University of Nairobi
School of Computing and Informatics

Investigating OFDM suitability to Link Adaptation as a modulation technique for data transfer

Submitted

By

Kenneth Odhiambo Ouma

Supervisor
Prof. Okelo-Odongo

Acknowledgement

I am thankful to God for his everlasting blessings, may his will be done upon my life. To my parents and family, I am very grateful for the support and precious prayers which helped us in continuing our project even in desperate times when we got stuck in the project.

I am also thankful to my supervisor, Professor Okelo-Odongo for valuable guidance and insight in the process of writing this literature. Secondly we appreciate the valuable comments and suggestions from Mr. Stephen Mburu who helped in this project as well as sharing their expertise and their knowledge of the subject which allowed us to complete our project. A special mention to panel members; Mr. Robert Oboko and MS Christine Ronge for their steadfastness in seeing us through this process.

Abstract

The project investigates the effectiveness of Orthogonal Frequency Division Multiplexing (OFDM) as a modulation technique for wireless radio applications. The main aim was to access the suitability of OFDM as a modulation technique for a fixed wireless data transfer system for geographically challenged areas in Kenya. However, its suitability for more general wireless applications is also accessed.

Most third generation mobile phone systems are using Code Division Multiple Access (CDMA) as their modulation technique. For this reason, CDMA is also investigated so that the performance of CDMA could be compared with OFDM on the basis of various wireless parameters. At the end it is concluded that the good features of both the modulation schemes can be combined in an intelligent way to get the best modulation scheme as a solution for wireless communication high speed requirement, channel problems and increased number of users.

Table of Contents

Table of Figures

List of Tables

Abbreviations and Acronyms

AWGN	Added white Gaussian noise
BWA	Broadband Wireless Access
CDMA	Code Division Multiple Access
CP	Cyclic Prefix
DFT	Discrete Fourier Transform
DPSK	Differential Phase Shift Keying
DSL	Digital Subscriber Line
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
ICI	Inter-Carrier Interference
IDFT	Inverse Discrete Fourier Transform
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
IP	Internet Protocol
ISI	Inter-symbol Interference
MCM	Multi Carrier Modulation
M-PSK	*M*-th order Phase Shift Keying
NLOS	Non Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PDU	Packet Data Unit
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
Symbol size	Number of bits per symbol to indicate number of levels represented by one symbol.
TCP	Transmission Control Protocol
TDD	Time Division Duplex
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
Word size	Essentially the same as symbol size, but it's the "symbol size" of the file data format in this simulation

1. Chapter 1 - Introduction

1.1. Background

Wireless communication has become increasingly important not only for professional applications but also for many fields in our daily routine and in consumer electronics. In 1990, a mobile telephone was still quite expensive, whereas today most teenagers have one, and they use it not only for calls but also for data transmission. More and more computers use wireless local area networks (WLANs), and audio and television broadcasting has become digital. (Schulze and Luder, 2005). But the cost of installing a wired phone network is very high. One method of reducing the high infrastructure cost of a wired system is to use a fixed wireless radio network. The problem with this is that for geographically challenged and urban areas, large cell sizes are required to get sufficient coverage. This presents extra problems as there are long delay times in multipath signal propagation.

As far as the multiple user access is concerned we have FDMA, TDMA and CDMA, these three are very well known schemes which shares the available bandwidth to multiple users in wireless systems. There are many extensions and hybrid techniques for these methods, such as OFDM and hybrid TDMA-FDMA. CDMA and OFDM both are wide-band wireless digital communication systems in general. CDMA is a spread spectrum technique that uses neither frequency channels nor time slots. With CDMA, the narrow-band messages (typically digitized voice data) are multiplied by a large band width signal that is a unique pseudo random noise code (PN code). All users in a CDMA system use the same frequency band and transmit simultaneously with different codes. The transmitted signal is recovered by correlating the received signal with the PN code used by the transmitter.

The orthogonal frequency division multiplexing (OFDM) is a multi-carrier modulation-transmission technique, which divides the available spectrum into many carriers, each one being modulated by a low rate data stream. OFDM can be similar to FDMA in that the multiple user access is achieved by subdividing the available bandwidth into multiple channels allocated to users. However, OFDM uses the spectrum much more efficiently by spacing the channels much closer together. This is achieved by making all the carriers orthogonal to one another, preventing ICI.

1.2. Evolution of Wireless Communication

The report of Global Trends and Policies (Technical Specification TS 25.201 v9.0.0, 2009) points out that information and communication technology (ICT) has reshaped the world over the past few decades. By connecting various people and areas together, ICT becomes the vital field in national, regional and global development, and decides the future. In particular, wireless communication is one of the most exciting ICT technologies which are penetrating every domain of our daily life. In 1897, Guglielmo Marconi, the dashing Italian, first demonstrated the ability of radio to provide wireless communication with ships sailing in the English Channel. Since then new wireless communication methods and services have been developed and used extensively worldwide. In the early time of the last century, after human speech was first sent wirelessly by Reginald Fessenden, by means of the regulations of the frequency allocation and wireless equipments, the wireless communication industry started to take shape (Linde, Staphorst, and Vlok, 2007). During the World War I and II, the envelope of wireless communication was further enlarged through numerous operational needs in the military. After the World War II, the driving demand of wireless technology changed from the military purpose to the public use. In late 70's, the first generation mobile communication system emerged and it introduced cellular structure to address the problems of limited available channel frequencies, high-power transmitters and poor coverage of large areas in other conventional mobile telephone systems. Consequently, each transceiver is connected to a central switching office, which controls and monitors overall system and provides the interface to the local telephone operators. Craig McCaw was one of the pioneers in the mobile telephone field, who then brought the cellular infrastructure from the analog into the digital era which led a revolution: In 1983 the average price of a cellular phone was $3,000, where by 1993 the price had dropped to less than $100. As a consequence, in less than a decade the number of mobile subscribers increased from less than 100,000 to over 16 million in the US and revenues went from less than half a billion to nearly $11 billion (3GPP, 2009). Worldwide, the rapid growth of mobile cellular use, various satellite services, and wireless Internet is generating tremendous changes in the telecommunications and networking field.

Previous Studies

Phase noise causes significant degradation in the performance of orthogonal frequency division multiplexing (OFDM)-based wireless communication systems. The presence of phase noise can reduce the effective signal-to-noise ratio (SNR) at the receiver, and consequently, limit the bit error rate (BER) and data rate. This is according to Qiyue Zou, Alireza Tarighat, and Ali H. Sayed in their paper Compensation of Phase Noise in OFDM Wireless Systems. Their simulations showed that you can effectively improve the system performance in terms of the effective SNR and the uncoded BER. By using a mathematical algorithm to reduce sensitivity of OFDM receivers to phase noise by about 8dB.

However, oscillators with ultralow phase noise usually have the disadvantage of high implementation cost and high power consumption.

According to R. Sandanalakshmi, Prof. T. G. Palanivelu, Prof. K. Manivannan of Pondicherry Engineering College who undertook a study on the effective SNR mapping for link error prediction In OFDM based systems, where they looked at OFDM as multicarrier communication systems as an adaptive modulation and coding systems. The aim was to predict performance of different links with the same SNR. However, it is very difficult to predict the performance of different links with same SNR.

1.3. Problem Statement

Society continually demands higher mobile data rates. As Smartphone sales are soaring, more users are demanding faster mobile internet. Current mobile data standards have several limitations. The problem addressed in this project is the simulation of a modulation technique capable of high data throughputs, by improving BER performance in the presence of AWGN. The current 3G technology is considered to be standard in high speed mobile data transmission. During 2007, CDMA subscriptions worldwide grew by 6.6 million subscriptions per month (Online. http://www.3gpp.org/article/wcdma). This number has certainly increased. HSDPA has improved UMTS spectral efficiency and peak data throughput, by using less noise immune 16- and 64-QAM modulation techniques (Technical Specification TR 25.950 v4.0.1, 2005). This project will investigate a modulation technique that could potentially be considered for next generation mobile data communication.

The challenge is to develop a modulation technique that allows higher data throughput than what is currently possible with CDMA technology. This technique should also minimize multi user interference while maintaining superior BER performance in the presence of AWGN
The primary limitation of this project is the 5 MHz DB bandwidth used in the CDMA standard ("Physical layer - General description (Release 9)," 3GPP, Technical Specification TS 25.201 v9.0.0, 2009).

Why use BER as the performance parameter

According to Gary Breed (2003, p. 1), one of the changes that a modern digital communications system has brought to radio engineering is the need for end-to-end performance measurements. The measure of that performance is usually bit-error rate (BER), which quantifies the reliability of the entire radio system from “bits in” to “bits out,” including the electronics, antennas and signal path in between. On the surface, BER is a simple concept— its definition is simply: *BER = Errors/Total Number of Bits*
With a strong signal and an unperturbed signal path, this number is so small as to be insignificant. It becomes significant when we wish to maintain a sufficient signal-to-noise ratio in the presence of imperfect transmission through electronic circuitry (amplifiers, filters, mixers, and digital/analog converters) and the propagation medium (e.g. the radio path or optical fiber).

SNR and BER

Noise is the main enemy of BER performance. Noise is a random process, defined in terms of statistics. The noise introduced by the circuitry is described with a Gaussian probability density function, while the signal path is usually described with a Rayleigh probability density function. A Rayleigh, or fading, signal path is not “noise” in the intuitive sense of the familiar hissing sound of “white noise,” but it is a random process that is analyzed in the same manner as Gaussian noise.

1.4. Objectives of the study

The main objective of this project is to study the propagation of signal using Orthogonal Frequency Division Multiplexing (OFDM) to determine its effectiveness in delivering quality signal. This will be achieved through:

- Using simulation to investigate OFDM signal propagation
- Analyze the effectiveness of signal transmission by determining the error rate during propagation under different modulation techniques; this will be done through comparing the bit error rates and signal to noise ratio of the OFDM and CDMA technologies, in order to determine any performance improvements of OFDM over CDMA.

Research question

An investigation as to whether the use of OFDM has brought any improvements in performance when compared to the current technology of CDMA by adding AWGN to the signals being propagated.

1.5. Significance of the study

In future mobile communication systems, high speed data transmission with low latency will be a key characteristic under different movement situations. OFDM is being considered as a modulation and multiple access method for 4^{th} generation wireless networks due to its good spectrum efficiency and tolerance of inter-symbol interference (ISI). The goal of a communication system is to transmit information efficiently and accurately to another location. In Kenya, we have areas such as Wajir where there is high temperatures and humidity that affect signal propagation, yet there areas also in the capital city such as Kileleshwa, which are highly vegetative and thus no clear line of sight between the stations transmitting the signals. The study of OFDM systems in areas with no clear line of sight is important as the demand for data transmission with higher rates changes and so is the focus on the deployment of wireless networks. Technologies that promise to deliver higher data rates are attracting more and more vendors and operators towards them. One of the most promising candidates of such arising technologies is WiMAX. Some other examples of current applications using OFDM include GSTN (General Switched Telephone Network), Cellular radio, DSL & ADSL modems, DAB (Digital Audio Broadcasting) radio, DVB-T (Terrestrial Digital Video Broadcasting), HDTV broadcasting, HYPERLAN/2 (High Performance Local Area Network standard), and the wireless networking standard IEEE 802.11 (Dr. Ahmadi, 2006).

2. Chapter 2 – Literature Review

Multiple access schemes are used to allow many simultaneous users to use the same fixed bandwidth radio spectrum. In any radio system, the bandwidth which is allocated to it is always limited. For mobile phone systems the total bandwidth is typically 50MHz, which is split in half to provide the forward and reverse links of the system. Sharing of the spectrum is required in order increase the user capacity of any wireless network. TDMA and CDMA are the two major methods of sharing the available bandwidth to multiple users in wireless system. There are many extensions, and hybrid techniques for these methods, such as OFDM. However, an understanding of the CDMA and OFDM methods is required for understanding why OFDM is becoming the preferred choice by service providers and consumers.

2.1. Single-Carrier Communication Systems for Multi-Access Technologies.

The term "multi-access" refers to the sharing of a communication resource, e.g. time and frequency bandwidth among different users. Multiple access technologies are a kernel in building multi-user mobile and wireless communication networks. Without the coordination provided by multiple access technologies, multiple users in the system cannot utilize the channel effectively. Traditional communication systems were based on multiple access technologies with single-carrier modulation, i.e. single-carrier communication systems, in which data frames from different users are modulated, multiplexed and transmitted on a single frequency (i.e. single-carrier). Figure 1 shows some conventional single-carrier multiple access

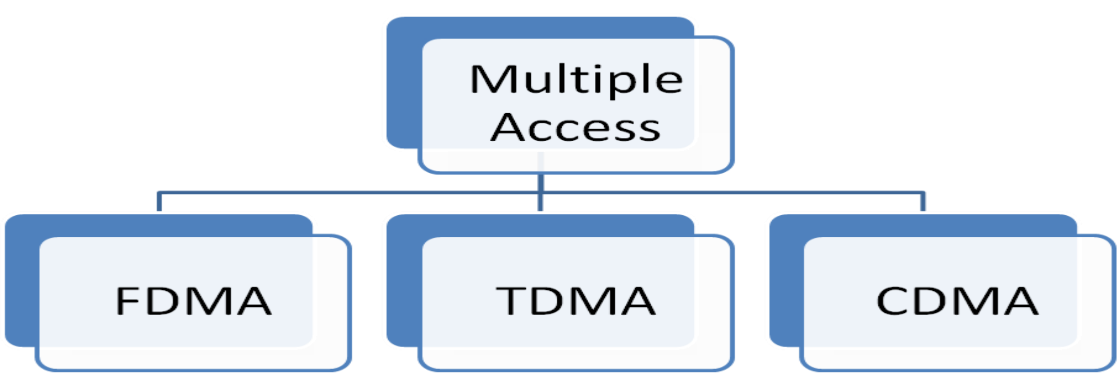


Figure 1: Multiple Accesses for single carrier communication equipment

technologies.

