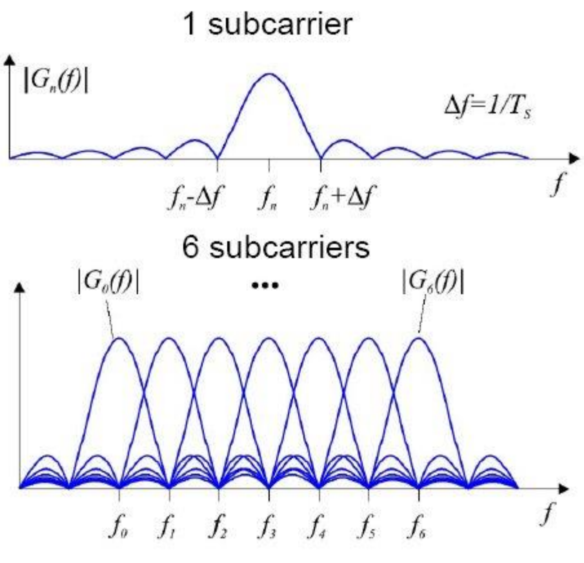


Figure 26: OFDM Sub-carriers in Frequency domain

Ultimately ISI is conquered, provided that orthogonality is maintained, OFDM systems perform better than single carrier systems particularly in frequency selective channels. Each subcarrier is multiplied by a complex transfer function of the channel and equalizing this is quite simple.

III.1.4 Combined BPSK and OFDM

Orthogonal frequency division multiplexing (OFDM) is a type of multicarrier modulation, uses overlapped orthogonal signals to divide a frequency-selective channel into a number of narrowband flat-fading channels. While the BPSK using a single carrier to transmitted data through the channel.

OFDM system convert the data stream from serial to parallel to transmitted the data at each sub-channel. While the PSK modulation allocated all bandwidth frequency channel to transmitted the same data stream.

BPSK alone: 0, 1 are converted to -1, 1 and BPSK signal is:

$$1 \rightarrow s(t) = A_c \cos(2\pi f_0 t) \; \ldots .. (39)$$

$$-1 \rightarrow s(t) = -A_c \cos(2\pi f_0 t) \ldots (40)$$

But combined BPSK with OFDM is to make symbol value C_{ki} taking either -1 or 1.

III.1.5 Combined QAM with OFDM

An OFDM modulator first converts a single high-data-rate stream into multiple lower-rate streams. These parallel streams are then modulated onto orthogonal carriers that minimize the mutual interference that the data symbols could create during impaired channel conditions. This modulation is carried out through a combination of multiple QAM modulators followed by an inverse fast Fourier transform (FFT) that maps the individual streams onto a broadband signal. The resultant signal is then amplitude modulated onto the final RF carrier. OFDM, due to its strong performance in a heavy interference environment, is an integral part of the 802.11 standards used for Wi-Fi and now WiMAX.

Combined in QAM-OFDM we have C_{kI} for I channel and C_{kQ} for Q channel.

III.2 Multipath Fading

The physical medium between the transmitter and receiver is known as channel. This channel results in random delay or random phase shift **[31]**, which causes selective fading, which in term cause Inter-Symbol Interference (ISI).

III.2.1 Selective and non-selective fading channel

In any radio transmission, the channel spectral response is not flat. It has dips or fades in the response due to reflections causing cancellation of certain frequency at the receiver. Reflections off nearby objects (e.g. ground, building, trees, etc.) can lead to multipath signals of similar signal power as the direct signal. This can result in deep nulls in the received signal power due to destructive interference.

In narrow bandwidth transmission if the null in the frequency response occurs at the transmission frequency, then entire signal can be lost.

For the communication channel theories:

Coherence bandwidth $\mathbf{B_C}$ in Hz for the transmitted signal it has transmitted bandwidth $\mathbf{B_T}$. for any channel such as (wireless, fiber optic, or satellite). Coherent bandwidth is a statistical measurement of the range frequencies over which the channel can be considered “flat” or in other words the approximate maximum bandwidth or frequency interval over which two frequencies of a signal are likely to experience comparable or correlated amplitude fading. If the multipath time delay spread equals **D** seconds, then the coherence bandwidth $\mathbf{W_c}$ in rad/s is given approximately by the equation:

$$W_c \approx \frac{2\pi}{D} \ldots \ldots \ldots (41)$$

Also coherence bandwidth **Bc** in Hz is given approximately the equation:

$$B_C \approx \frac{1}{D} \ldots \ldots \ldots (42)$$

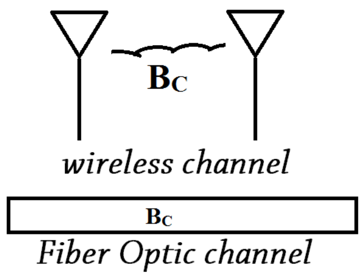


Figure 27: Coherent Bandwidth

If the $\mathbf{B_C > B_T}$ we have a non-selective fading channel, or flat fading and no dispersion and we don't have ISI illustrate in **Figure (28)**. So this is ideal signal we hope to obtain in digital communication.

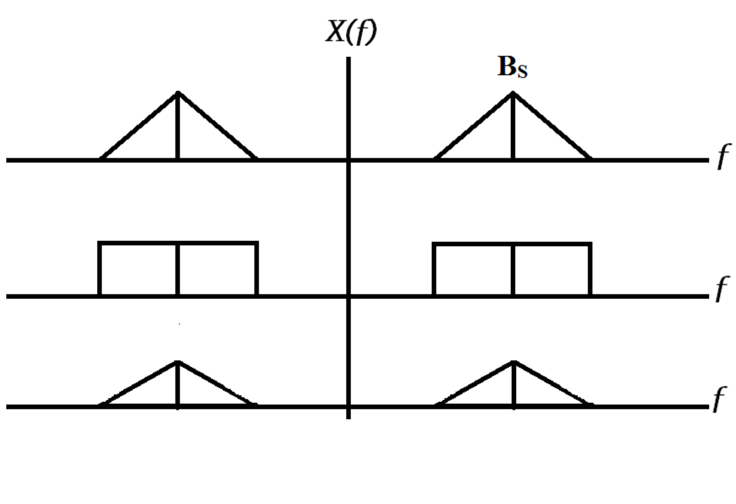


Figure 28: Non-Selective channel

If the BC < BT we have selective fading channel i.e. some frequency component in the signal spectrum get attenuated more than other illustrate in **Figure (29)**.

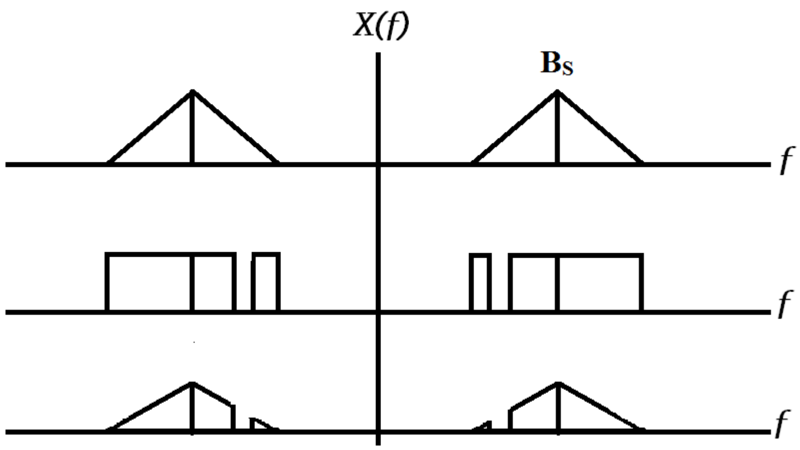


Figure 29: Selective channel

III.2.2 Propagation in multipath reflection signal

Multipath is the propagation signals reaching the receiver by two or more paths. Causes of multipath include reflection and refraction, because mountains and buildings illustrated in **Figure (30)**.

The effects of multipath include constructive and destructive interference, and phase shifting of the signal. Destructive interference causes fading. Where the magnitudes of the signals arriving by the various paths have a distribution known as the Rayleigh distribution, this is known as Rayleigh fading. Where one component (often, but not necessarily, a line of sight component) dominates, a Rician distribution provides a more accurate model, and this is known as Rician fading.

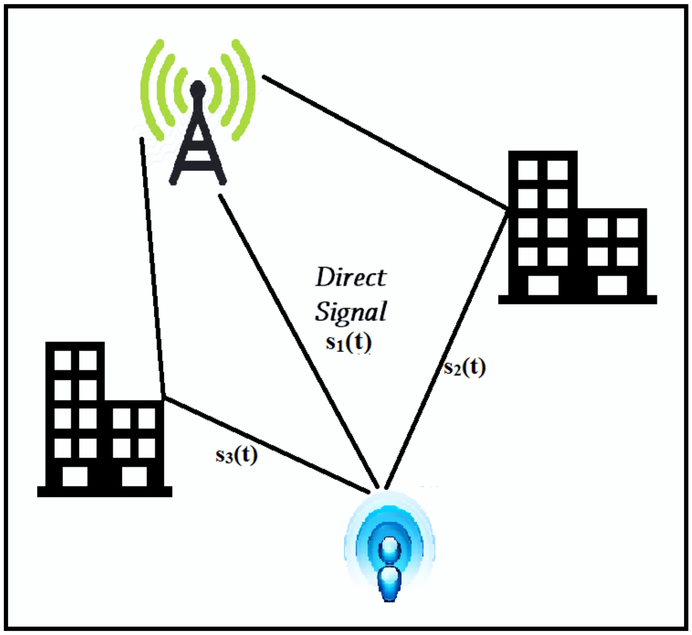


Figure 30: Multipath received signals

The received signal is:

$$y(t) = y_1(t) + y_2(t) + y_3(t) + \cdots + y_n(t) \ldots\ldots\ldots\ldots (43)$$

$$y(t) = h(0)x(t) + h(1)x(t-1) + h(2)x(t-2) + \cdots + h(n)x(t-n) \ \ldots\ldots\ldots (44)$$

$$y(t) = \sum_{n=0}^{N} h(n)x(t-n) \ldots\ldots\ldots (45)$$

In time domain $$y(t) = h(t) \otimes x(t) \ \ldots\ldots\ldots (46)$$

In Frequency domain $$Y(f) = H(f)X(f) \ldots\ldots\ldots\ldots (47)$$

The total received signal ***s(t)*** is the summation of multiple signal from multipath, the main problem with multipath is the different delay received data streams which will causes Inter-symbol interference, the solution is used equalizer of the signal. The OFDM modulation system has been reported to give much better performance in the multipath environment when it's compared to other modulation systems such as BPSK, QPSK and QAM.

III.2.3 Impulse response of the channel

The impulse response h(t) of a liner filter of the channel is the output y(t)=h(t) when a Dirac impulse is applied x(t)=δ(t).

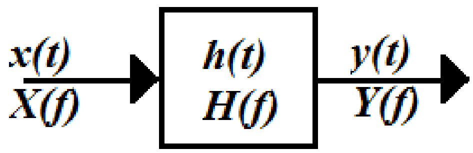


Figure 31: The Linear-Time-Invariant filter

For the simulated selective fading channel having direct and reflected paths is:

$$h(t) = \delta(t) - 0.9\delta(t - \tau i) \ldots \ldots (48)$$

The channel frequency is characteristics H(f) is found by taking the Fourier transform of impulse response h(t) as

$$H(f) = \mathcal{F}\{h(t)\} \ldots \ldots (49)$$

$$H(f) = \ \mathcal{F}\{\delta(t) - 0.9\delta(t - \tau i)\} \ldots .. (50)$$

$$H(f) = 1 - 0.9e^{-j\omega\tau i} \ldots \ldots \ldots (51)$$

So, the power transfer is:

$$|H(f)|^2 = H(f)H^*(f) \ldots \ldots \ldots \ldots \ldots \ldots .. \ldots (52)$$

$$= \left(1 - 0.9e^{-j\omega\tau i}\right)\left(1 - 0.9e^{j\omega\tau i}\right)$$

$$= 1 - 0.9e^{j\omega\tau i} - 0.9e^{-j\omega\tau i} + (0.9)^2$$

$$= [1 + (0.9)^2] - 0.9\left(e^{j\omega\tau i} + e^{-j\omega\tau i}\right)$$

$$= [1 + 0.81] - (2x0.9)\frac{e^{j\omega\tau i} + e^{-j\omega\tau i}}{2}$$

$$= 1.81 - 0.18\cos\omega\tau i$$

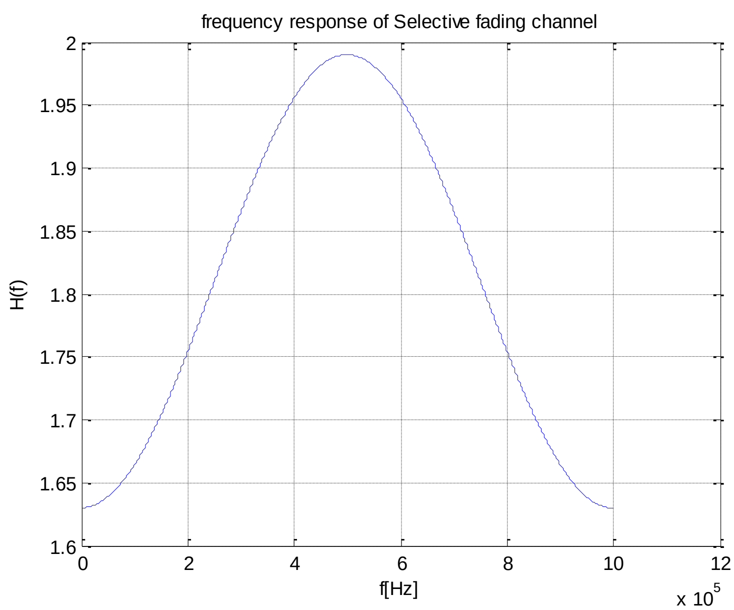


Figure 32: Impulse response signal

III.2.4 Inter Symbol Interference (ISI)

When the signal travels through a channel, objects in transmission path can create multiple echoes of the signal. Hoes occur at the receiver and overlap in successive slots. This is known as inter-symbol interference equalizers at the receiver can be used to compensate the effect of ISI created by multi-path within the time dispersive channel.

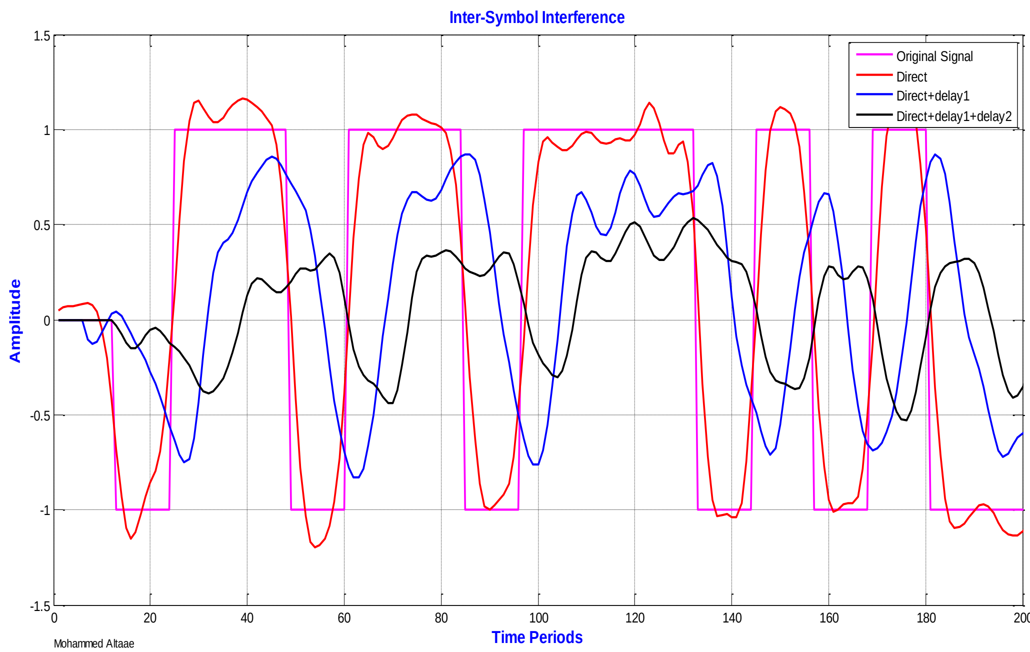


Figure 33: Inter-Symbol Interference represent in Multipath channel

This **Figure (33)** is explain the ISI in multipath channel, which is represent the signal detected without delay and with delay in received signal, we will explain in depth at simulation chapter in section (IV.7).

Chapter IV: Simulation

IV.1 Input Binary Data

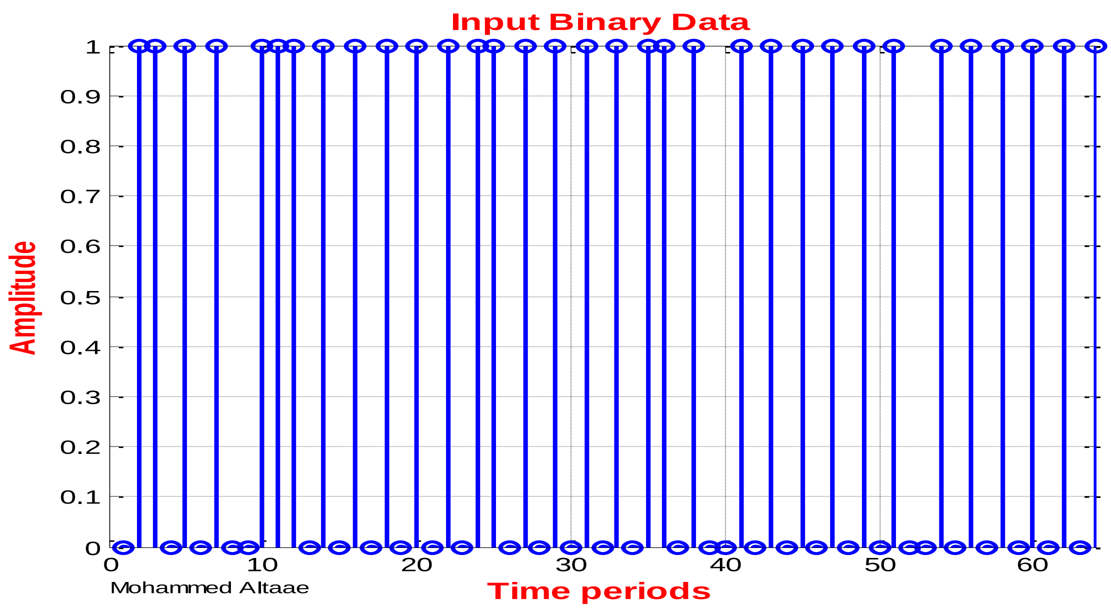


Figure 34: Input Binary Data Stream

In **Figure (34)** Generated Baseband information for 64-bit block. Note that the size of this generated data is L=64 is equal to 2^6, so that it will be suitable for IFFT which is used in OFDM later on.

IV.2 Base-band Time Signal

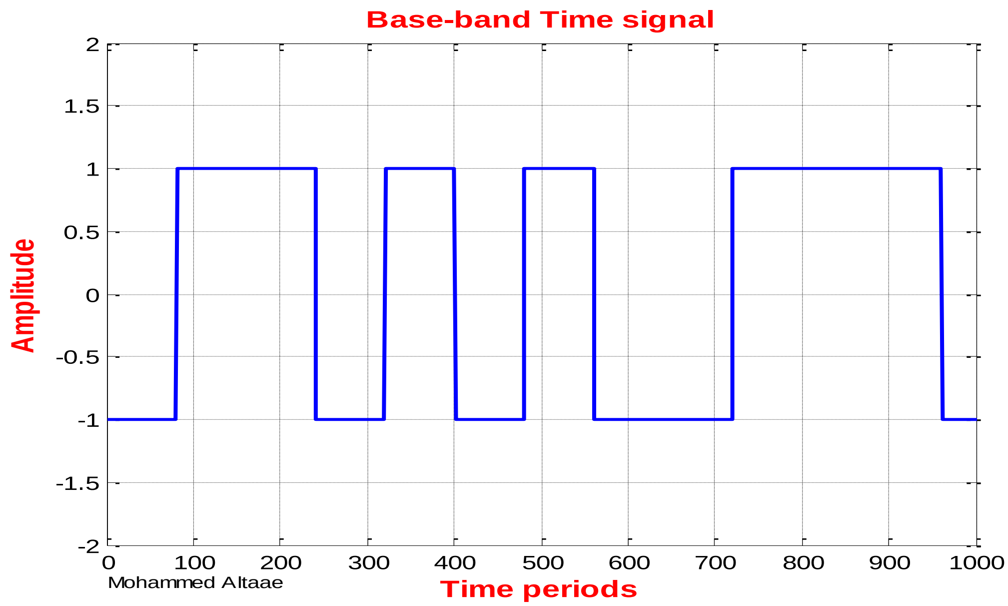


Figure 35: Base-Band Time signal

We convert the stream of bits 101010….. Into Time domain signal, where the bit have a number of sample (80) samples. Where one corresponds to 1 volt and the Zero corresponds -1 volt illustrated in **Figure (35)**.

IV.3 BPSK Modulated Signal

IV.3.1 BPSK Modulated signal without noise

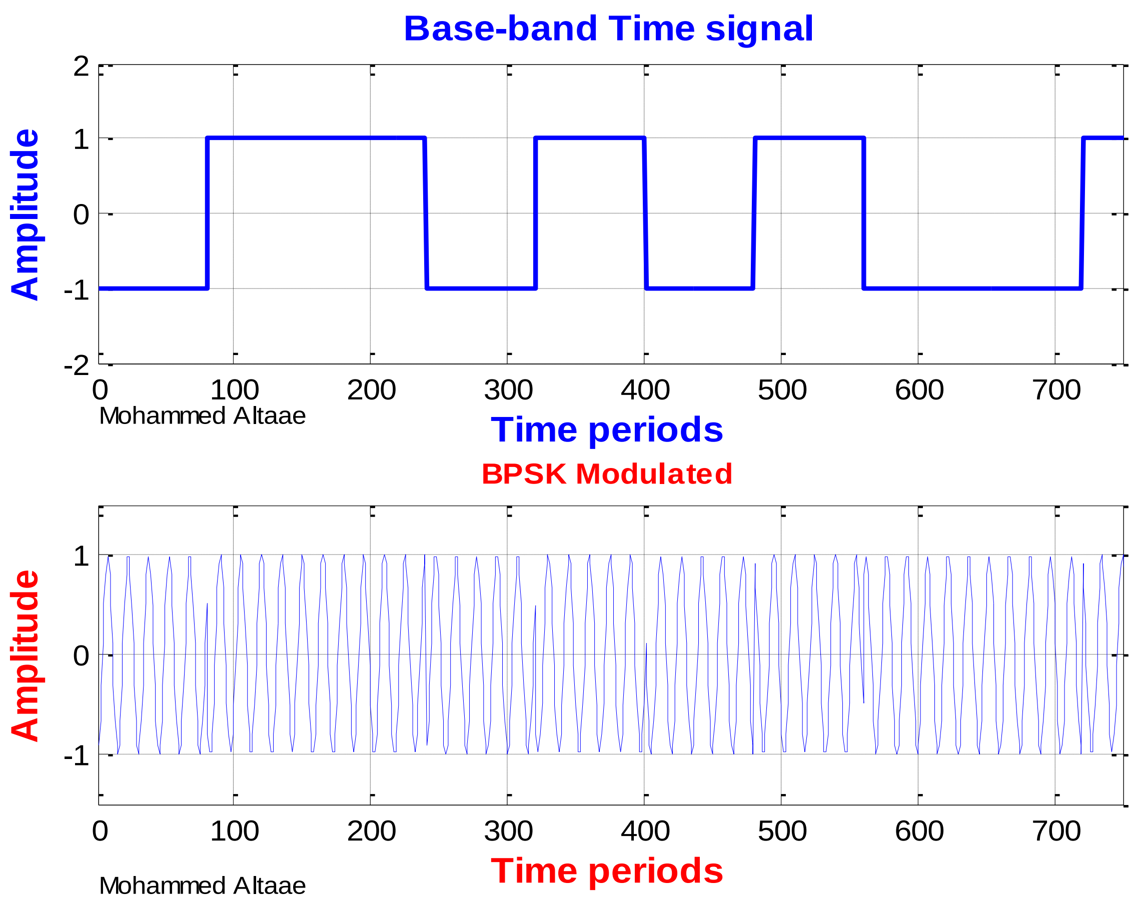


Figure 36: BPSK Modulated Signal

Subplot 1 represents the BPSK Modulated data. Notice the inverse phase when change bit from zero to one and vice versa depends on subplot 2 at baseband Time signal illustrated in **Figure (36).**