2.1.1. Frequency Division Multiple Access

As an early and simple technology of transmitting telephony signal simultaneously.

Frequency Division Multiple Access (FDMA) assigns dedicated frequency channels in sequence to each user as shown in Figure 2. During the period of the call, no other user can use the same channel. Band-pass modulation and guard band are normally used to enable frequency separation between different users.

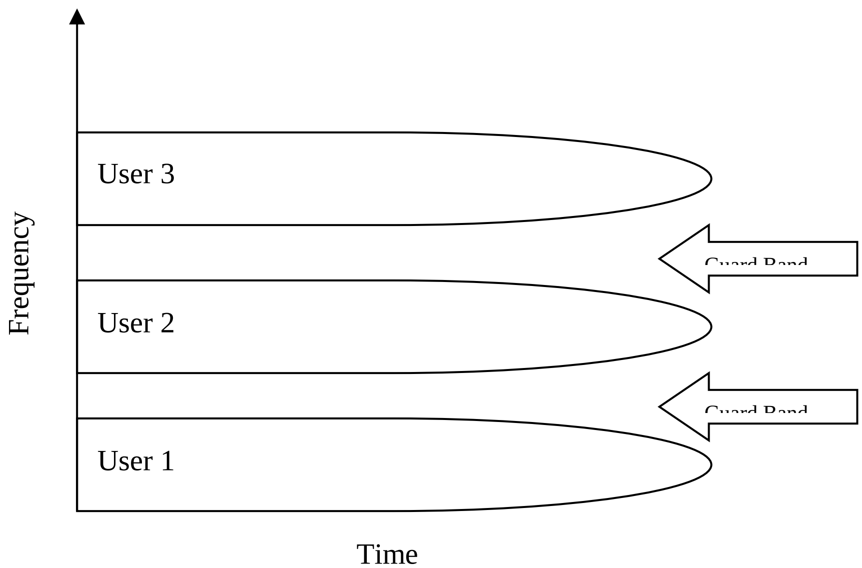


Figure 2: FDMA Frequency Channels

2.1.2. Time Division Multiple Access

In Time Division Multiple Access (TDMA), time domain is divided into a number of slots allocated to each user, as shown in Figure 3. Thus, the signals transmitted by various users are separated through different time slots which are isolated by guard time. However, different from FDMA, TDMA must ensure all transmitters and receivers to be synchronized (Souter & David, 2005).

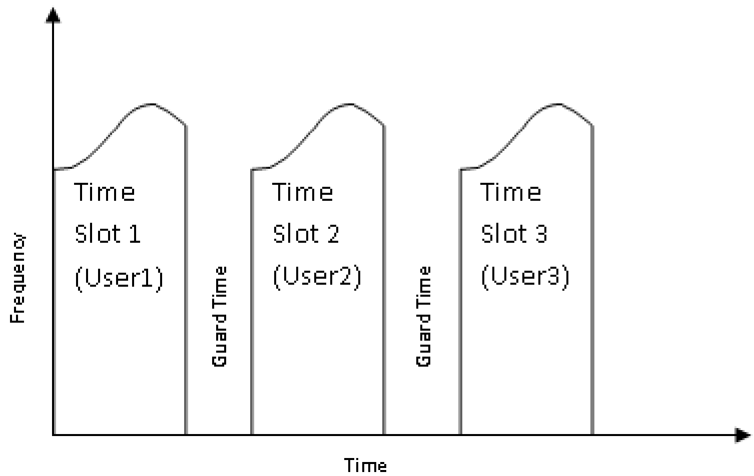


Figure 3: Time Division Multiple Access

2.1.3. Code Division Multiple Access

Code division multiple access (CDMA) is an application of spread-spectrum techniques. Figure 4 indicates that in a typical CDMA system, all users can transmit at the same frequency simultaneously and their signals are separated from each other by means of a series of unique spreading codes. Correspondingly, the receiver dispreads the signal by correlating assigned code that is identical to the spreading code used at the transmitter.

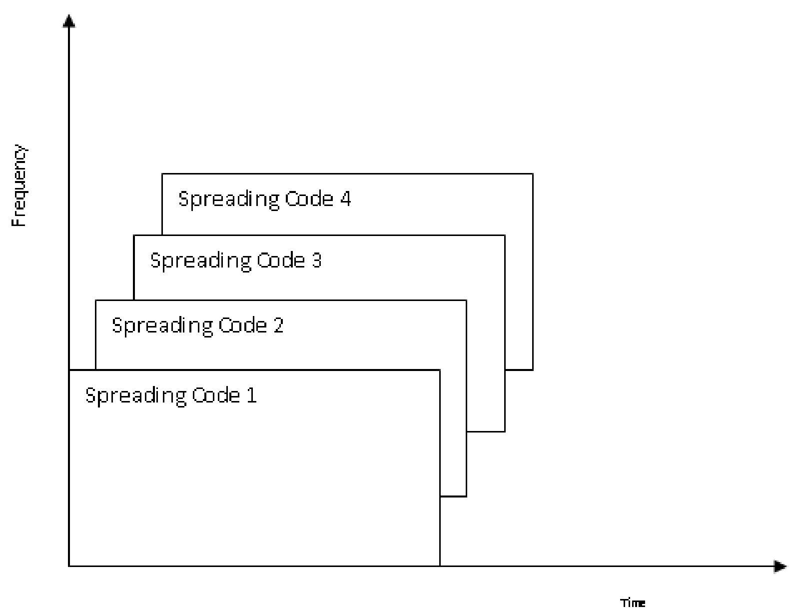


Figure 4: Code Division Multiple Access

Figure 3 - and Figure 4 - illustrates the spreading and de spreading processes, respectively. Spreading signal is the product of data signal and code signal in the spreading process whereas the reverse step is conducted in the de spreading process, which the spreading signal is converted back to the data signal by multiplying the same spreading code used in previous spreading process. The time duration of a code bit is called chip duration T_{chip} and the frequency of code signal is called chip rate R_{chip}. Therefore,

$T_{chip} = 1 / R_{chip}$

Note that one chip denotes one spreading sequence symbol which is different from information data symbol.

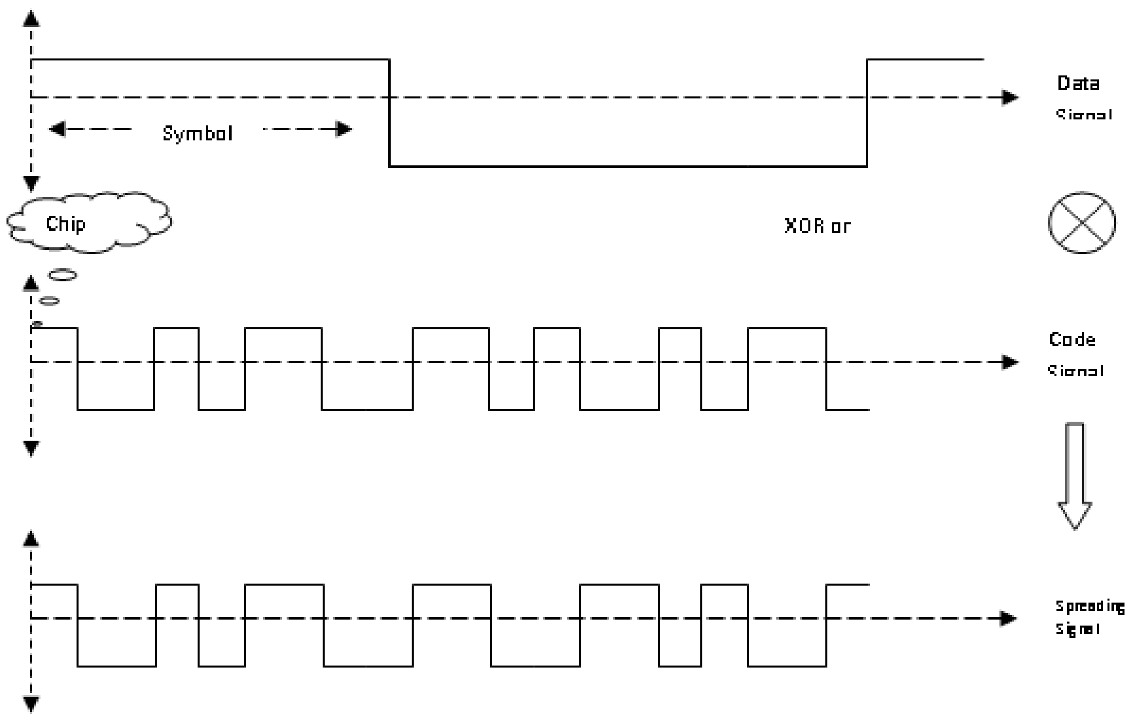


Figure 5: Spreading process

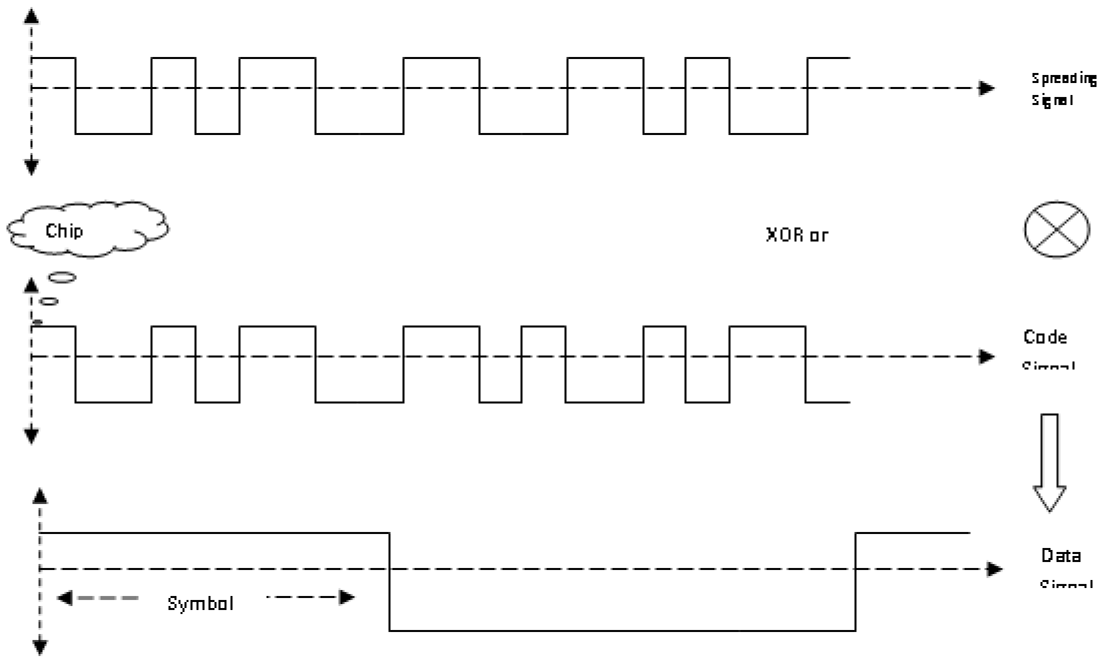


Figure 6:Despreading process

As one of the current commercial standards for the 20 systems, CDMA (or more explicitly the IS-95 standard) uses a spreading spectrum technology in its air interface design. Instead of using different time slots to identify different users in TDMA or different frequency bands to separate users in FDMA, CDMA divides multiple users based on a set of orthogonal codes in a same frequency domain and time domain.

The key feature of CDMA is "spreading spectrum", which is implemented by oversampling information signal in the time domain. As a consequence, the transmission bandwidth is wider than the bandwidth of the original information signal.

Typically, a pseudo-random (PN) sequence is used to 'spread' the bandwidth of the information signal in frequency domain.

The advantages of CDMA system include:

- Signal hiding and noninterference with conventional systems;
- Anti-jam and interference rejection;
- Privacy;
- Accurate ranging;
- Multiple access;

- Multipath mitigation with the aid of RAKE receiver;
- Variable bit rate and adaptive rate transmission.

2.1.4. CDMA Process Gain

One of the most important concepts required in order to understand spread spectrum techniques is the idea of process gain. The process gain of a system indicates the gain or signal to noise improvement exhibited by a spread spectrum system by the nature of the spreading and de-spreading process. The process gain of a system is equal to the ratio of the spread spectrum bandwidth used, to the original data bit rate. Thus, the process gain can be written as: *Gp*= $\frac{BW_{rf}}{BW_{\inf 0}}$

Where BW_{RF} is the transmitted bandwidth after the data is spread, and BW_{info} is the bandwidth of the information data being sent.

Figure 3 shows the process of a CDMA transmission. The data to be transmitted (a) is spread before transmission by modulating the data using a PN code. This broadens the spectrum as shown in (b). In this example the process gain is 125 as the spread spectrum bandwidth is 125 times greater the data bandwidth. Part (c) shows the received signal. This consists of the required signal, plus background noise, and any interference from other CDMA users or radio sources. The received signal is recovered by multiplying the signal by the original spreading code. This process causes the wanted received signal to be de-spread back to the original transmitted data. However, all other signals which are uncorrelated to the PN spreading code used become more spread. The wanted signal in (d) is then filtered removing the wide spread interference and noise signals.