IV.3.2 BPSK Modulated Signal with Noise (AWGN)

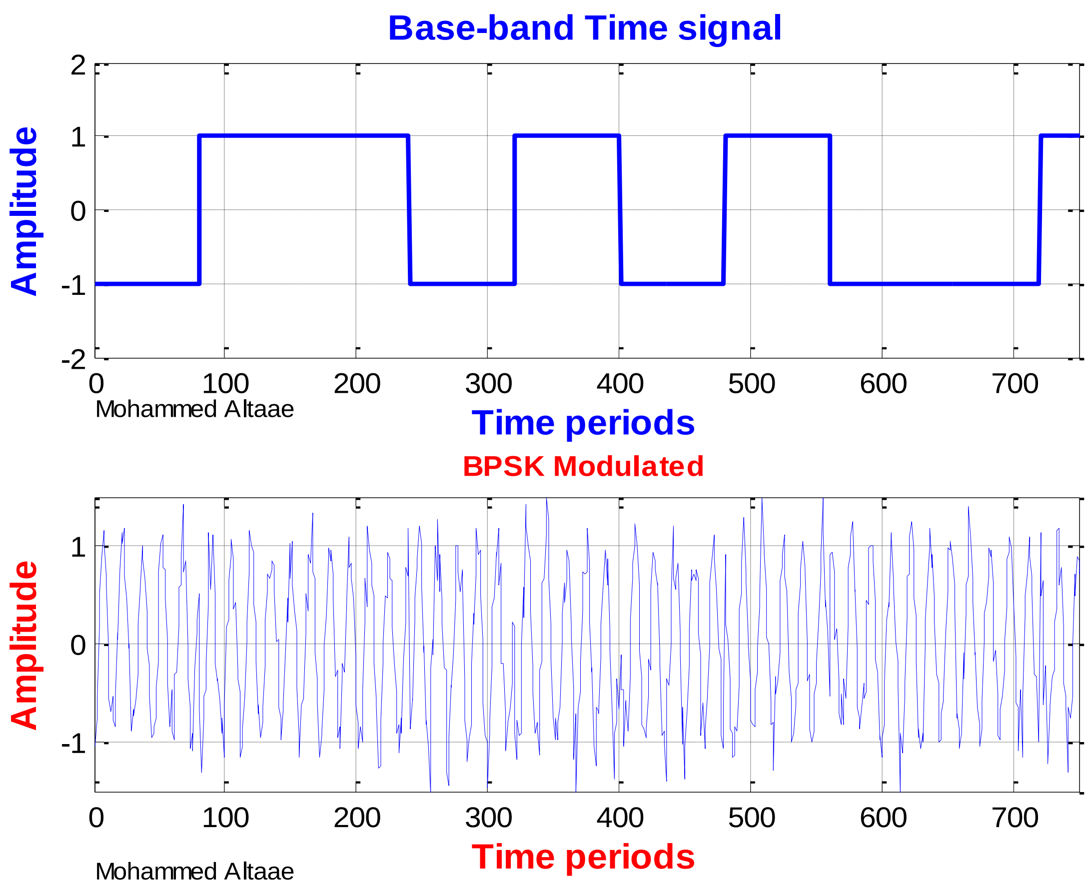


Figure 37: BPSK Modulated Signal with (AWGN)

This simulation we get the received signal for BPSK modulated signal through the channel with added AWGN and SNR=0dB.

IV.4 BPSK Demodulated Signal without Noise

IV.4.1 Block Diagram of BPSK Coherent Demodulator

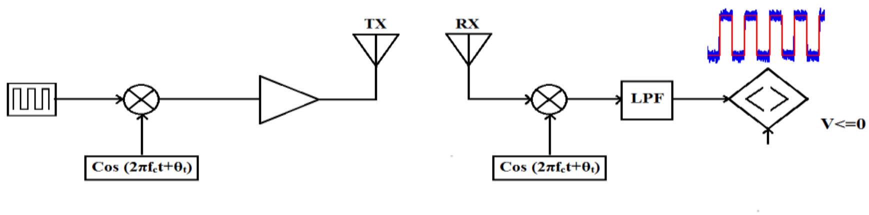


Figure 38: Block Diagram of Coherent BPSK Modulator and Demodulator

Modulated and Demodulated signal should have the same carrier frequency (f_c) and the same phase (θ_t) to a recover the correct data.

IV.4.2 Output Signal of Multiplier (Mixer)

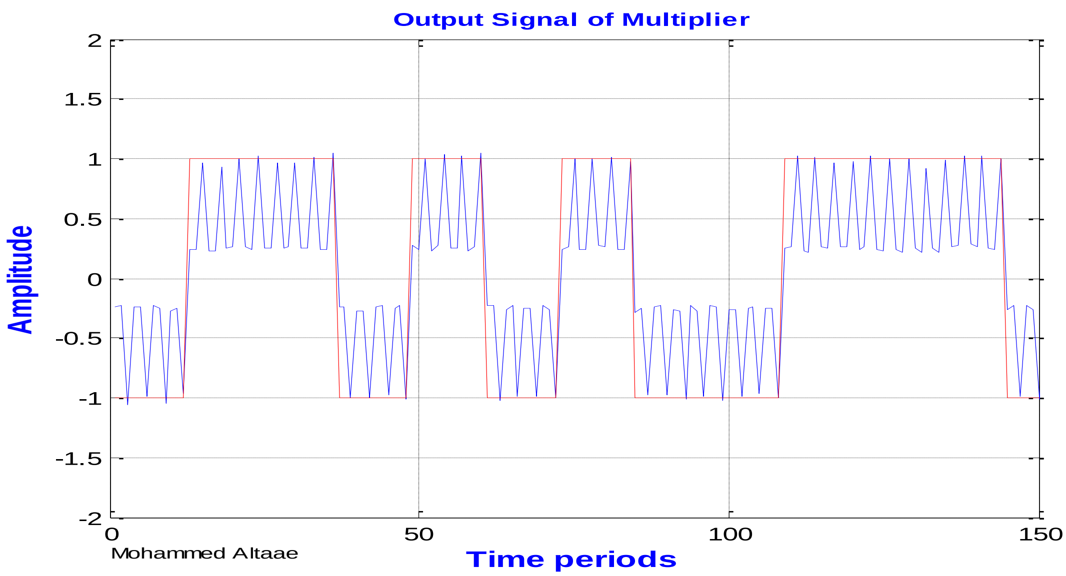


Figure 39: Output Signal of Multiplier

The BPSK modulated signal is the process by which phase of the carrier signal is varied in according to modulating signal. **Figure (38)** shown a simple of block diagram of BPSK modulated and demodulated signal. Depending for the logical condition of the digital input signal, the carrier transmitted to the output, either in phase or 180º with reference to the carrier modulated. The input signal to the detector can be $-\cos(wt)$ or $+\cos(wt)$.

In **Figure (39)** the output of the multiplier is shown (blue line) which contains residue of the carrier. This residue if filtered out be the LPF to produce the data (red signal).

IV.4.3 Frequency Response of LPF

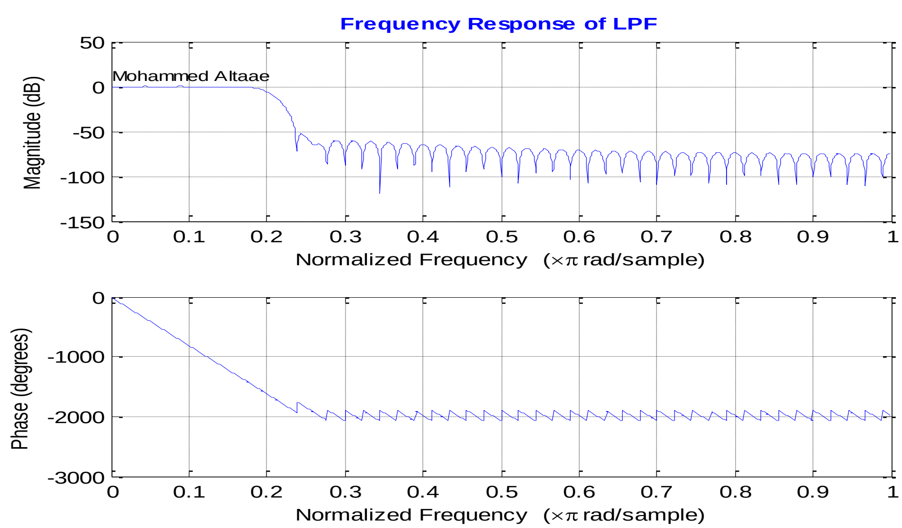


Figure 40: Frequency response of LPF

The LPF filter used in the demodulator is implemented (simulated) using Finite Impulse Response (FIR) filters. Are one primary types of digital signal processing (DSP) applications, the basic idea of filter design is that the ideal frequency response of the desired filter is equal to “1” for all pass band frequencies, and equal to "0" for all stop band frequencies, then the filter impulse response is obtained by taking the Discrete Fourier Transform (DFT) of the ideal frequency response.

IV.4.4 Output Signal of the Coherent demodulator (i.e. output of LPF)

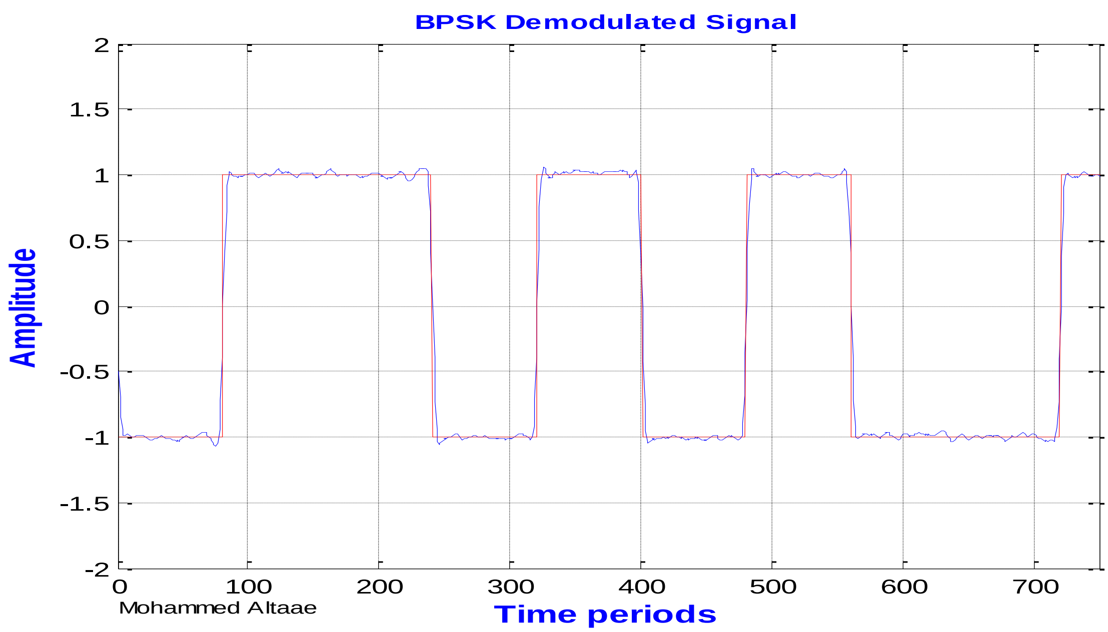


Figure 41: Demodulation signal with SNR 30dB

Simulation result **Figure (41)** of the demodulated signal with SNR 15dB to recovered the original Binary data stream signal.

IV.4.5 Output of the comparator

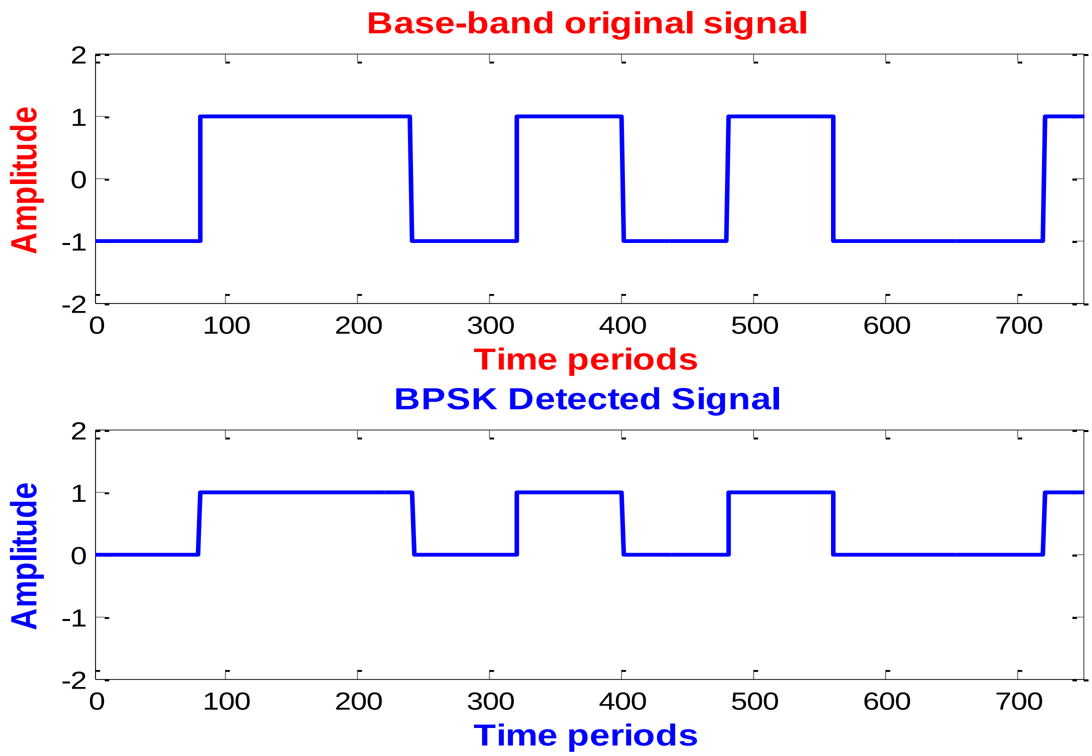


Figure 42: Detected data

We see in **Figure (42)** the BPSK detected signal from baseband original signal have the same period and the same pulse shape.

IV.5 BPSK Demodulated Signal with AWGN

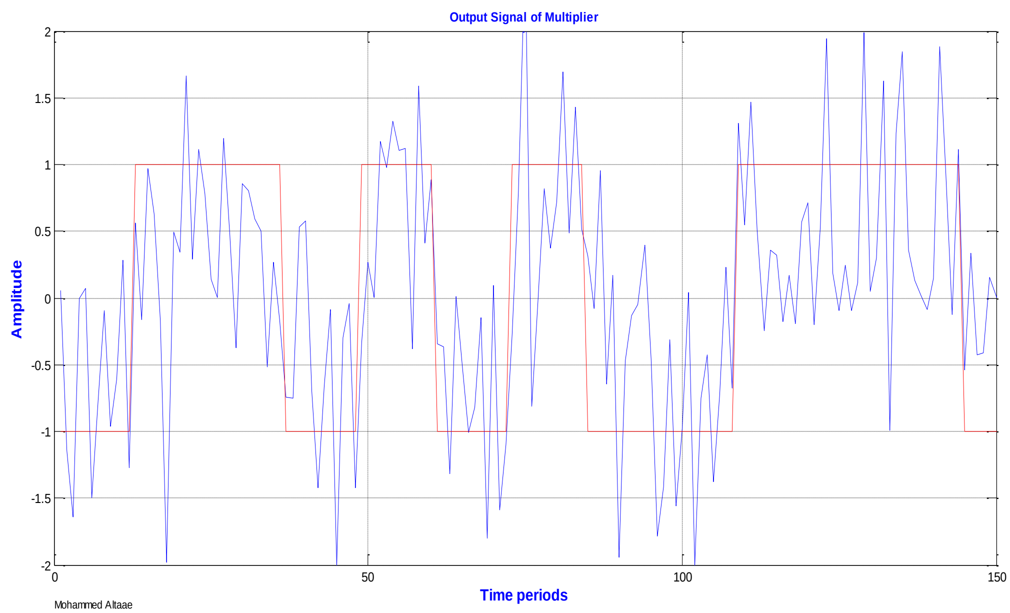


Figure 43: Output Signal of Multiplier with SNR=0dB

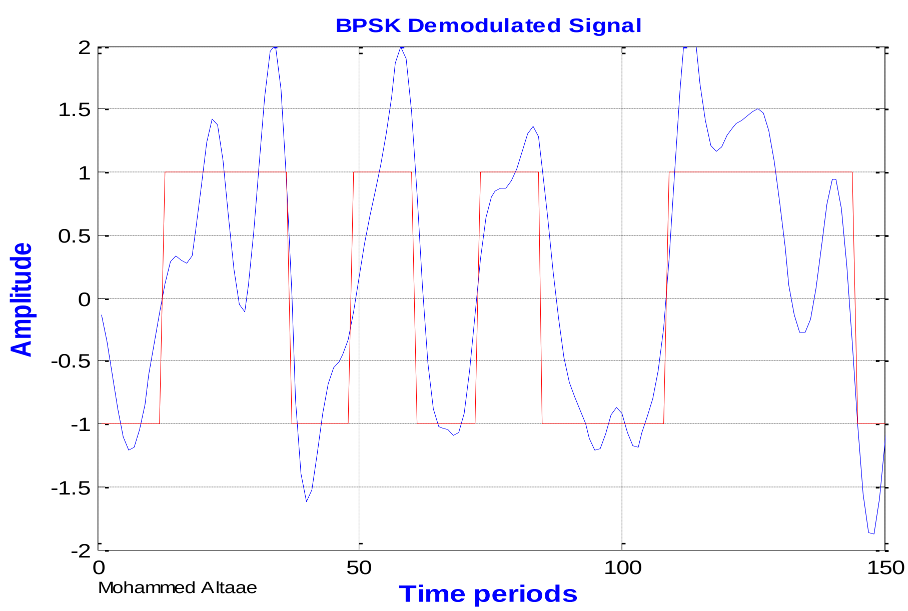


Figure 44: Demodulated signal with SNR=0dB

Before LPF filter **Figure (43)** and after LPF filter **Figure (44)** we can see the effect of LPF filter where it remove the residue of the carrier and reduce the noise power.

IV.6 BPSK Recovered original signal

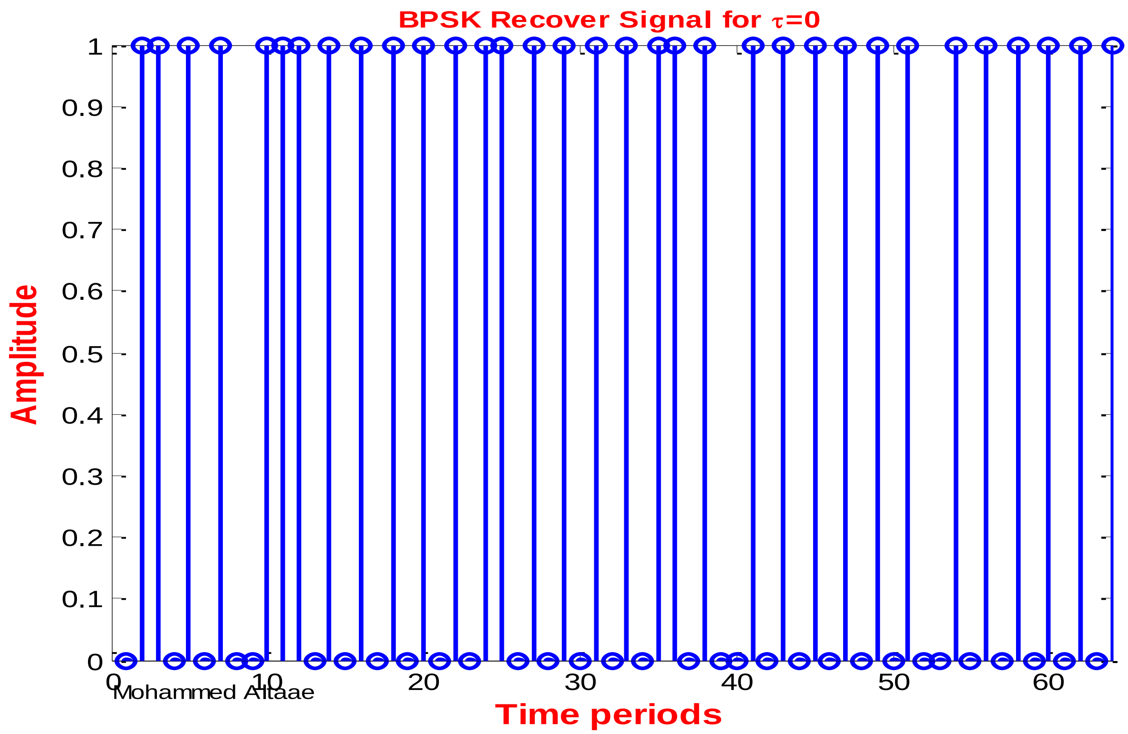


Figure 45: The original signal recovery (64-bits)

This signal is recovered through channel after BPSK demodulated signal from original Binary Data generated (64-bits).

IV.7 BPSK Demodulated Signal with Multipath

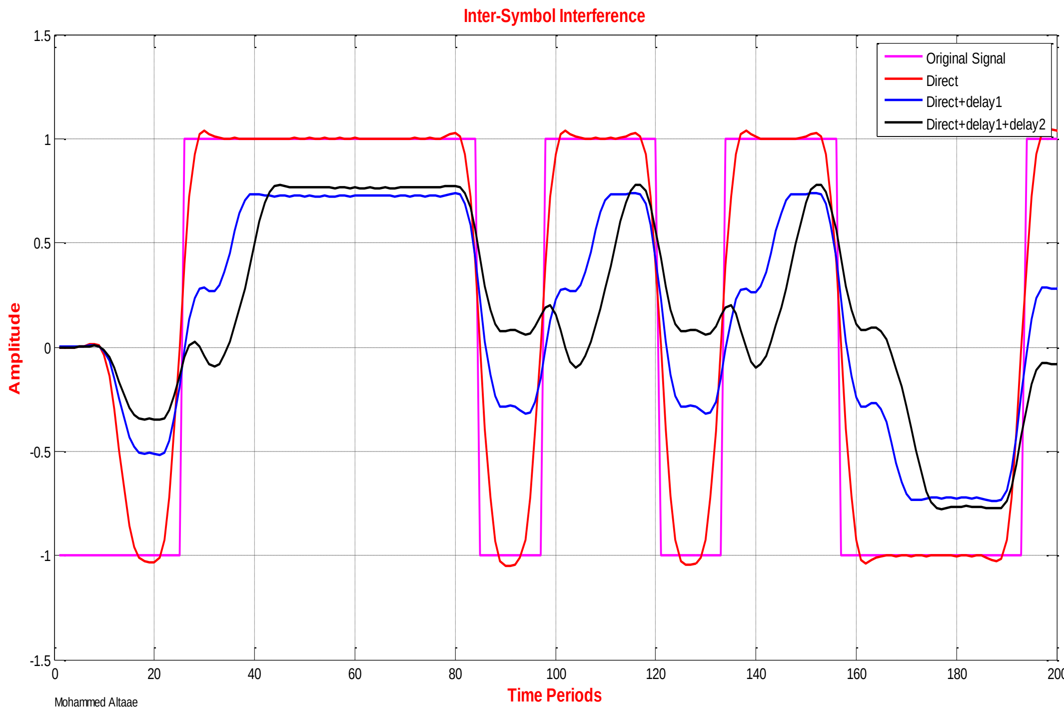


Figure 46: Inter-Symbol Interference

In simulation result for MATLAB program, we can see in **Figure (46)** the interference between the symbols for different paths propagation in the detector signal received. In BPSK modulation we suffer from ISI.