2.1.5. CDMA Generation

CDMA is achieved by modulating the data signal by a pseudo random noise sequence (PN code), which has a chip rate higher than the bit rate of the data. The PN code sequence is a sequence of ones and zeros (called chips), which alternate in a random fashion. The data is modulated by modular-2 adding the data with the PN code sequence. This can also be done by multiplying the signals, provided the data and PN code is represented by 1 and -1 instead of 1 and 0. Figure 4 shows a basic CDMA transmitter.

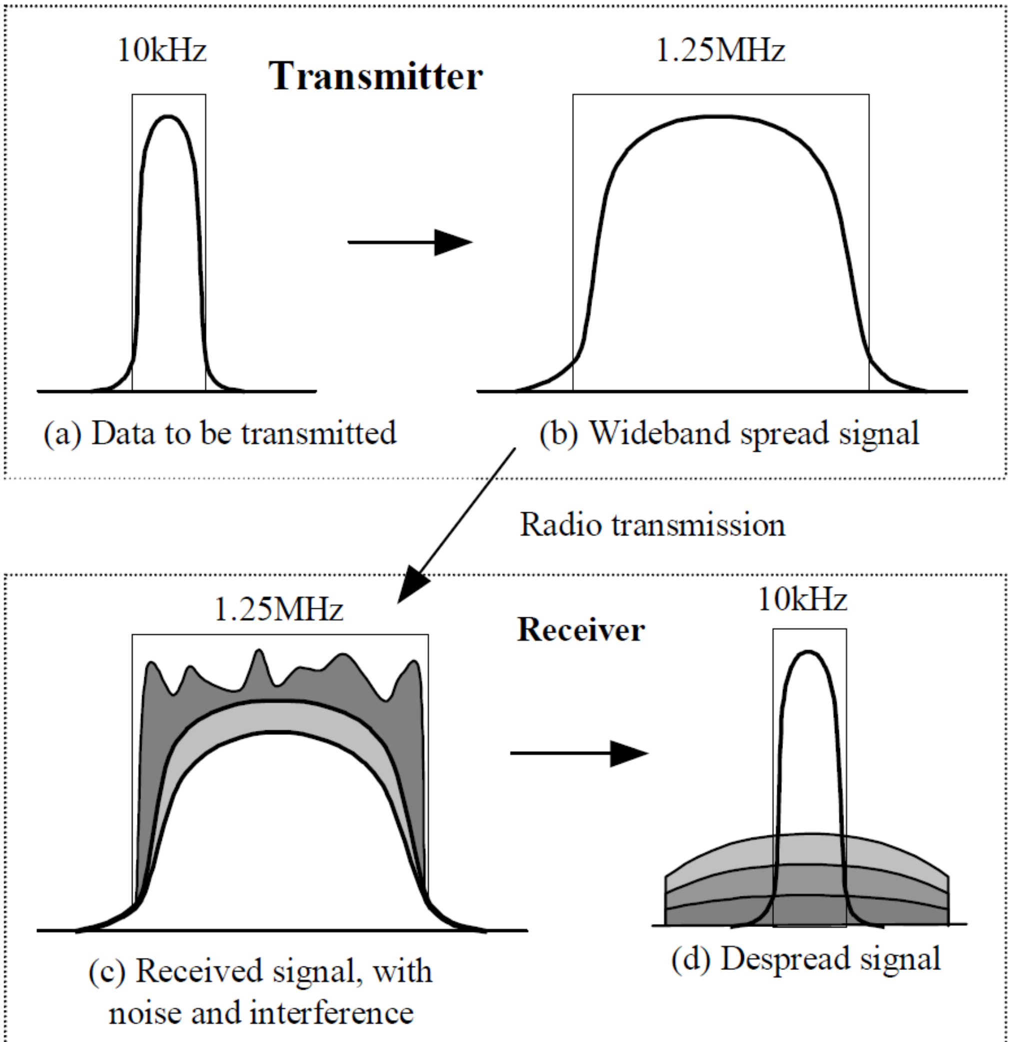


Figure 7: Basic CDMA Transmission

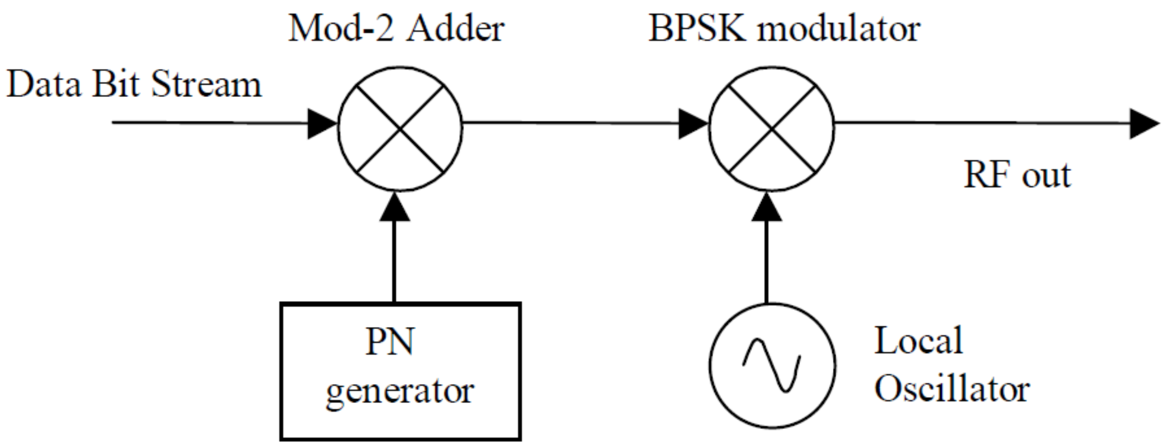


Figure 8: Simple direct sequence modulator

The PN code used to spread the data can be of two main types. A short PN code (typically 10-128 chips in length), can be used to modulate each data bit. The short PN code is then repeated for every data bit allowing for quick and simple synchronization of the receiver. Figure 5 shows the generation of a CDMA signal using a 10-chip length short code. Alternatively a long PN code can be used. Long codes are generally thousands to millions of chips in length, thus are only repeated infrequently. Because of this they are useful for added security as they are more difficult to decode.

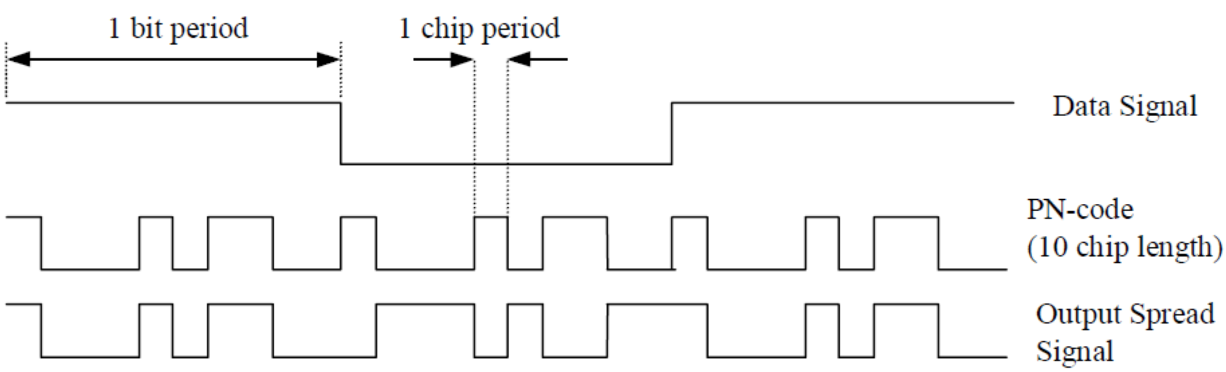


Figure 9: Direct sequence signals

2.1.6. CDMA Forward Link Encoding

The forward link, from the base station to the mobile, of a CDMA system can use special orthogonal PN, codes called Walsh code, for separating the multiple users on the same channel. These are based on a Walsh matrix, which is a square matrix with binary elements, and dimensions which are a power of two. It is generated from the basis that *Walsh(1) = W1 = 0* and that:

$$W_{2n} = \begin{matrix} W_n & W_n \\ W_n & W_n \end{matrix}$$

Where, W_n is the Walsh matrix of dimension n. For example

$$W_2 = \begin{matrix} 0 & 0 \\ 0 & 1 \end{matrix}$$

$$W_4 = \begin{matrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 \end{matrix}$$

Walsh codes are orthogonal, which means that the dot product of any two rows is zero. This is due to the fact that for any two rows exactly half the number of bits match and half do not. Each row of a Walsh matrix can be used as the PN code of a user in a CDMA system. By doing this the signals from each user is orthogonal to every other user, resulting in no interference between the signals. However, in order for Walsh codes to work the transmitted chips from all users must be synchronized. If the Walsh code used by one user is shifted in time by more than about 1/10 of chip period, with respect to all the other Walsh codes, it loses its orthogonal nature. This results in inter-user interference. For the forward link signals for all the users originate from the base station, allowing the signals to be easily synchronized.

2.1.7. CDMA Reverse Link Encoding

The reverse link is different to the forward link because the signals from each user do not originate from a same source as in the forward link. The transmission from each user will arrive at a different time, due to propagation delay, and synchronization errors. Due to the unavoidable timing errors between the users, there is little point in using Walsh codes as they will no longer be orthogonal. For this reason simple pseudo random sequence which are uncorrelated, but not orthogonal are used for the PN codes of each user. The capacity is different for the forward and the reverse links because of the differences in modulation. The reverse link is not orthogonal, resulting in significant inter-user interference. For this reason the reverse channel sets the capacity of the system.

2.2. Multi-Carrier Communication System for Multiple Access Technologies

Compared to conventional Single-Carrier (SC) communication system, most of recent research interests are focusing on Multi-Carrier (MC) communication system, which is identified as the cogent candidate for future 4G mobile and wireless communication systems. The basic principle of MC communication system is that it partitions the single high data rate channel into multiple parallel orthogonal low data rate sub-channels (or called subcarriers), which can be realized by Orthogonal Frequency Division Multiplexing (OFDM) technology.

Since the symbol rate of an MC communication system on each subcarrier is much lower than that of SC system, the symbol duration through each subcarrier is accordingly enlarged against propagation delay spread. Therefore, one promising advantage of MC communication systems is to reduce or eliminate the side effect of propagation delay spread in order to simplify the complexity of equalizer. Furthermore, if the guard band between transmitting MC symbols is reasonably selected and designed, the equalizer could even be wiped off from the system.

2.2.1. Orthogonal Frequency Division Multiplexing

The idea of OFDM comes from Multi Carrier Modulation (MCM) transmission technique. OFDM is a special form of spectrally efficient MCM technique, which employs densely spaced orthogonal subcarriers and overlapping spectrums. It has been shown that multi-carrier spread spectrum (MC-SS) offers high spectral efficiency, robustness, and flexibility (Souter & David, 2005). The uses of band-pass filters are not required in OFDM because of the orthogonality nature of the subcarriers. Hence, the available bandwidth is used very efficiently without causing the Inter-Carrier Interference (ICI). In digital communications, information is expressed in the form of bits. The term symbol refers to a collection, in various sizes, of bits. OFDM data are generated by taking symbols in the spectral space using M-PSK, QAM, etc, and convert the spectra to time domain by taking the Inverse Discrete Fourier Transform (IDFT). Since Inverse Fast Fourier Transform (IFFT) is more cost effective to implement, it is usually used instead. Once the OFDM data are modulated to time signal, all carriers transmit in parallel to fully occupy the available frequency bandwidth (Understanding an OFDM transmission, 2008). During modulation, OFDM symbols are typically divided into frames, so that the data will be modulated frame by frame in order for the received signal be in sync with the receiver. Long symbol periods diminish the probability of having inter-symbol interference, but could not eliminate it. To make ISI nearly eliminated, a cyclic extension (or cyclic prefix) is added to each symbol period. An exact copy of a fraction of the cycle, typically 25% of the cycle, taken from the end is added to the front. This allows the demodulator to capture the symbol period with an uncertainty of up to the length of a cyclic extension and still obtain the correct information for the entire symbol period.

In figure 10 below a comparison between a precisely detected symbol period and a delayed detection illustrates the effectiveness of the cyclic extension.

OFDM is defined as a physical layer modulation technique that divides a high data rate signal into multiple low data rate subcarriers in parallel (Henrik and Luders, 2005). Figure 10 illustrates the conception of OFDM as a modulation scheme in two dimensions. In OFDM one single user occupies all frequency resource at the transmitted symbol duration. A number of parallel information data symbols are simultaneously modulated and transmitted by different subcarriers within OFDM symbol duration.

Moreover, the subcarrier frequencies are carefully chosen in order to be mutually orthogonal to each other with overlapping over the symbol duration as shown in Figure 11. Thereby, the frequency bandwidth resource is efficiently exploited.

Additionally, the symbol rate of parallel transmissions in OFDM is lower than that of serial transmission in SC communication systems, so the symbol duration is increased accordingly. Therefore, an OFDM symbol is more robust to inter-symbol interference (ISI) and multi-path fading than SC modulated signal so that frequency-domain channel equalizer can be eradicated, which is a significant merit of the system. OFDM is a low-complex bandwidth-efficient modulation scheme and hence will be a promising candidate (Henrik and Luders, 2005), for next-generation high-speed wireless communication. The practical applications of OFDM include high-speed modems, digital audio broadcast, digital video broadcast, and high-speed wireless access systems, etc (Henrik and Luders, 2005). A number of advantages of using OFDM for future wireless communication can be summarized as follow:

- Multi-path delay spread tolerance;
- Effectiveness against channel distortion;
- Throughput increment;
- Invulnerability against impulse noise;
- Frequency diversity.

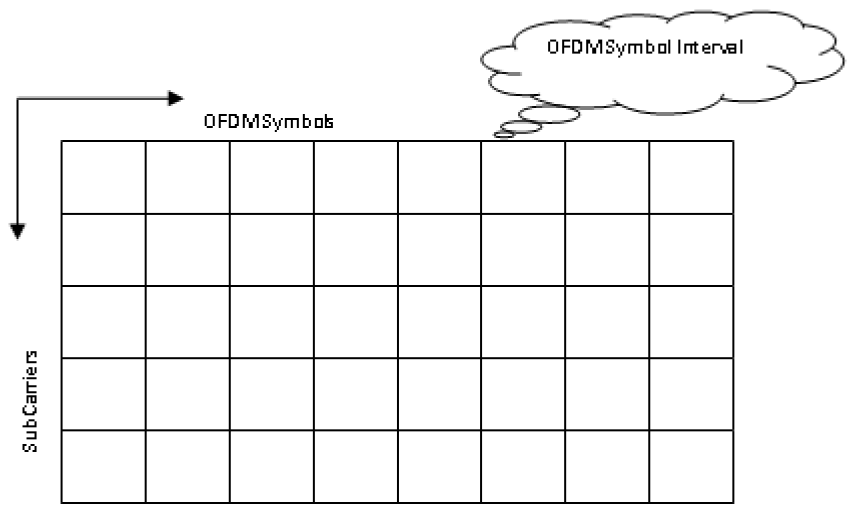


Figure 10: Conception of OFDM as a modulation scheme in two dimensions

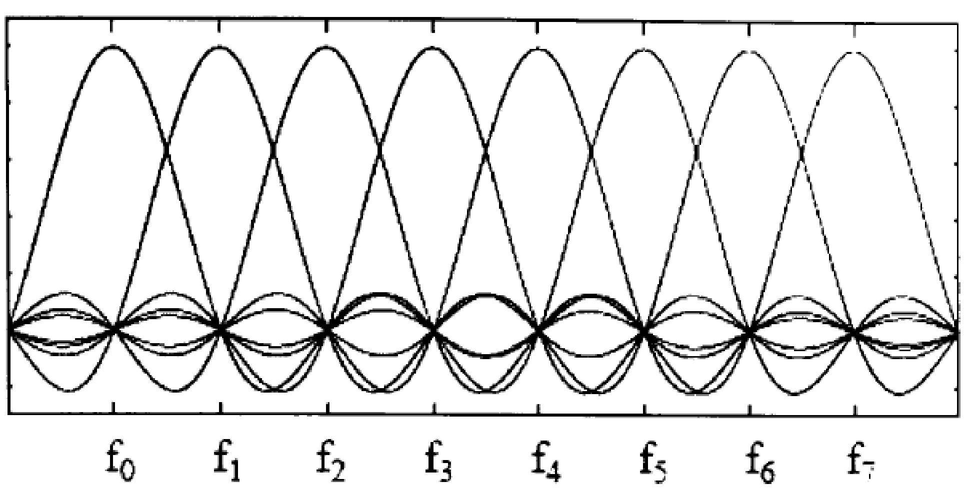


Figure 11: Orthogonal Subcarrier Frequencies

Figure 12 illustrates the block diagram of OFDM transmitter. The input data signal is firstly converted from serial to parallel. Then each subcarrier is modulated using Inverse Discrete Fourier Transformation (IDFT) or Inverse Fast Fourier Transformation (IFFT). Guard-interval is added on the serial symbol after parallel-to-serial conversion of the IFFT output to resist the effect of lSI and multi-path interference. Next, the serial OFDM symbol is converted from digital to analog and then sent into the propagation channel.

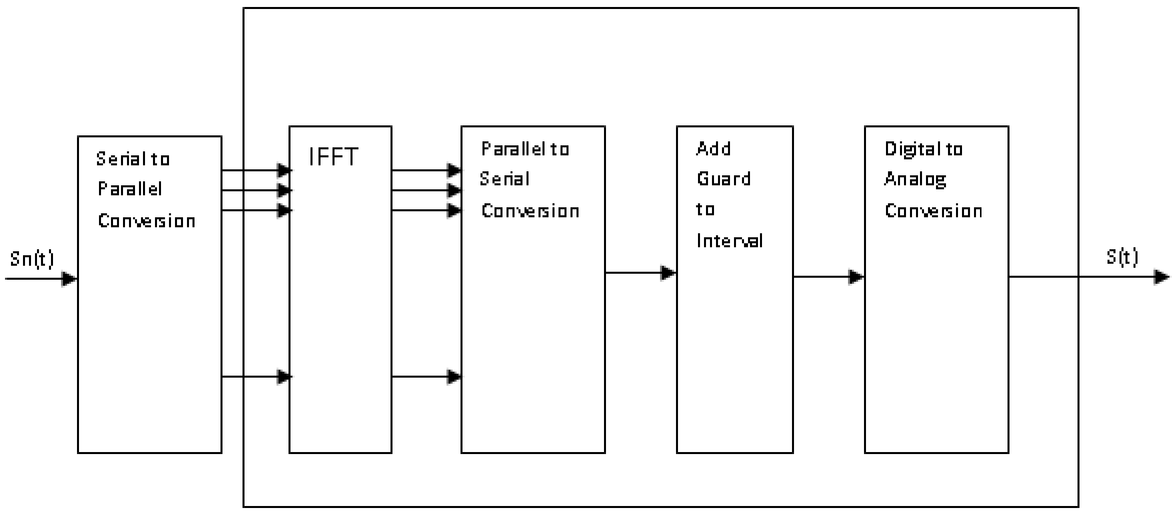


Figure 12: Block Diagram of OFDM Transmitter

As an example, we assume that BPSK modulation is used. A serial of parameters are defined as follows

BPSK modulated information signal is denoted by $S_n(t)$, where n= 1, 2, ... , N_c and N_c denotes the number of data symbols within a frame.

- A bit duration is denoted by T_b.
- The frame duration is denoted by T_s, thus we have

$T_s = N_c T_b$

- Subcarrier frequency is denoted by f_n, where

$F_n = n/T_s$, n=0,1,….N_c-1

- Hence, the spacing of subcarrier frequencies *I1f* is calculated by

$$\Delta f = \frac{1}{T_s}$$

- Maximum multipath spread delay is denoted by τ_{max}

- Guard interval between OFDM symbols is represented as τ_{guard}. In order to resolve the propagation delay in guard interval, a cyclic guard interval is required to add at both the front and the end of an OFDM symbol, denoted by

$$\tau_{max} \geq \tau_{guard}$$

- After adding guard interval, the frame duration changes as

$$\tau'_s = \tau_{guard} + \tau_s$$

- By fulfilling preceding assumptions, the complex envelope of OFDM symbol is formed as

$$s(t) = \frac{1}{\sqrt{N_c}} \sum_{n=0}^{N_c-1} S_n(t)\, e^{j2\pi f_n t} \qquad 0 \leq t \leq N_c T_b$$

  Where, $\frac{1}{\sqrt{N_c}}$ is a normalized factor of power.

Furthermore, the energy density spectrum is given by

$$|s(f)|^2 = \frac{1}{N_c} \left| \sum_{n=0}^{N_c-1} S_n T_s \frac{\sin(\pi (f - f_n) T_s)}{\pi (f - f_n) T_s} \right|^2$$

Figure 13 gives an example about normalized energy density spectrum of 16 subcarriers for an OFDM symbol, which is calculated by Equation (2.36). If we sample the modulated signal $s(t)$ the time nT_b with the interval T_b , where $n = 0,1, \ldots N_c -1$. So we have the sampled data formed as

$$s(nT_b) = \frac{1}{\sqrt{N_c}} \sum_{n=0}^{N_c-1} S_n e^{j2\pi f_n (nT_b)}$$

After normalization, the modulated signal set) becomes a sequence of samples of discrete signal expressed as

$$s(n) = \frac{1}{\sqrt{N_c}} \sum_{n=0}^{N_c-1} S_n(t)\, e^{j2\pi f_n n}$$

Thus, the modulation or multiplexing of data source symbols could be implemented by IDFT or IFFT elaborated in

$$[s(n)]^T = IFFT\{[S_n]^T\}, n = 1,2, \ldots . N_c$$

Where $.^{T}$ denotes transposition of a vector sequence.

Figure 13 Normalized energy density spectrum vs. subcarrier frequency of an OFDM symbol with the symbol duration $T_s=N_cT_b$

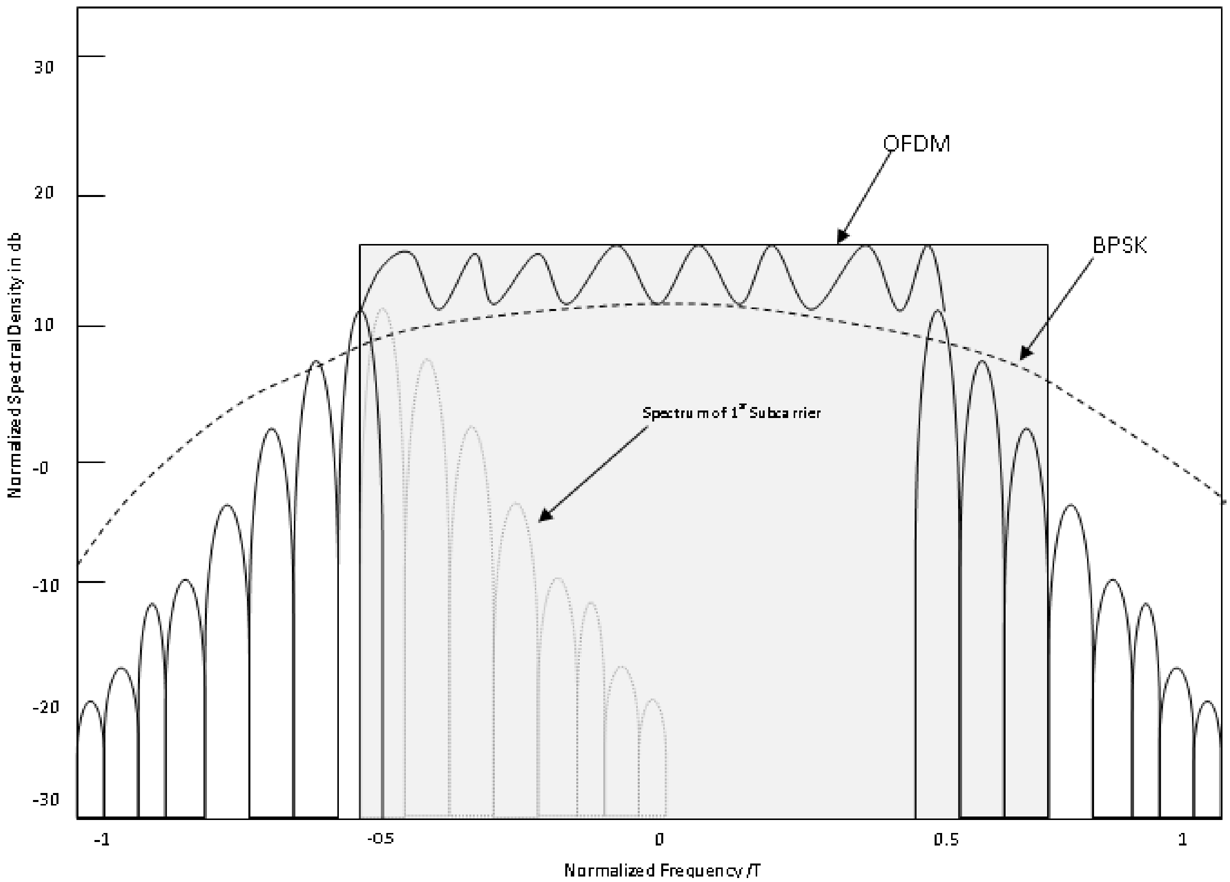


Figure 13: Normalized energy density spectrum vs. subcarrier frequency of an OFDM symbol

2.2.2. OFDM generation

To generate OFDM successfully the relationship between all the carriers must be carefully controlled to maintain the orthogonality of the carriers. For this reason, OFDM is generated by firstly choosing the spectrum required, based on the input data, and modulation scheme used. Each carrier to be produced is assigned some data to transmit. The required amplitude and phase of the carrier is then calculated based on the modulation scheme (typically differential BPSK, QPSK, or 16PSK). The required spectrum is then converted back to its time domain signal using an Inverse Fourier Transform. In most applications, an Inverse Fast Fourier Transform

(IFFT) is used. The IFFT performs the transformation very efficiently, and provides a simple way of ensuring the carrier signals produced are orthogonal.

The Fast Fourier Transform (FFT) transforms a cyclic time domain signal into its equivalent frequency spectrum. This is done by finding the equivalent waveform, generated by a sum of orthogonal sinusoidal components. The amplitude and phase of the sinusoidal components represent the frequency spectrum of the time domain signal. The IFFT performs the reverse process, transforming a spectrum (amplitude and phase of each component) into a time domain signal. An IFFT converts a number of complex data points, of length which is a power of 2, into the time domain signal of the same number of points. Each data point in frequency spectrum used for an FFT or IFFT is called a bin.