For example the original signal at i=140 is “1” whereas the detected signal with multipath (black line) is “0” which produce error due to Intersymbol Interference ISI.

IV.8 Power density spectrum of BPSK signal

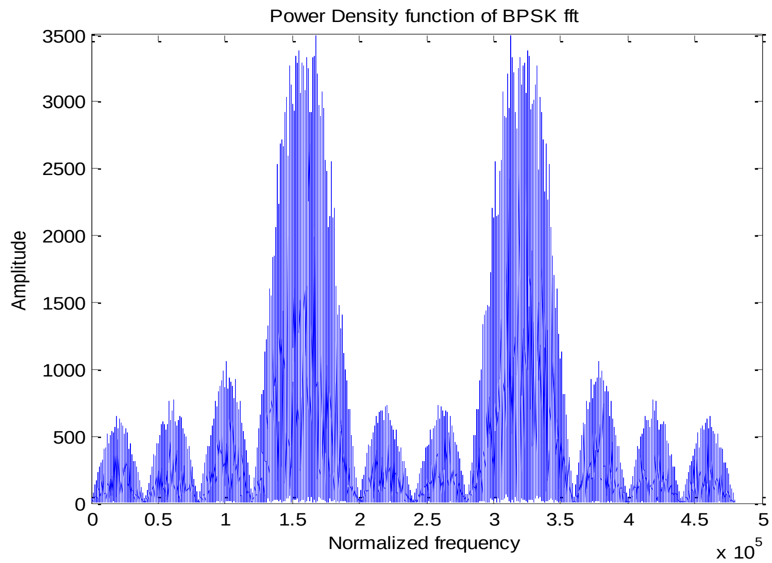


Figure 47: Power Density spectrum of BPSK signal

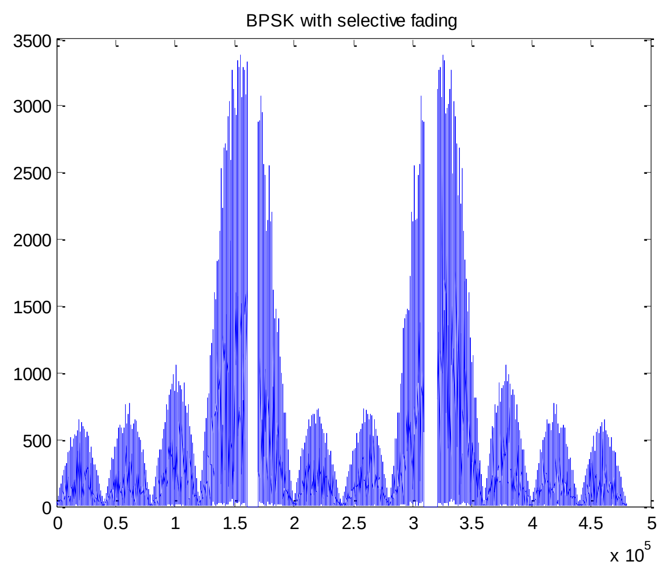


Figure 48: Power Density spectrum of BPSK signal with selective fading

This simulation result of **Figure (48)** shows the effect of selective fading of BPSK signal. We have simulated the multipath effect i.e. selective channel by forcing zeros "Attenuation" at the spectrum of the BPSK signal as shown in **Figure (47-48)**. The was achieved as follows Fast Fourier Transform (FFT) has been taken for BPSK time domain signal resulting in spectrum as shown in **Figure (47)** then zeros has been forced at frequencies ranging from ($1.602*10^5$-$1.702*10^5$) and ($3.099*10^5$-$3.206*10^5$) as shown in **Figure (48)**, then the time domain of BPSK signal is obtain by taken the Invers Fast Fourier Transform (IFFT) which is equivalent two time domain of BPSK signal after passing selective channel.

IV.9 Simulated BER for BPSK signal

Depend on the equation of multipath received signal represent by Equation (43). We have in this program simulation three path propagation represents a direct signal, delay1, and delay2. The ideal signal received is a direct propagation signal without any reflection. Because of multipath we have an N of signals propagated. In our simulation we create three paths (N=3) to evaluate the BER for each one.

In our simulation have first path is direct signal propagation. The second signal has delayed "1 sample" which correspond to time delay τ=20ns representing the reflected signal. Therefor the result of total signal for two paths is summation between the direct signal and the second signal with τ=20ns with small amplitude attenuation ρ_1=0.9.

The third path has delayed "5 samples" correspond to $\tau 2$=100ns and lower amplitude attenuation ρ_2=0.8 than second signal. And when we have the third paths or "N paths" the total signal received from one source is the sum of all signals with respect the attenuation for each one.

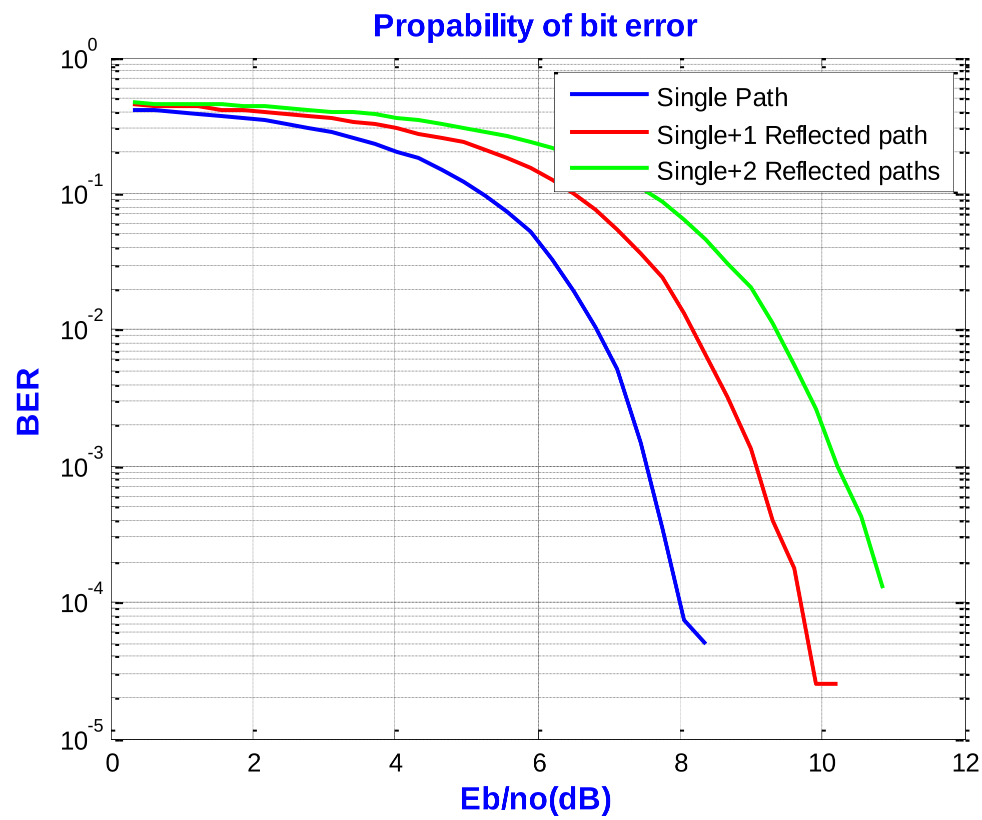


Figure 49: BER Curves for Multipath for BPSK modulation

In this program simulation **Figure (49)**, we have BER vs. of SNR for three cases the range of SNR between (-19:15). The single path is represented by the color "blue curve", the second case for delay (τ1) represents the color "red curve", and the third case for delay (τ2) is represented by the color "green curve". There results illustrate that the BER of BPSK modulation get worse when we have multipath propagation.

For example with case two paths signal (Red curve) the BER is worse by 2dB for BER=10^{-4} compared with single path (Blue curve), and for case three paths signal (Green curve) the BER is worse 3dB for BER=10^{-4} compared too with single path (Blue curve).

IV.10 BPSK through selective channel

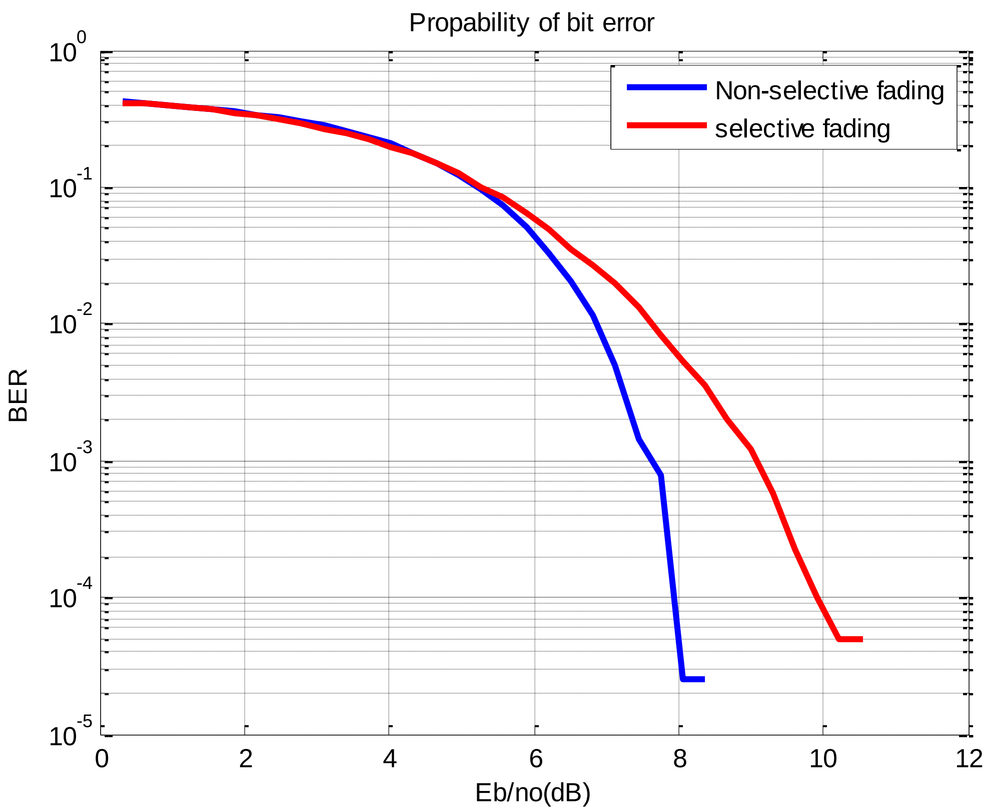


Figure 50: BER for BPSK with selective fading

Simulation of selective fading by forcing zeros at BPSK spectrum by ratio $w_0/w=0.125$ where w_0 is width of the forcing zero on the BPSK spectrum and w is width of the total BPSK spectrum, as shown in **Figure (48)** as we can see clearly in **Figure (50)** the performance of BPSK for selective fading "Red curve" get worse by 2dB for BER=10^{-4} when it is compared with non-selective fading (single path) represent by "Blue curve".

IV.11 16-QAM Modulated Signal

The following simulation we simulated 16-QAM constellation and simulated the various stage of demodulation which are shown in following.

IV.11.1 16-QAM Constellation method to generate

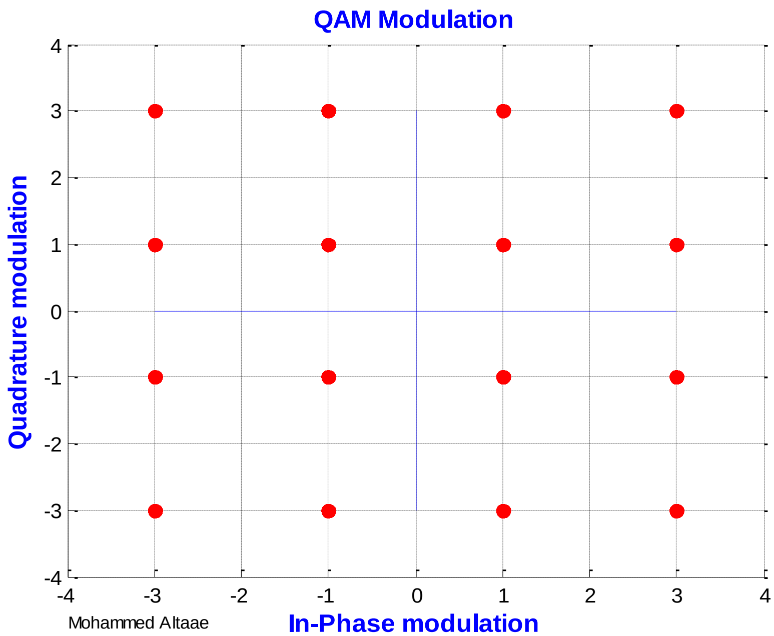


Figure 51: 16-QAM Constellation for I and Q

Figure (51) represent simulation result of MATLAB program to 16-QAM modulation has 16 constellation each one has real and imaginary represent (In-phase and Quadrature), to modulate the total binary bits stream by divided total bits stream / 4, and converted the binary signal into analog signal to modulation each value at each location of constellation see in **Figure (20)**, we can see that each value of analog signal has certain position at the 16-QAM constellation.

IV.11.2 16-QAM Modulation through channel

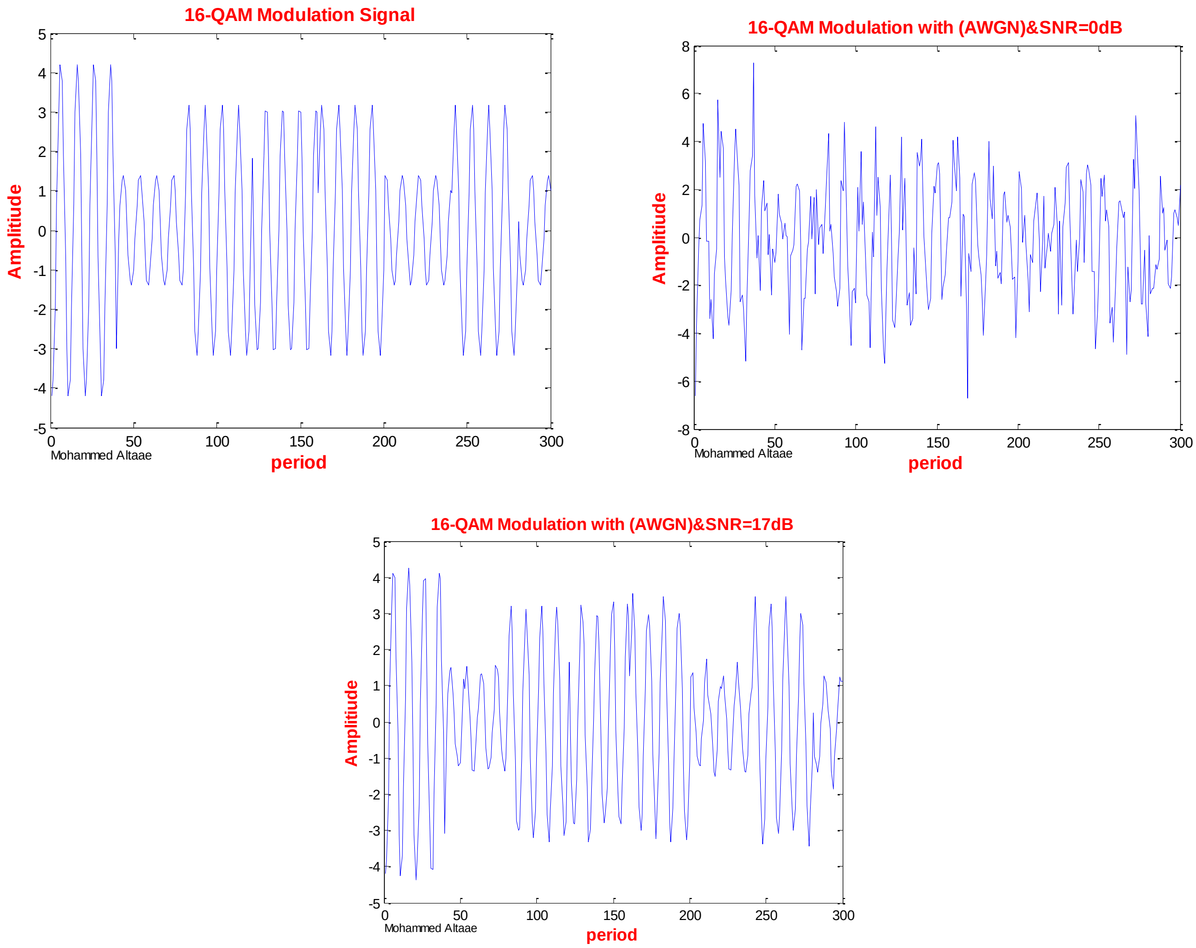


Figure 52: represent the effect signal by AWGN

To simulate the effects of the channel we use the additive white Gaussian noise, which we choose to run in signal to noise ratio mode for the modulation signal. We see in **Figure (52)** effects AWGN on the signal when SNR=0dB the signal has more of noise and in other value of SNR=17 the signal has noise less than previous values.

IV.12 16-QAM Demodulation

IV.12.1 16-QAM Demodulated Signal

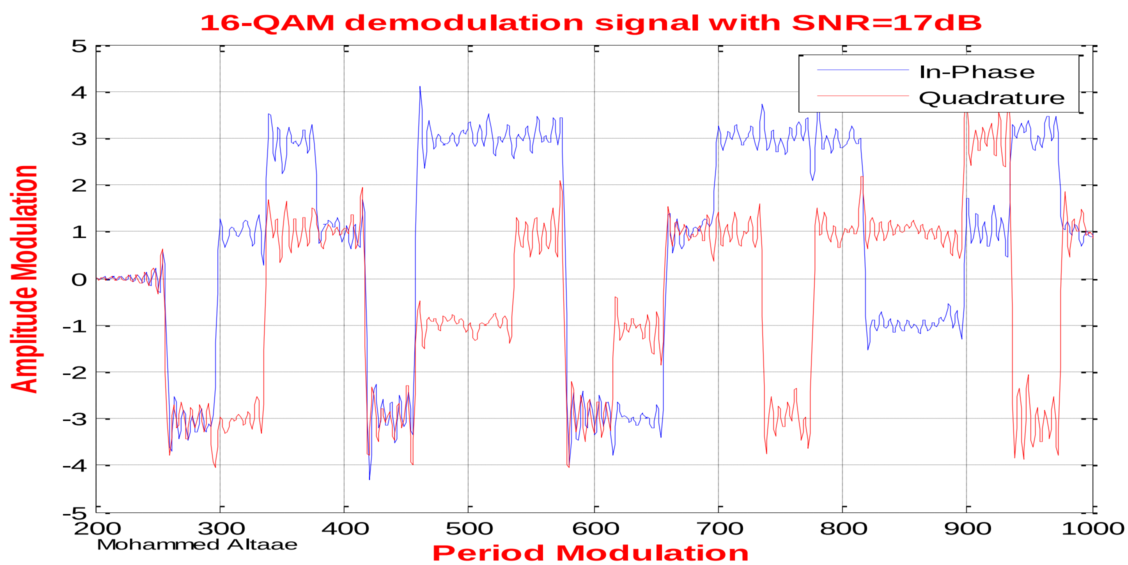


Figure 53: Represent Phase of I and Q

Figure (53) is the simulation result to demodulation signal after pass though LPF filter we can see the in-phase and quadrature signal that is represent the same phase used to modulation signal represent [-3 -1 1 3] for in-phase and quadrature signals. From this signal we can recovered the data stream that are modulated.

IV.12.2 Multiple Figure for Several SNR with (AWGN)

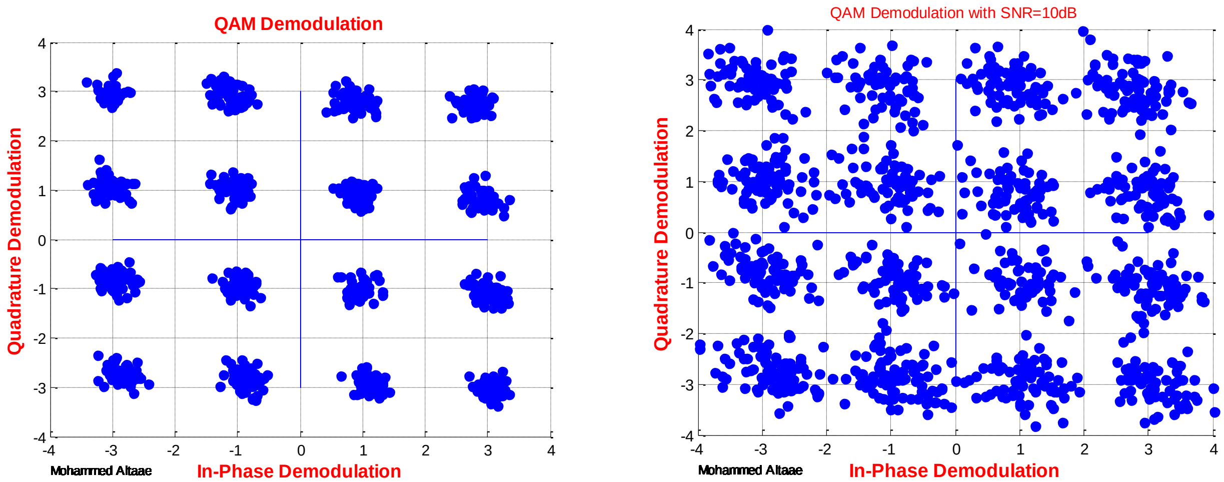


Figure 54: 16-QAM Demodulation with different SNR value

We can see in this simulation result the effect the AWGN with SNR for different values. When SNR was equal 0dB the constellation is more effects to the noise, and when SNR was equal 17dB the spreading in constellation points is lower bit error.

IV.13 BER of QAM modulation

After us using 16-QAM to transmitted (64000-bits) though the multipath channel we obtain the multiple curve for each case. The ideal BER curve represents the single path have color “Blue”. The BER curve have color “Red” represent the second case affected by the reflection with delay ($\tau1=1$ sample) and undergoes to the same Equation (44). And the third BER curve have color “Green” undergoes to Equation (44) with delay ($\tau2=1$sample) but have a different value of attenuation.

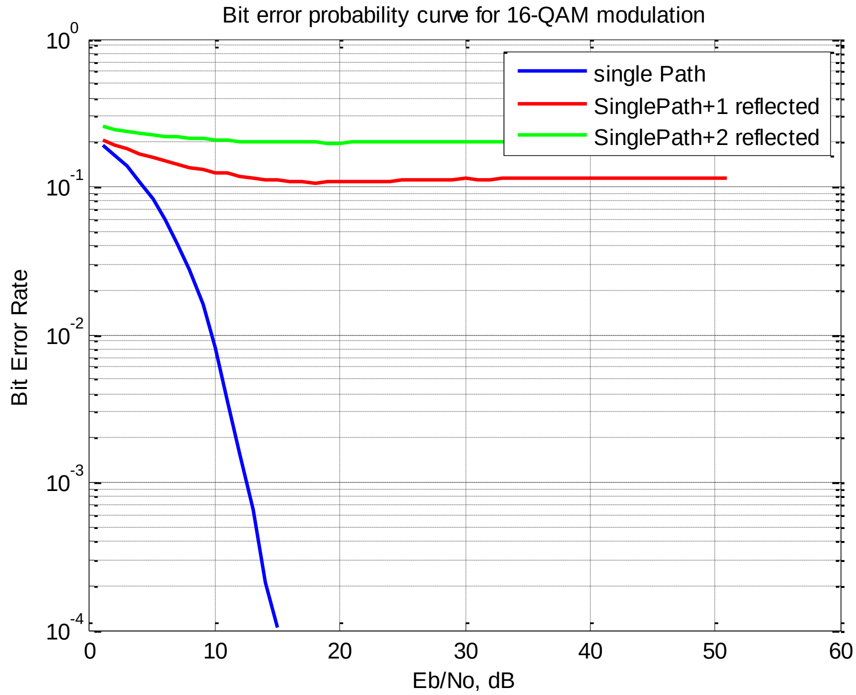


Figure 55: BER curves for Multipath channel

The problem (ISI) is very acute in QAM demodulation when detected the original signal that is represent the summation for multipath. We can see in **Figure (55)** the BER curve “Red color” represent a summation of two paths (direct signal and the second path that’s have the same data of direct signal with $\rho=0.9$ and 1 sample delay). We conclude from the effect of BER curve “Red” color get worse, because the distance between adjacent points D2 in 16-QAM less than D1 in BPSK modulation illustrated in **Figure (56)**. Therefore, the effect ISI on the multipath in 16-QAM more than BPSK signal.