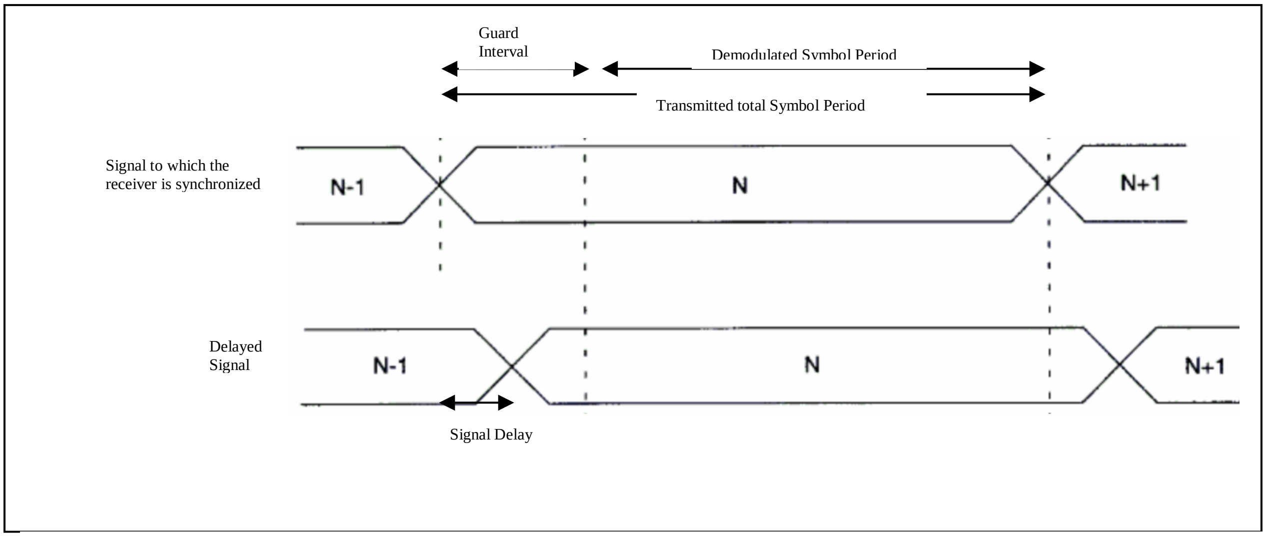


Figure 14: Effectiveness of the Cyclic Extension

The orthogonal carriers required for the OFDM signal can be easily generated by setting the amplitude and phase of each bin, then performing the IFFT. Since each bin of an IFFT corresponds to the amplitude and phase of a set of orthogonal sinusoids, the reverse process guarantees that the carriers generated are orthogonal. Figure 14 shows the setup for a basic OFDM transmitter and receiver. The signal generated is a baseband, thus the signal is filtered, then stepped up in frequency before transmitting the signal

2.2.3. Adding a Guard Period to OFDM

One of the most important properties of OFDM transmissions is the robustness against multipath delay spread. This is achieved by having a long symbol period, which minimizes the inter-symbol interference. The level of robustness can in fact be increased even more by the addition of a guard period between transmitted symbols. The guard period allows time for multipath signals from the previous symbol to die away before the information from the current symbol is gathered. The most effective guard period to use is a cyclic extension of the symbol. If a mirror in time, of the end of the symbol waveform is put at the start of the symbol as the guard period, this effectively extends the length of the symbol, while maintaining the orthogonality of the waveform. Using this cyclic extended symbol the samples required for performing the FFT (to decode the symbol), can be taken anywhere over the length of the symbol. This provides multipath immunity as well as symbol time synchronization tolerance.

As long as the multipath delay echo's stay within the guard period duration, there is strictly no limitation regarding the signal level of the echoes: they may even exceed the signal level of the shorter path! The signal energy from all paths just adds at the input to the receiver, and since the FFT is energy conservative, the whole available power feeds the decoder. If the delay spread is longer than the guard interval then they begin to cause intersymbol interference. However, provided the echoes are sufficiently small they do not cause significant problems. This is true most of the time as multipath echo's delayed longer than the guard period will have been reflected of very distant objects.

2.2.4. OFDM Parameters and Characteristics

The number of carriers in an OFDM system is not only limited by the available spectral bandwidth, but also by the IFFT size

(The relationship is described by:$\text{number of carriers} \leq \frac{\text{ifft size}}{2} - 2$), which is determined by the complexity of the system. The more complex (also more costly) the OFDM system is, the higher IFFT size it has; thus a higher number of carriers can be used, and higher data transmission rate achieved. The choice of M-PSK modulation varies the data rate and Bit Error Rate (BER). The higher order of PSK leads to larger symbol size, thus less number of symbols needed to be transmitted, and higher data rate is achieved. But this results in a higher BER since the range of

0-360 degrees of phases will be divided into more sub-regions, and the smaller size of sub-regions is required, thereby received phases have higher chances to be decoded incorrectly. OFDM signals have high peak-to-average ratio, therefore it has a relatively high tolerance of peak power clipping due to transmission limitations (Lin, Phoong, Vaidyanathan, 2011).

2.2.5. Orthogonality

The principle of multi-carrier transmission is to convert a serial high rate data stream on to multiple parallel low rate sub-streams. The key to OFDM is maintaining orthogonality of the carriers. If the integral of the product of two signals is zero over a time period, then these two signals are said to be orthogonal to each other. Two sinusoids with frequencies that are integer multiples of a common frequency can satisfy this criterion. Therefore, orthogonality is defined by: $\int_0^T cos(2\pi n f_0 t)\, cos\left(2\pi m f_0 t\right) dt = 0 \ (n \neq m)$

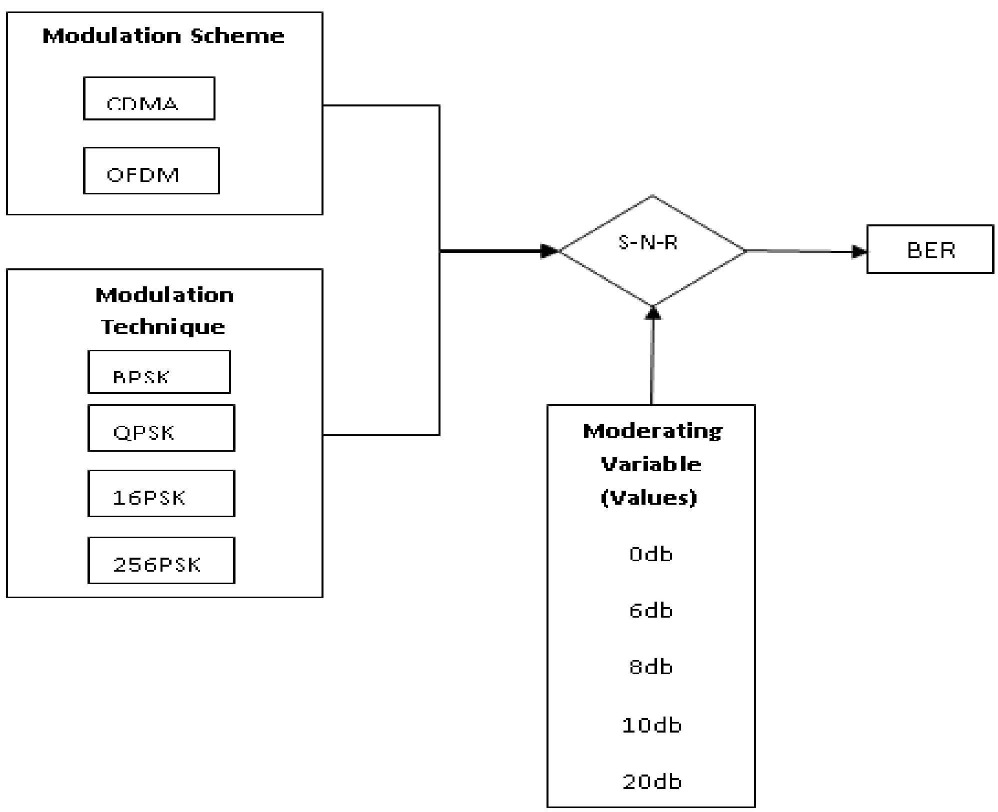
Where n and m are two unequal integers; f_0 is the fundamental frequency; T is the period over which the integration is taken. For OFDM, T is one symbol period and f_0 set to $\frac{1}{T}$ for optimal effectiveness (Understanding an OFDM transmission, 2008).

3. Chapter 3 – Methodology

3.1. Research framework

A major problem in most wireless systems is the presence of a multipath channel. In a multipath environment, the transmitted signal reflects off of several objectives. As a result, multiple delayed versions of the transmitted signal arrive at the receiver. The multiple versions of the signal cause the received signal to be distorted. But because of these multipath channels in OFDM, symbol interference occurs within the subcarriers. An Adaptive modulation and coding technique to overcome any Intra-symbol Interference (ISI) and analyze the performance of BER is proposed here with a comparative BER Performance of digital modulation techniques, in which the performance of the OFDM is tested for BPSK, QPSK, 16PSK and 256PSK using MATLAB.

These tests are compared for both the OFDM and CDMA technologies. The project presents BER performance comparison results with SNR being used as the moderating variable to represent different environments. Below is a diagrammatic explanation.



3.2. MATLAB

The project will use a simulation approach, with the preferred tool as Matlab version 7.14. We will use the model in Figure 15 shown as a block diagram of a generic OFDM system. A comparison with CDMA will be performed based on the work done by Khoja, Bredrow and Al-Shalash (2003) on their journal title “Simulation of CDMA systems using dynamic simulator”.

Since MATLAB has a built-in function “ifft()” which performs Inverse Fast Fourier Transform, IFFT is opted for the development of this simulation.

Six m-files are written to develop this MATLAB program of OFDM simulation.

One of them is the main program script file, which is the only file that needs to be run, while other m-files will be invoked accordingly. A 256-grayscale bitmap image is required as the source input. Another bitmap image file will be generated at the end of the simulation as the output.

Three MATLAB data storage files (*err_calc.mat, ofdm_parameters.mat, and received.mat*) are generated during the simulation.

- *err_calc.mat* is to archi5ve the baseband data before the transmission, and be retrieved at the end of the simulation for the purpose of error calculations.
- *ofdm_parameters.mat* is to archive the parameters initialized at the beginning of the simulation and reserve them for the receiver to use later. In the reality, the receiver would always have these parameters; in this simulation, these parameters are configured by the user at the beginning, so they are passed to the receiver by ofdm_parameters.mat as if being preset in the receiver.
- *received.mat* stores the time signal after it travels through the channel, and lets the receiver to read it directly.

When the simulation proceeds through the OFDM transmitter and communication channel, it pauses and waits for the user to trigger for proceeding to the receiver. The reason for using the last two **mat* files is that as soon as the OFDM receiver proceeds, the program will clear all data/variables stored in MATLAB workspace.

This is to simulate the real situation in which OFDM receivers have no knowledge of the data except for the received signal at the exit of the communication channel.

Simulation runtime for both the transmitter and receiver are measured and shown on MATLAB command screen as a rough measurement of relative data rate.

3.3. Description of the Experiment - Model Design

The model is explained as follows:

Data Source: The Source data for this simulation is taken from an 8-bit grayscale (256 gray levels) bitmap image file (*.bmp) based on the user's choice. The image data will then be converted to the symbol size (bits/symbol) determined by the choice of MPSK from four variations provided by this simulation.

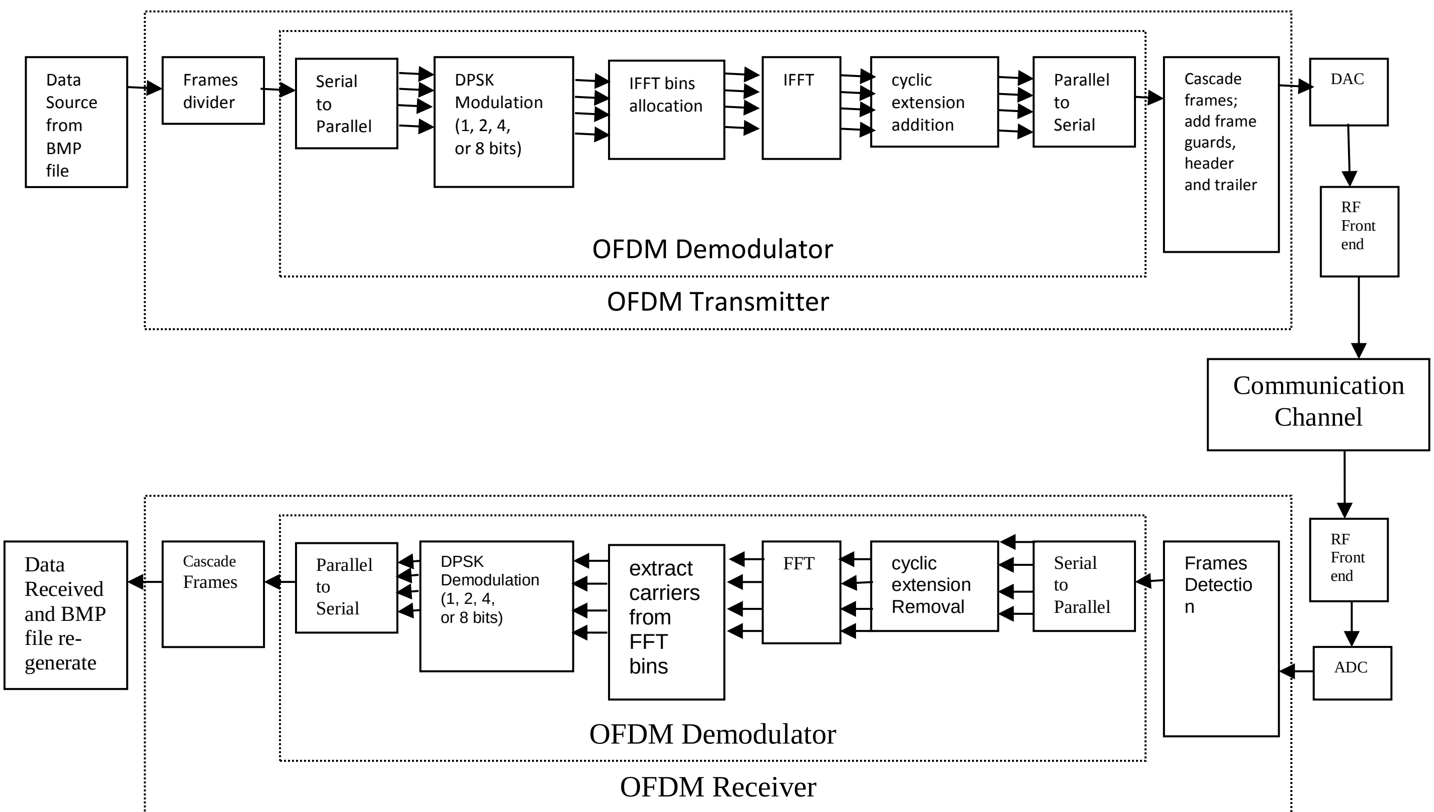


Figure 15: OFDM System Model

Data mapping: The input data stream is available serially, converted into parallel stream according to digital modulation scheme. The data is transmitted in parallel by assigning each data word to one carrier in the transmission. The converted data will then be separated into multiple frames by the OFDM transmitter. The OFDM modulator modulates the data frame by frame. Before the exit of the transmitter, the modulated frames of time signal are cascaded together along with frame guards inserted in between as well as a pair of identical headers added to the beginning and end of the data stream.