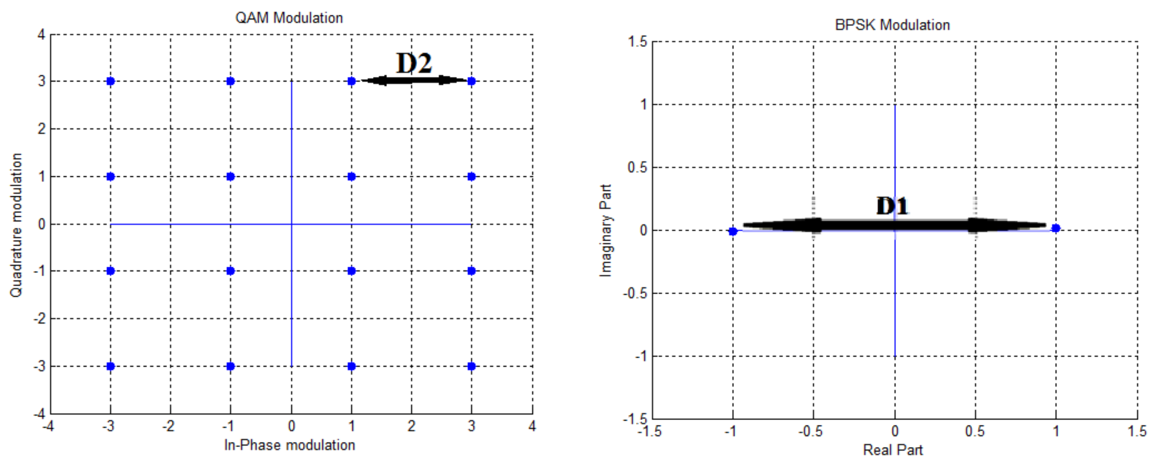


Figure 56: 16-QAM and BPSK Constellation Diagram

IV.14 Simulation of OFDM system

IV.14.1 Spectrum of OFDM transmitted signal

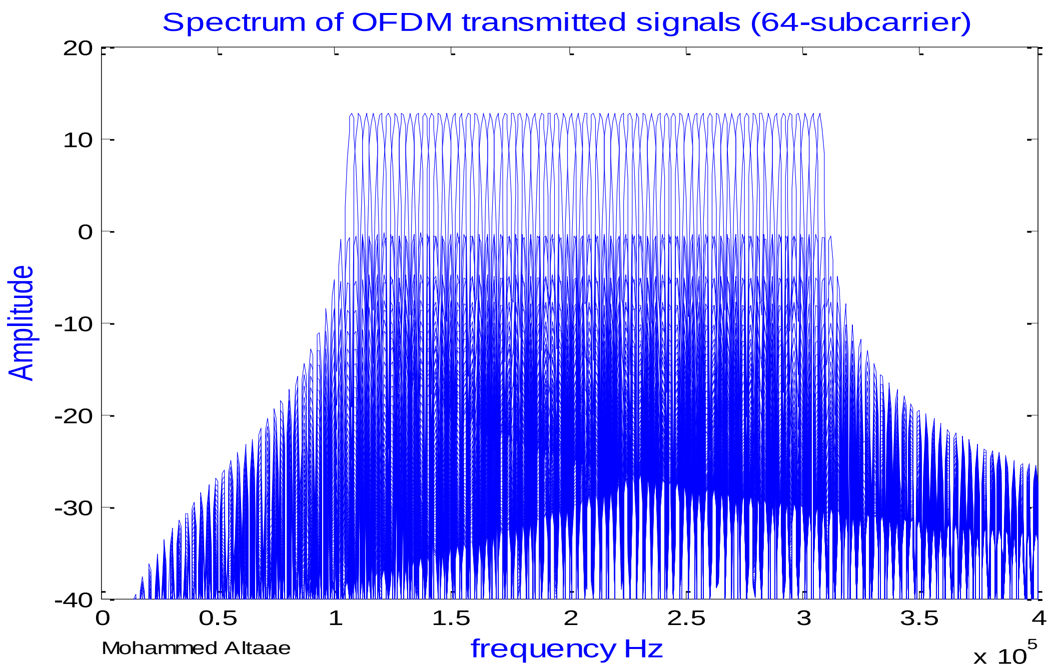


Figure 57: Spectrum of OFDM transmitted signal of 64 subcarriers

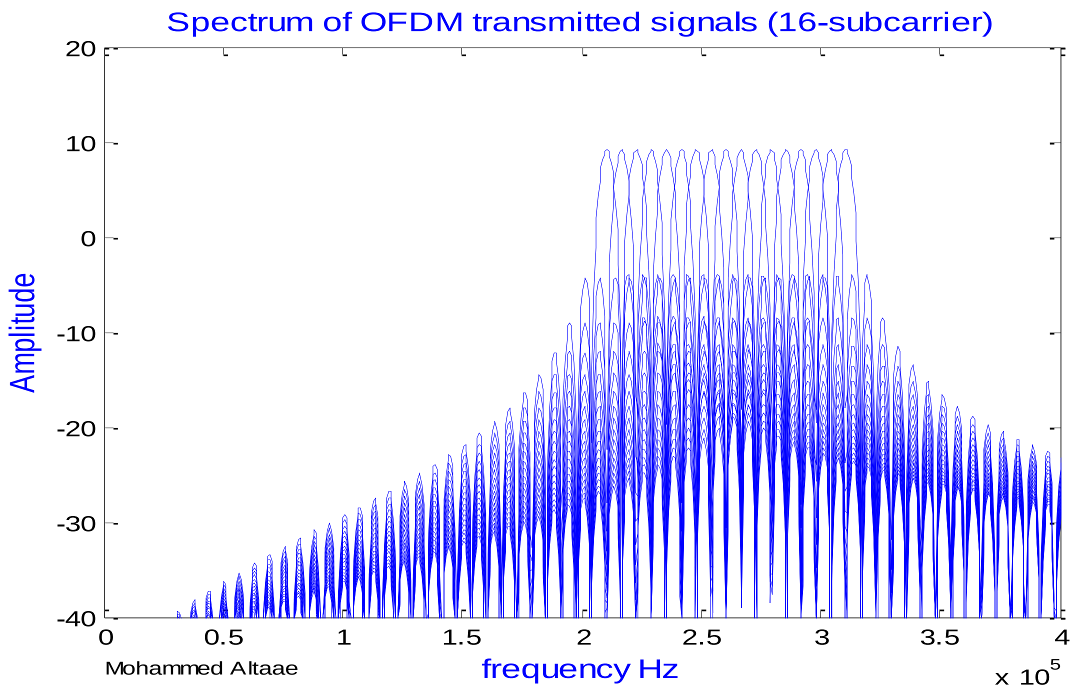


Figure 58: Spectrum of OFDM transmitted signal of 16 subcarriers

OFDM, like FDM, separates the channel bandwidth into multiple narrow-band subcarriers to carry the information, to provide adjacent carrier interference (ACI). This result in a waste spectrum of OFDM, to solve this problem of OFDM uses a special subcarrier that are all subcarriers orthogonal to each other. That is not only permits to remove the guard bands, but since the subcarriers are completely orthogonal, they can be overlap to each other. This is why OFDM is bandwidth efficient.

The use of narrow-band sub-channels makes the system is very resistant to fading channel. In this simulation result **Figure (57)** and **(58)** represent the spectrum of OFDM transmitted signal for 64-subcarriers and 16-subcarriers. As we can see the occupied OFDM bandwidth increases with the number of sub-carrier but still much less than multiple carrier case.

IV.14.2 Cyclic Prefix in OFDM signal

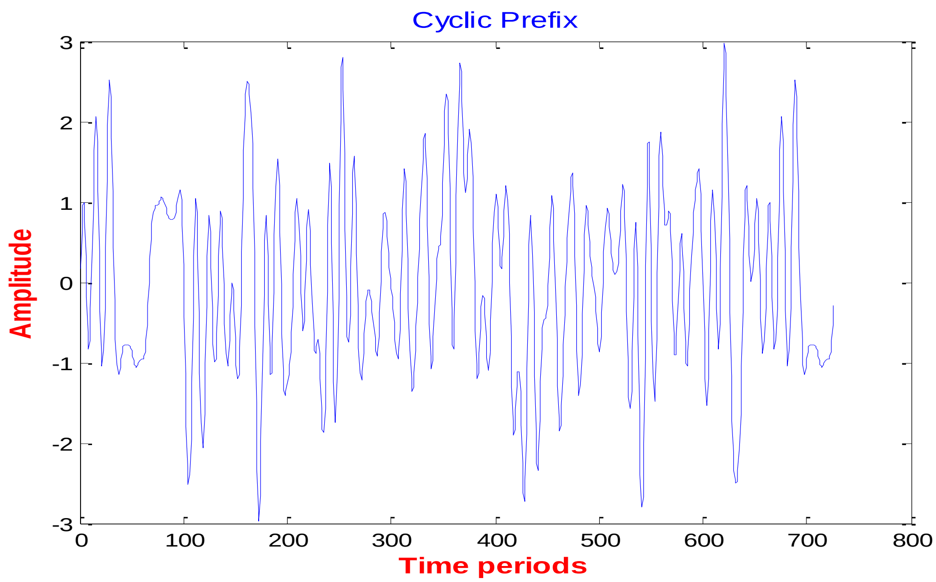


Figure 59: Cyclic Prefix in OFDM Signal

The simulation result shown the cyclic prefix practically as in **Figure (59)**, is to extend the OFDM symbol by copying the Last segment of the OFDM symbol into head side of the same symbol, here we presented CP occupies 10% from symbol duration.

Let **Tsym** and **T_{cp}** denote the length of CP in term of samples and symbol duration with guard interval respectively. Therefore, the extended OFDM symbols now have the duration of $T_{OFDM} = T_{sym} + T_{CP}$ illustrated in **Figure (60)** It can be seen from this figure that if the length of the CP is set longer than or equal to the maximum delay of multipath channel, we will remove the ISI and maintaining the orthogonality among the subcarriers **[32][33]**.

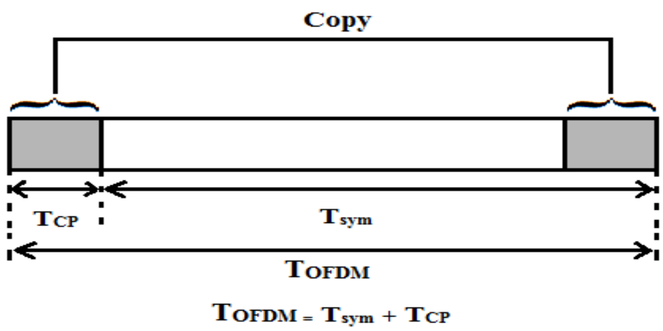


Figure 60: OFDM symbol with Cyclic Prefix

IV.14.3 OFDM through selective channel

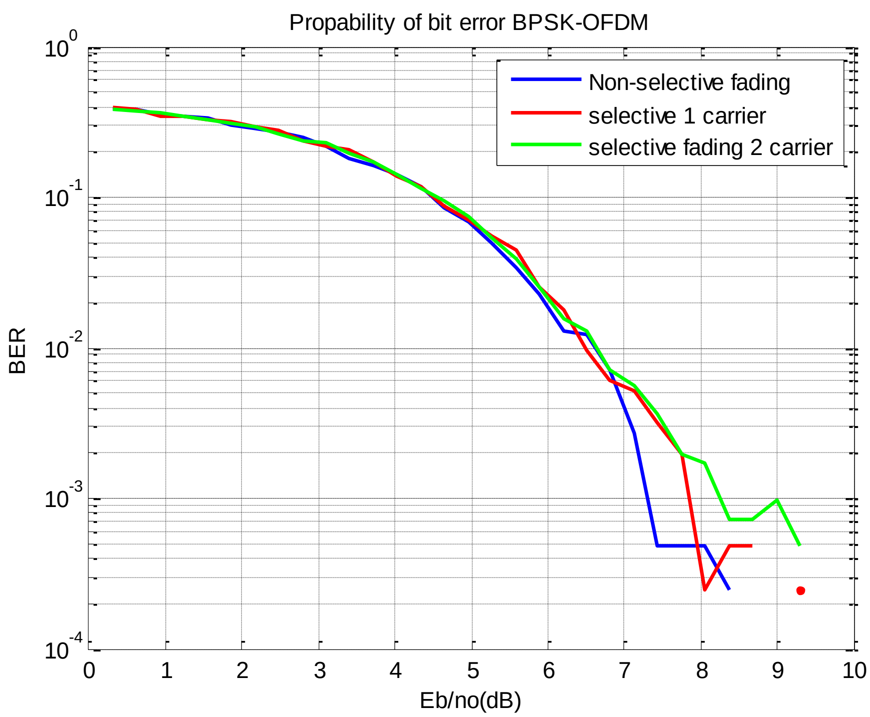


Figure 61: BER for OFDM with Fading Signal

In this simulation result in **Figure (61)** selective fading for 1 carrier and selective fading for 2 carriers and was 20dB. We can see clearly form figure that the BER has change only slightly, which prove that the OFDM system has repost performance in selective fading channel. We can repeat for selective fading 30dB fading for 1 carrier and for 2 carriers illustrated in **Figure (62)**.

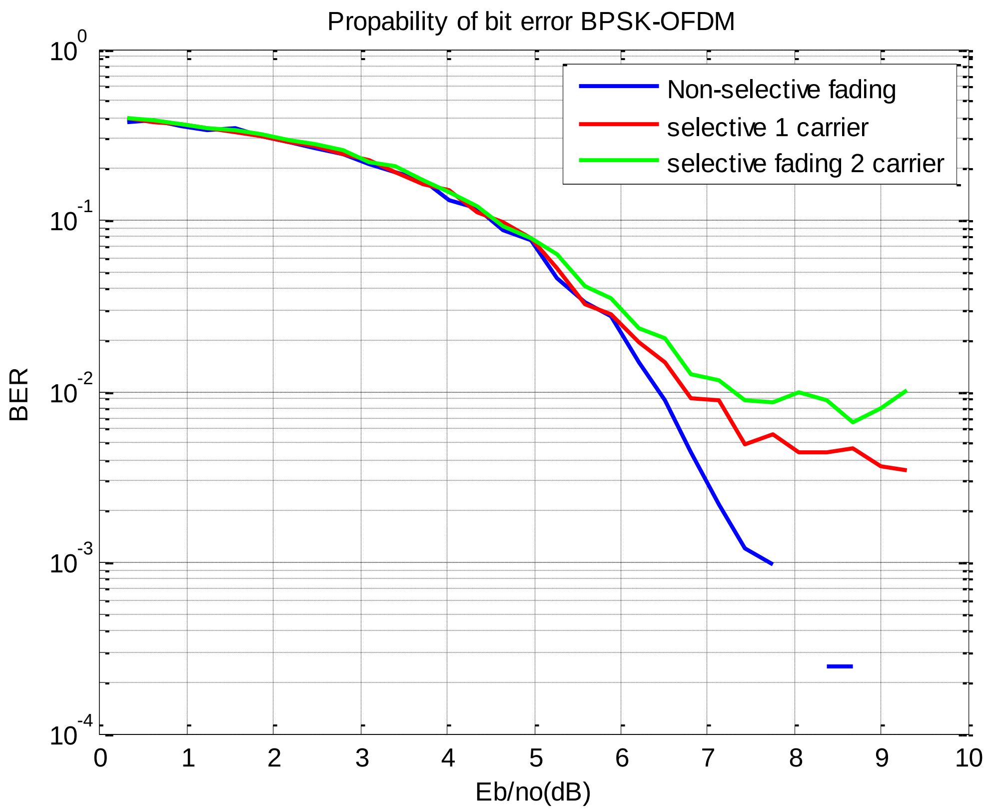


Figure 62: Selective fading of 30dB

For BER 10^{-2} we can see that's performance of OFDM system has worsen by 1dB and 2dB for one carrier and two carrier fading respectively.

IV.14.4 Effect of CP-length on BER

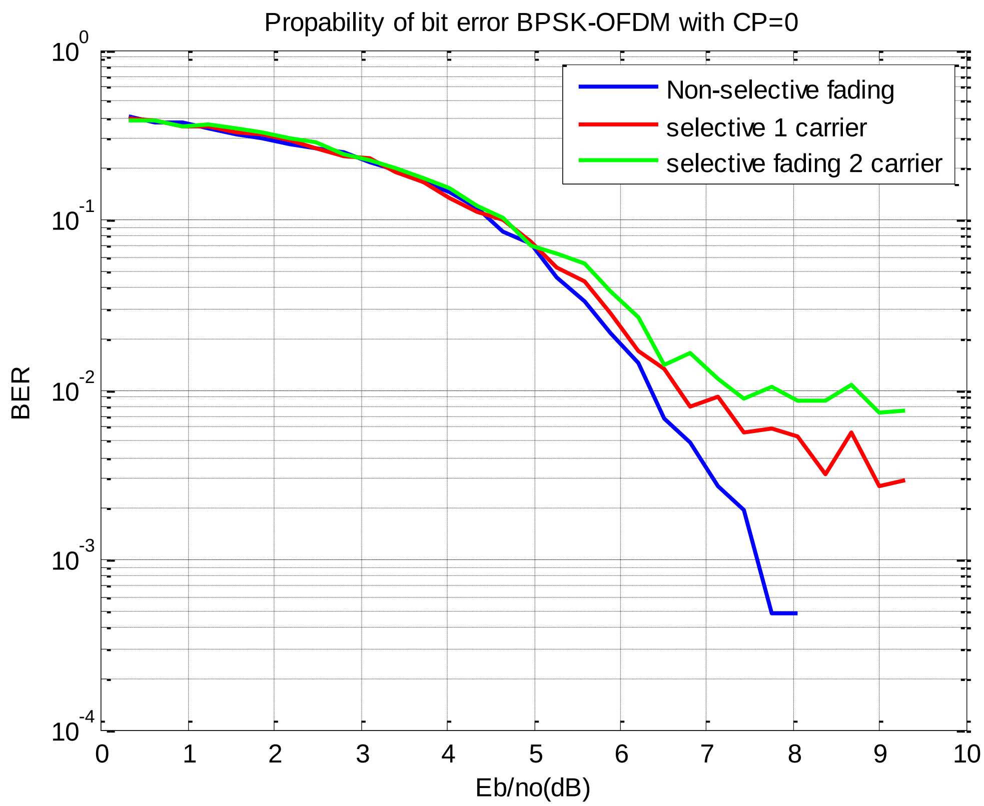


Figure 63: BER for OFDM signal with CP=0

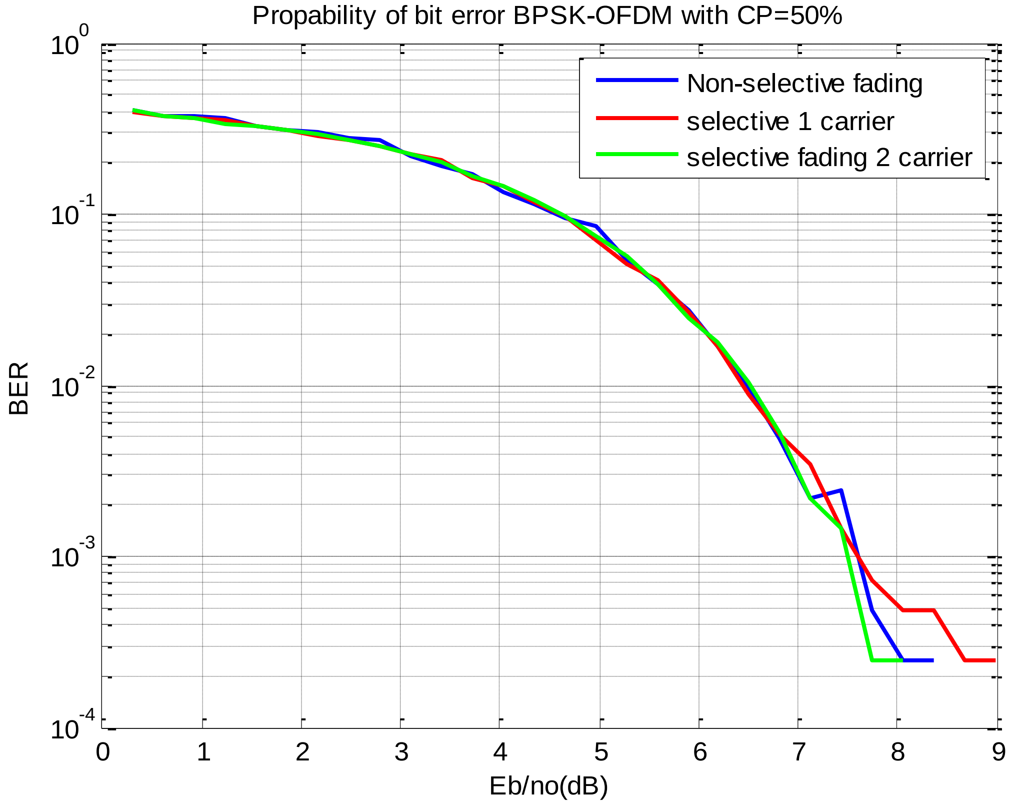


Figure 64: BER for OFDM signal with CP=50%

Figure (63-64) in this simulation results we can see the effected cyclic prefix in OFDM signal, this simulation proved that the performance of OFDM is effected by multipath represent by "red" and "green" curve.

In **Figure (63)** we denote the effects selective fading on the signal for second case "Red curve" have selective fading (30dB) for one carrier the BER is worse 0.3dB for BER=10^{-2} compared with non-selective fading "blue curve" and for third case "Green curve" we have selective fading (30dB) for two carriers the BER is worse 1dB for BER=10^{-2} compared too with "Blue curve".

And in the **Figure (64)** shows OFDM performance after adding CP=50% the all curves for selective fading and non-selective fading have approximately the same Curve of BER non-selective fading, instead of the cyclic prefix is a good solution for selective fading. Therefore, the OFDM signal is provide solution for digital communication than other modulations signal.

Conclusion and Suggestion for future work

OFDM modulation scheme performance has been studied and researched extensively when operating in wireless channel as well as in wire channel such as ADSL.

Little work was concerned with OFDM performance in Multi-Mode Optical Fiber MMOF.

In this work we have studied the performance of OFDM modulation scheme over MMOF channel as well as the performance of Counterparts modulation scheme such as BPSK and QAM. All performance of the above mentioned modulation schemes are measured in term of Bit Error rate (BER) versus signal to Noise ratio per bit.

By the end of this work we obtained through extensive MATLAB simulation a quantitative evaluation of both BPSK, QAM and OFDM Modulation scheme in Multi-Mode Optical Fiber. We demonstrated the effectiveness of OFDM modulation scheme when operation with multipath (selective fading) channel such as Multi-Mode Optical Fiber MMOF. The performance of OFDM modulation scheme which was measured in term of Bit Error Rate (BER) has been proved to be superior to that of conventional BPSK or QAM modulation scheme, when both are operated in MMOF channel. For single delay for τ=20ns and double delay with $\tau 1$=20ns and $\tau 2$=50ns. These delays are associated with chromatic dispersion in MMOF.

For future work we suggest to carry out extensive research on the problem of high peak to average power ratio (PAPR) which is associated with OFDM modulation scheme and the relatively narrow dynamic range associated with optical fiber.

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