In general, the selection of modulation scheme applied to each sub-channel depends solely on the compromise between the data rate requirement and transmission robustness.

An **AWGN** channel model is then applied to transmitted signal. The model allows for the Signal to Noise Ratio (SNR) variation. The receiver performs the reverse operation of the transmitter. The receiver consists of removal of guard band, FFT, cyclic extension remover and demapping of data.

Guard Period: The effect of ISI on an OFDM signal can be eliminated by the addition of a guard period at the start of each symbol. This guard period is a cyclic copy that extends the length of the symbol waveform. The guard period adds time overhead, decreasing the overall spectral efficiency of the system. Guard duration should be longer than channel delay spread. After the guard band has been added, the symbols are converted into serial form.

One frame length duration T = Ts + Tg, where Ts = NT, N = number of carriers. This is the OFDM base band signal, which can be up converted to required transmission frequency.

IFFT-Frequency domain to time domain conversion: The IFFT converts frequency domain data into time domain signal and at the same time maintains the orthogonality of subcarriers. The real signal output can be generated by arranging conjugate subcarriers

Error calculations are performed at the end of the program. Representative plots are shown throughout the execution of this simulation.

3.4. Model Parameters and configurations

The OFDM system is modeled using MATLAB to allow various parameters of the system to be varied and tested. The following OFDM system parameters are considered for the simulation

- Input file – an 8-bit grayscale (256 gray levels) bitmap file (*.bmp);
- IFFT size – an integer of a power of two;
- Number of carriers – not greater than [(IFFT size)/2 – 2];

- OFDM transmitted frame size: 64+16 = 80
- Digital modulation method – BPSK, QPSK, 16-PSK, or 256-PSK;
- Signal peak power clipping in dB;
- Signal-to-Noise Ratio in dB.

The number of carriers needs to be no more than [(IFFT size)/2 – 2], because there are as many conjugate carriers as the carriers, and one IFFT bin is reserved for DC signal while another IFFT bin is for the symmetrical point at the Nyquist frequency (Hypothetical spectrum of a bandlimited signal as a function of frequency) to separate carriers and conjugate carriers (Wilson, Turcotte and Halpern, 2003). All user-inputs are checked for validity and the program will request the user to correct any incorrect fields with brief guidelines provided (See Below table 1).

Table 1: Validation Script

source data filename:	MyFile ("MyFile" does not exist in current directory)
source data filename	ken.bmp
Output file will be:	ken_OFDM.bmp
IFFT size	1200 (IFFT size must be at least 8 and power of 2.)
IFFT size	2048
Number of carriers:	1000 (Must NOT be greater than ("IFFT size"/2-2))
Number of carriers	500
Modulation(1=BPSK, 2=QPSK, 4=16PSK, 8=256PSK):	3 (Only 1, 2, 4, or 8 can be chosen)
Modulation(1=BPSK, 2=QPSK, 4=16PSK, 8=256PSK	4

This validation is in form of a script which also determines how the carriers and conjugate carriers are allocated into the IFFT bins, based on the IFFT size and number of carriers defined by the user. Figure 8 shows an example of 100 carriers spreading out on 512 IFFT bins.

3.5. Input and Output

The program reads data from an input image file and obtains an h-by-w matrix where h is the height of the image and w is the width (in pixels). This matrix is rearranged into a serial data stream. Since the input image is an 8-bit b grayscale bitmap, its word size is always 8 bits/word. The source data will then be converted to the symbol size corresponding to the order of PSK chosen by the user. ofdm_base_convert.m performs this conversion. It converts the original 8-bits/word data stream to a binary matrix with each column representing a symbol in the symbol size of the selected PSK order. This binary matrix will then be converted to the data stream with such a symbol size, which is the baseband to enter the OFDM transmitter.

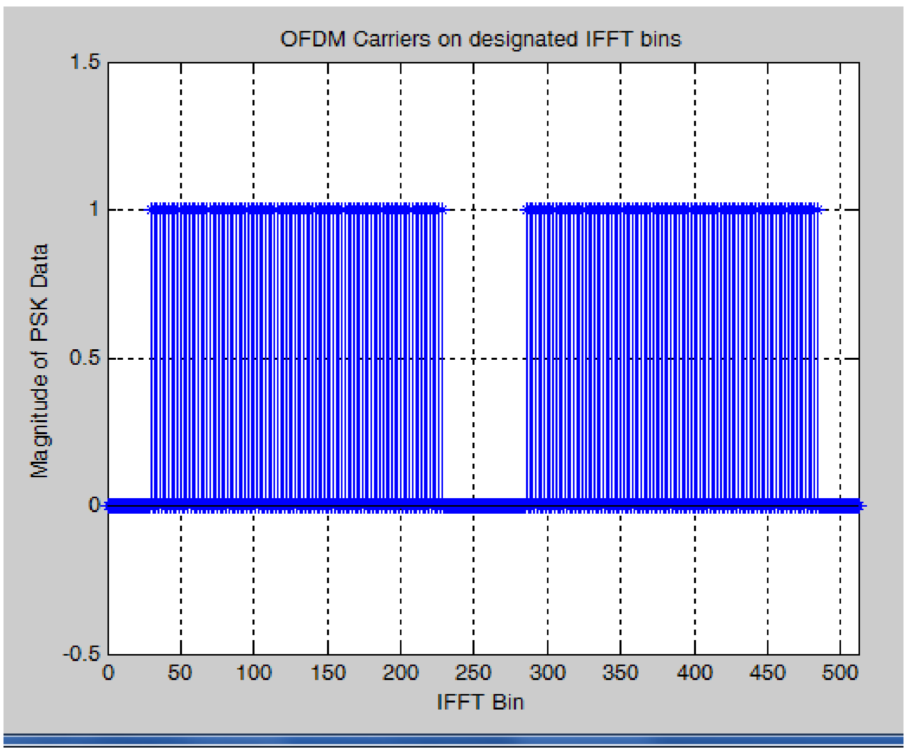


Figure 16: Allocation of carriers

For example, when QPSK (4 bits/word) is selected, a data stream in 8-bits/word is [36, 182, and 7] will go through the following process:

$$36,7,182 \quad \rightarrow \quad \begin{matrix} 00 & 00 & 10 \\ 01 & 01 & 01 \\ 10 & 01 & 11 \\ 00 & 01 & 10 \end{matrix} \quad \rightarrow \quad 2,4,0,7,11,6$$

Three 8-bit words Binary Six bit symbols

2, 4, 0, 7, 11, 6

At the exit of the OFDM receiver, a demodulated data stream needs to go through the base conversion again to return to 8-bits/word. This time, since the PSK symbol size might be less than 8 bits/symbol, ofdm_base_convert.m would trim the data stream to a multiple of 8/symbol-size before the base conversion in order to let each symbol conversion have sufficient bits. If the OFDM receiver does not detect all the data frames at the exactly correct locations, demodulated data may not be in the same length as the transmitted data stream. [2, 4, 0, 7, 11] may be the received data stream instead of [2, 4, 0, 7, 11, 6]. For this instance, “11” is dropped and only [2, 4, 0, 7] will be converted for generating the output image.

The output image

Sometimes the OFDM receiver’s outcome may also happen to be a data stream that is longer than the original transmitted data stream due to some imprecision processing caused by channel noise. In such cases, the received data stream is trimmed to the length of the original data stream in order to fit the dimensions of the original image.

On the contrary, the received data would more likely have a length less than the original. In these cases, the program would consider the number of the full missing rows as the amount to trim h, the height of the original image. Some treatment is processed for the partially missing row if it exists. When one or more full missing rows occur, the program shows a warning message informing the user that the output image is in a smaller size than the original image. For the partially missing row of received pixel data, the program would fill a number of pixels to make it in the same length as all other rows. Each of these padded pixels would have the same grayscale level as the pixel right above it in the image (one less row, same column). This would make the partial missing row of pixels nearly seamless.

3.6. OFDM Transmitter

3.6.1. Frame guards

Table 2: Single module

Header	Frame Guard	Modulated Signal	Frame Guard	Header

The core of the OFDM transmitter is the modulator, which modulates the input data stream frame by frame. Data is divided into frames based on the variable symb_per_frame, which refers to the number of symbols per frame per carrier (Otto & Denier, 2005). It is defined by: symb_per_frame = ceil(2^13/carrier_count). This limits the total number of symbols per frame (symb_per_frame * carrier_count) within the interval of [2^13, 2*(2^13-1)], or [8192, 16382]. However, the number of carriers typically would not be much greater than 1000 in this simulation, thus the total number of symbols per frame would typically be under 10,000. This is an experimentally reasonable number of symbols that one frame should keep under for this MATLAB program to run efficiently; thereby symb_per_frame is defined by the equation shown above. If the total number of symbols in a data stream to be transmitted is less than the total number of symbols per frame, the data would not be divided into frames and would be modulated all at once. As shown in **Table 6**, even if the data stream is not sufficiently long to be divided into multiple frames, two frame guards with all zero values and in a length of one symbol period are still added to both ends of the modulated time signal.

Table 3: multiple frames

Header	Frame Guard	Modulated Signal	Frame Guard	Modulated Signal	>>>>	Frame guard	Header

This is to assist the receiver to locate the beginning of the substantial portion of the time signal. As shown in **Table 7**, for modulated signals with multiple frames, a frame guard is inserted in between any two adjacent frames as well as both ends of the cascaded time signal. Finally, a pair of headers is padded to both ends of the guarded series of frames. The headers are scaled to the RMS level of the modulated time signal.

3.6.2. OFDM Modulator

It is normal that the total number of transmitting data is not a multiple of the number of carriers. To convert the input data stream from serial to parallel, the modulator must pad a number of zeros to the end of the data stream in order for the data stream to fit into a 2-D matrix(Otto & Denier, 2005). Suppose a frame of data with 11,530 symbols is being transmitted by 400 carriers with a capacity of 30 symbols/carrier. 470 zeros are padded at the end in order for the data stream to form a 30-by-400 matrix, as shown in Figure 9. Each column in the 2-D matrix represents a carrier while each row represents one symbol period over all carriers.

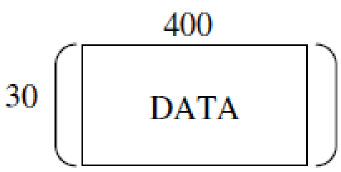


Figure 17: Data TX Matrix

3.6.3. Differential Phase Shift Keying (DPSK) Modulation

Before differential encoding can be operated on each carrier (column of the matrix), an extra row of reference data must be added on top of the matrix. The modulator creates a row of uniformly random numbers within an interval defined by the symbol size (order of PSK chosen) and patches it on the top of the matrix(Otto & Denier, 2005). Figure 10 shows a 31-by-400 resulted matrix. For each column, starting from the second row (the first actual data symbol), the value is changed to the remainder of the sum of its previous row and itself over the symbol size (power 2 of the PSK order). An illustration below shows how this operation is carried out for a QPSK (symbol size = 2^2 = 4).

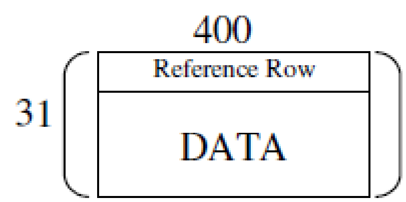


Figure 18: Differential Matrix

$\begin{matrix} 0 \\ 3 \\ 2 \\ 1 \end{matrix}$ with [2] added as the reference becomes $\begin{matrix} 2 \\ 0 \\ 3 \\ 2 \\ 1 \end{matrix}$, which is then differentiated to $\begin{matrix} 2 \\ 2 \\ 1 \\ 3 \\ 0 \end{matrix}$

Every symbol in the differentiated matrix is translated to its corresponding phase value from 0 to 360 degrees. Therefore,

2		*180^0*
2		*180^0*
1	is translated to	*90^0*
3		*270^0*
0		*0^0*

The modulator generates a DPSK matrix filled with complex numbers whose phases are those translated phases and magnitudes are all ones. These complex numbers are then converted to rectangular form for further processing.

3.6.4. IFFT: Spectral Space to Time Signal

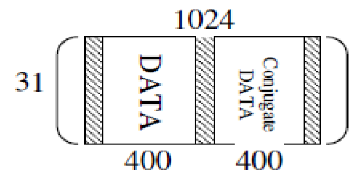


Figure 19: Pre- IFFT matrix

Figure 11 shows that the matrix is widened to IFFT size (for example: IFFT size = 1024) and becomes a 31-by-1024 IFFT matrix. Since each column of the DPSK matrix represents a carrier, their values are stored to the columns of the IFFT matrix at the locations where their corresponding carriers should reside (Otto & Denier, 2005). Their conjugate values are stored to the columns corresponding to the locations of the conjugate carriers (refer to Figure 8). All other columns in the IFFT matrix are set to zero. To obtain the transmitting time signal matrix, Inverse Fast Fourier Transform (IFFT) of this matrix is taken. Only the real part of the IFFT result is useful, so the imaginary part is discarded

3.6.5. Periodic Time Guard Insertion

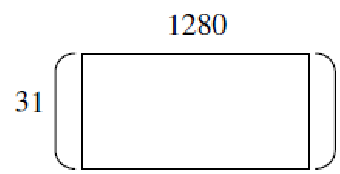


Figure 20: modulated Matrix

An exact copy of the last 25% portion of each symbol period (row of the matrix) is inserted to the beginning. As shown in Figure 12, the matrix is further widened to a width of 1280. This is the periodic time guard that helps the receiver to synchronize when demodulating each symbol period of the received signal. The matrix now becomes a modulated matrix. By converting it to a serial form, a modulated time signal for one frame of data is generated.

3.6.6. Communication Channel

Two properties of a typical communication channel are modeled. A variable clipping in this MATLAB program is set by the user. Peak power clipping is basically setting any data points with values over clipping below peak power to clipping below peak power. The peak-to- RMS ratios of the transmitted signal before and after the channel are shown for a comparison regarding this peak power clipping effect. An example is shown in Table 8.

Table 4: Summary of OFDM Transmission

Summary of the OFDM transmission and channel modeling: Peak to RMS power ratio at entrance of channel is: 14.893027 dB Peak to RMS power ratio at exit of channel is: 11.502826 dB #******** OFDM data transmitted in 5.277037 seconds ********#

Channel noise is modeled by adding a white Gaussian noise (AWGN) defined by:

$$\sigma \text{ of AWGN} = \sqrt{\frac{\text{variance of the modulated signal}}{Linear\ SNR}}$$

It has a mean of zero and a standard deviation equaling the square root of the quotient of the variance of the signal over the linear Signal-to-Noise Ratio, the dB value of which is set by the user as well (Otto & Denier, 2005).

3.7. OFDM Receiver

3.7.1. Frame detector

A trunk of received signal in a selective length is processed by the frame detector (*ofdm_frame_detect.m*) in order to determine the start of the signal frame. For only the first frame, this selected portion is relatively larger for taking the header into account. The selected portion of received signal is sampled to a shorter discrete signal with a sampling rate defined by the system. A moving sum is taken over this sampled signal. The index of the minimum of the sampled signal is approximately the start of the frame guard while one symbol period further from this index is the approximate location for the start of the useful signal frame. The frame detector will then collect a moving sum of the input signal from about 10% of one symbol period earlier than the approximate start of the frame guard to about one third of s symbol period further than the approximate start of the useful signal frame. The first portion, with a length of one less than a symbol period of this moving sum is discarded. The first minimum of this moving sum is the detected start of the useful signal frame.

3.7.2. Demodulation Status Indicator

As mentioned, received OFDM signal is typically demodulated frame by frame. The OFDM receiver shows the progress of frames being demodulated.

However, the total number of frames may vary by a wide range depending on the total amount of information transmitted via the OFDM system. It is a neat idea to keep the number of displays for this progress within a reasonable range, so that the MATLAB command screen is not overwhelmed by these status messages, nor the amount of messages shown is less than useful. To achieve this, the first and last frames are designed to show for sure, the rest would have to meet a condition:

rem(k,max(floor(num_frame/10),1))==0 where k is the variable to indicate the k-th frame being modulated, and *num_frame* is the total number of frames. It means that for a total number of frames being 20 or more, it only displays the *n-th* frame when *n* is an integer multiple of the round-down integer of a tenth of the total number of frames; and for a total number of frames being 19 or less, it shows every frame that is being modulated. This would keep the total number of displays within the range from 11 to 19, provided that the total number of frames is more than 10; otherwise, it simply shows as many messages as the total number of frames.

3.7.3. OFDM Demodulator

Like any typical modulation/demodulation, OFDM demodulation is basically a reverse process of OFDM modulation. And like its modulator, the OFDM demodulator demodulates the received data frame by frame unless the transmitted data has length less than the designed total number of symbols per frame.

3.7.4. Periodic Time Guard Removal

The previous example used in section 4.4.2 "OFDM Modulator" shall continue to be used for illustration. Figure 13 shows that after converting a frame of discrete time signal from serial to

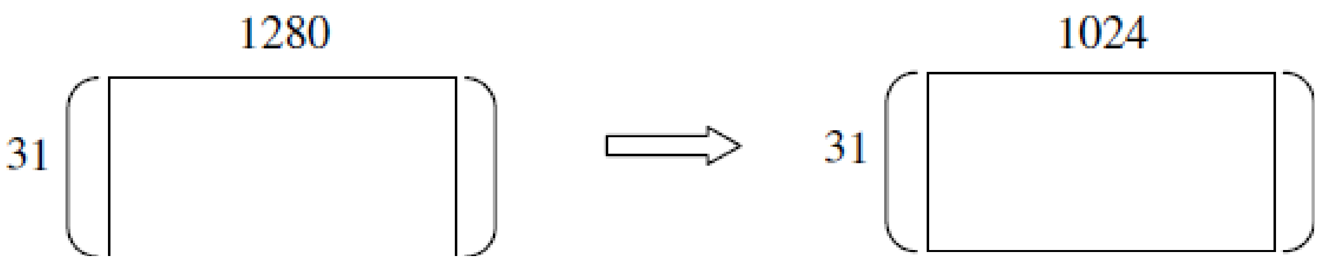


Figure 21: Time Guard Removal

parallel, a length of 25% of a symbol period is discarded from all rows. Thus the remaining is then a number of discrete signals with the length of one symbol period lined up in parallel.

3.7.5. FFT: Time Signal to Spectral Space

Fast Fourier Transform (FFT) of the received time signal is taken. This results the spectrum of the received signal. As shown in Figure 14, the columns in the locations of carriers are

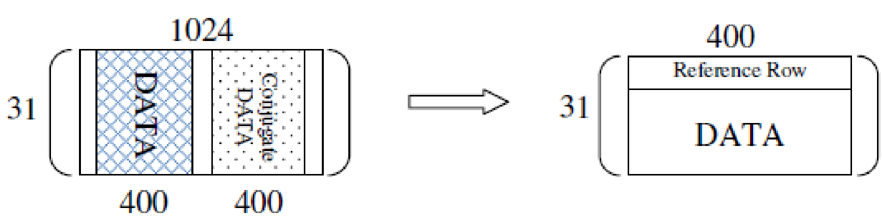


Figure 22: carriers are extracted

extracted to retrieve the complex matrix of the received data.

3.7.6. Differential Phase Shift Keying (DPSK) Demodulation

The phase of every element in the complex matrix is converted into 0-360 degrees range and translated to one of the values within the symbol size. The translated values form a new

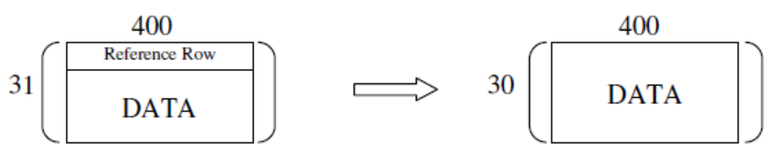


Figure 23: differential DeModulation

matrix. The differential operation is performed in parallel on this new matrix to retrieve the demodulated data. This differential operation is basically calculating the difference between every two consecutive symbols in a column of the matrix. As shown in Figure 15, the reference row is removed during this operation. Finally, a parallel to serial operation is performed and the demodulated data stream for this frame is obtained. Note that a series of zeros may have been padded to the original data before transmission in order to make each carrier have the same number of data symbols. Therefore, the modulator may have to remove the padded zeros from the last portion of the demodulated data stream before the final version of the received data can be obtained. The number of padded zeros is calculated by taking the remainder of total number of data symbols over the number of carriers.

4. Chapter 4 – Research Findings and Discussions

An OFDM system was modeled using Matlab to allow various parameters of the system to be varied and tested. The aim of doing the simulations was to measure the performance of OFDM under different channel conditions, and to allow for different OFDM configurations to be tested and compared against the current technology of CDMA. This will give us an understanding of the simulation outputs. To begin with, we first have to determine how errors are calculated

4.1. Error Calculations

Data loss

As mentioned in section 3.3 "Input and Output," one or more of full rows of pixels may be missing at the output of the receiver. In such cases, this program would show the number of missing data and the total number of data transmitted, as well as the percentage of data loss, which is the quotient of the two.

Bit Error Rate (BER)

Demodulated data is compared to the original baseband data to find the total number of errors. Dividing the total number of errors by total number of demodulated symbols, the bit-error-rate (BER) is found.

Phase Error

During the OFDM demodulation, before being translated into symbol values, the received phase matrix is archived for calculating the average phase error, which is defined by the difference between the received phase and the translated phase for the corresponding symbol before transmission.

Percent Error of Pixels in the Received Image

All aforementioned error calculations are based on the OFDM symbols. What is more meaningful for the end-user of the OFDM communication system is the actual percent error of pixels in the received image. This is done by comparing the received image and original image pixel by pixel.

Program Display - A summary showing the above error calculations is displayed at the end of the program. In an example shown in Table 9, an 285-by-228 image is transmitted by 400 carriers using an IFFT size of 1024, through a channel with 5 dB peak power clipping and 30 dB SNR.

Table 5: Errors Summary

#**************** Summary of Errors ****************#
Data loss in this communication = 0.669437% (1740 out of 259920)
Total number of errors = 676 (out of 258180)
Bit Error Rate (BER) = 0.261833%
Average Phase Error = 7.481238 (degree)
Percent error of pixels of the received image = 0.811500%

4.2. Plotting

Seven graphs are plotted during this OFDM simulation:

1) Magnitudes of OFDM carrier data on IFFT bins; *since all magnitudes are ONE, what this plot really shows is how the carriers are spread out in the IFFT bins.*

2) Phases translated from the OFDM data;
In this graph, it's easy to see that the original data has a number of possible levels equal to 2 raised to the power of symbol size.

3) Modulated time signal for one symbol period on one carrier;

4) Modulated time signal for one symbol period on multiple (limiting to six) carriers;

5) Magnitudes of the received OFDM spectrum;
This is to be compared to the first graph.

6) Phases of the received OFDM spectrum;
This is to be compared to the second graph.

7) Polar plot of the received phases;
A successful OFDM transmission and reception should have this plot show the grouping of the received phases clearly into 2^symbol-size constellations.

The first four plots are derived from OFDM modulation while the last three are from demodulation. None of these plots include a complete OFDM data packet. The first three plots represent only the first symbol period in the first frame of data, whereas the fourth plot represents up to the first six symbol periods in the first frame. Since the first and last portion of the received/modulated data have higher probability of getting errors due to imprecision in synchronization, a sample of symbol period used by the fifth, sixth, and seventh plots is from the approximate middle of a frame, which is also approximately the middle one among all data frames. However, it's still possible that the sample taken for the demodulation plots is still erroneous on certain trials of this MATLAB simulation. It is important to note that even if the fifth, sixth, and seventh plots don't show reasonable information, the overall OFDM transmission and reception would still likely be valid since these plots only represent one symbol period among many. Below are examples of these plots based on the table parameters below.

Table 6: OFDM Plots for a Single Symbol Period

Input for the OFDM Simulation	source data filename: 8bit.bmp Output file will be: 8bit_OFDM.bmp IFFT size: 1024 Number of carriers: 500 Modulation(1=BPSK, 2=QPSK, 4=16PSK, 8=256PSK): 4 Amplitude clipping introduced by communication channel (in dB:3 Signal-to-Noise Ratio (SNR) in dB: 15
Summary of the OFDM transmission and channel modeling:	Peak to RMS power ratio at entrance of channel is: 13.712444 dB Peak to RMS power ratio at exit of channel is: 11.946108 dB #******** OFDM data transmitted in 9.310725 seconds ********# #********** OFDM data received in 3.691622 seconds *********# WARNING: Output image smaller than original due to data loss in transmission.
* Summary of Errors	Data loss in this communication = 0.389877% (1670 out of 428340) Total number of errors = 111876 (out of 426670) Bit Error Rate (BER) = 26.220733% Average Phase Error = 8.824401 (degree) Percent error of pixels of the received image = 45.066954%

Input/Output Image		

4.3. Transmission Graphs

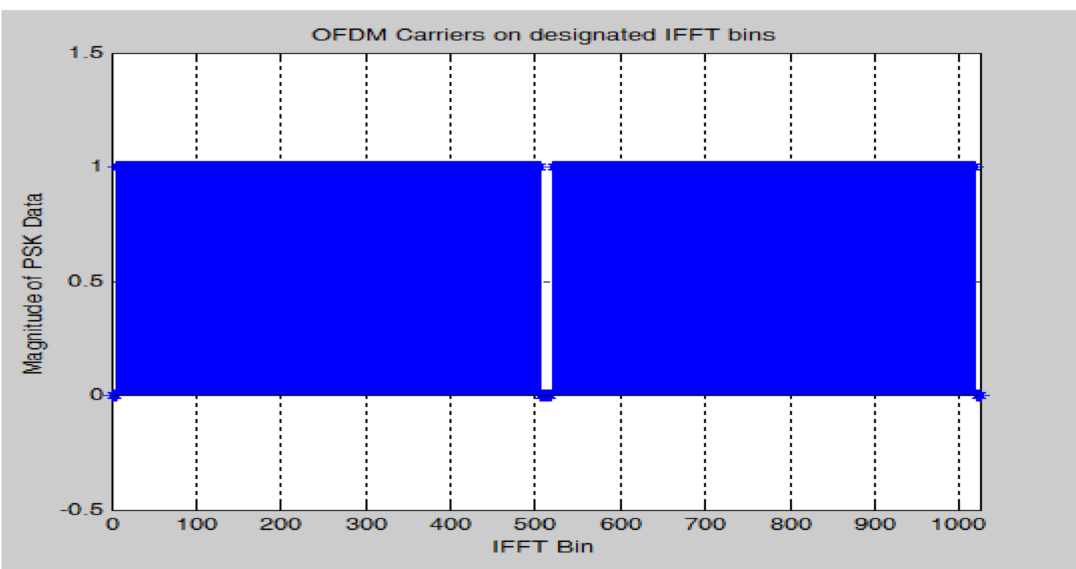


Figure 24: Magnitudes of OFDM carrier data on IFFT bins

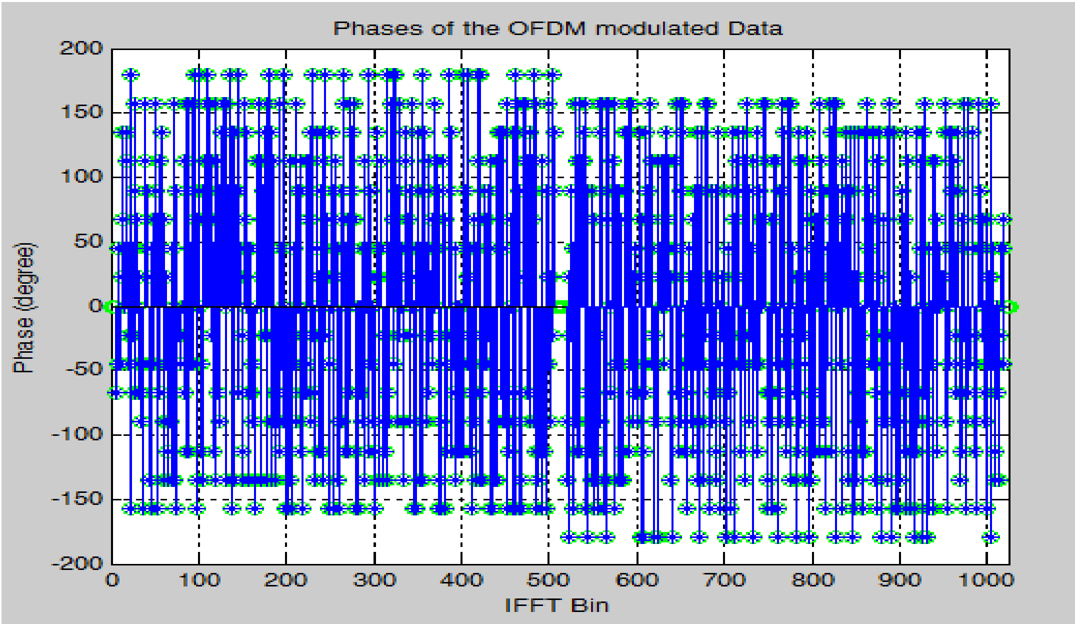


Figure 25: Phases translated from the OFDM data

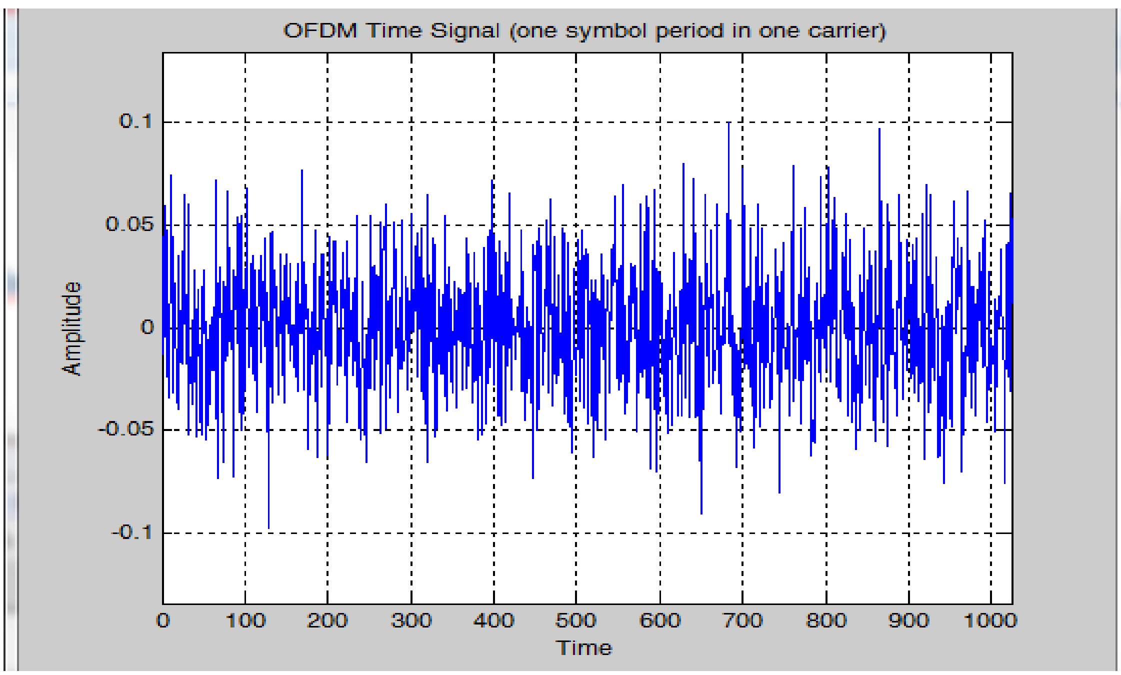


Figure 26: Modulated time signal for one symbol period on one carrier

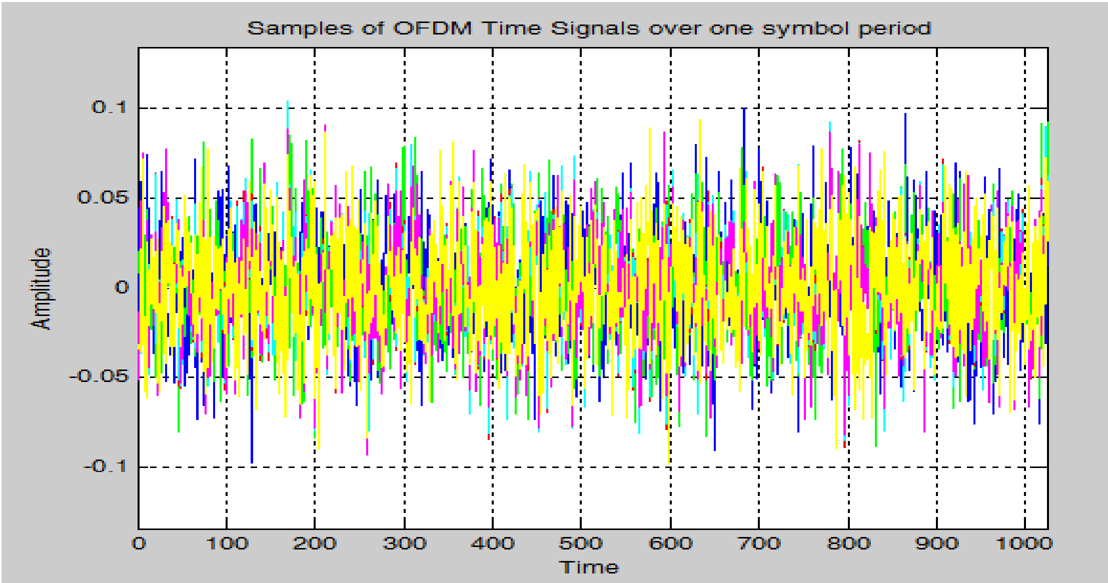


Figure 27: Modulated time signal for one symbol period on multiple (limiting to six) carriers

4.4. Receiver Graphs

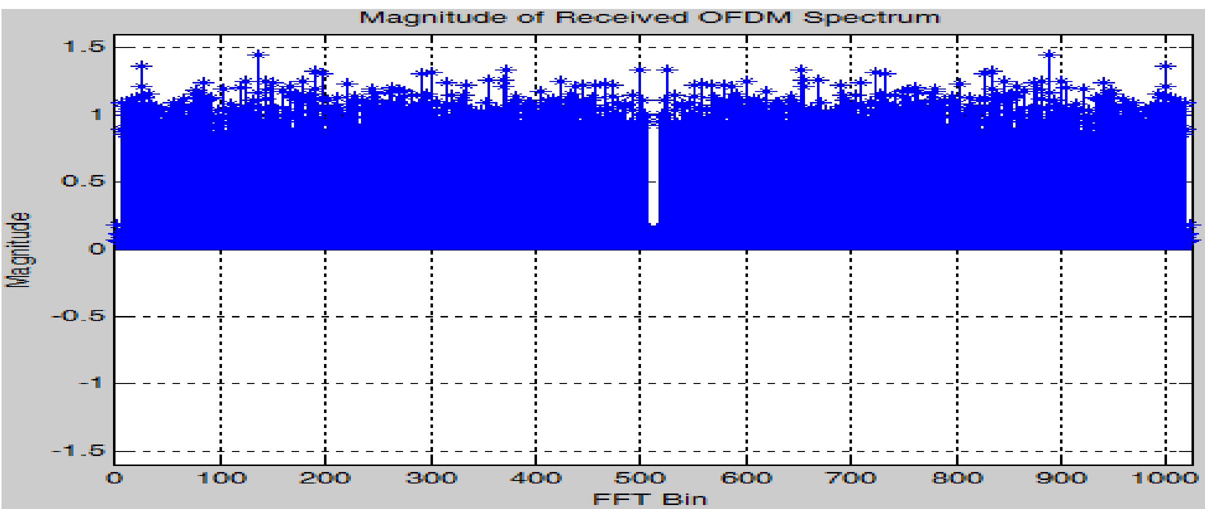


Figure 28: Magnitudes of the received OFDM spectrum

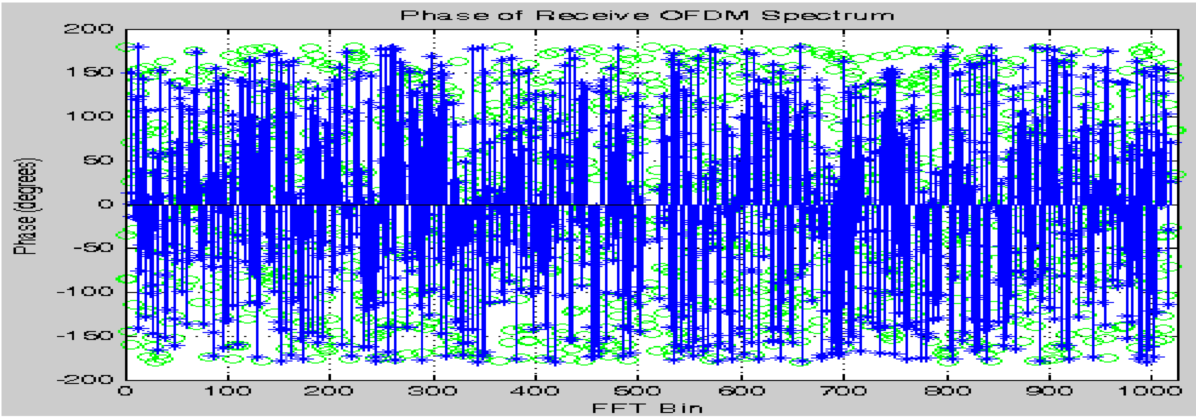


Figure 29: Phases of the received OFDM spectrum

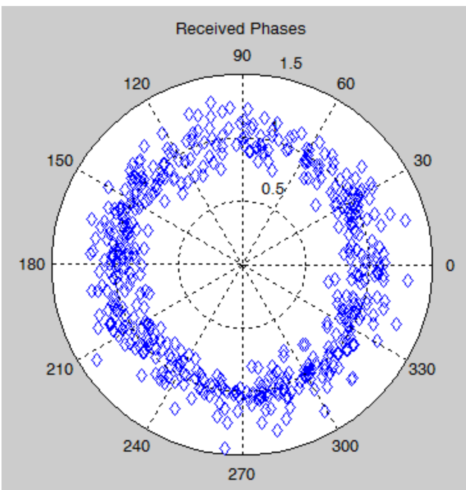


Figure 30: Polar plot of the received phases

4.5. Simulation Results

Table 7: BER for OFDM System

SNR(E_b/N_o)	Number of Errors	Bit Error Rate(BER) %
6	94995	9%
8	34731	3%
10	9249	1%
12	4481	2%

These results indicate that SNR is inversely proportional to error rates. To demonstrate this in an experiment, we use the parameters in the table below. Figure 31 shows the relationship between the two for all four *M*PSK methods. As expected, higher order PSK requires a larger SNR to minimize BER. *Assuming a constant Amplitude power clipping of 5db*

Table 8: OFDM BER with 5db Amplitude power clipping

SNR/ BER	0	6	8	10	20	40	60
BPSK	13.54%	0.33%	0%	0%	0.05%	0.00%	0.00%
QPSK	41.44%	9%	3%	1%	0.37%	0.00%	0%
16PSK	83.46%	66.07%	58%	48.15%	4.10%	0.00%	0.00%
256PSK	98.94%	97.87%	97%	96.53%	89.21%	0.00%	0.00%

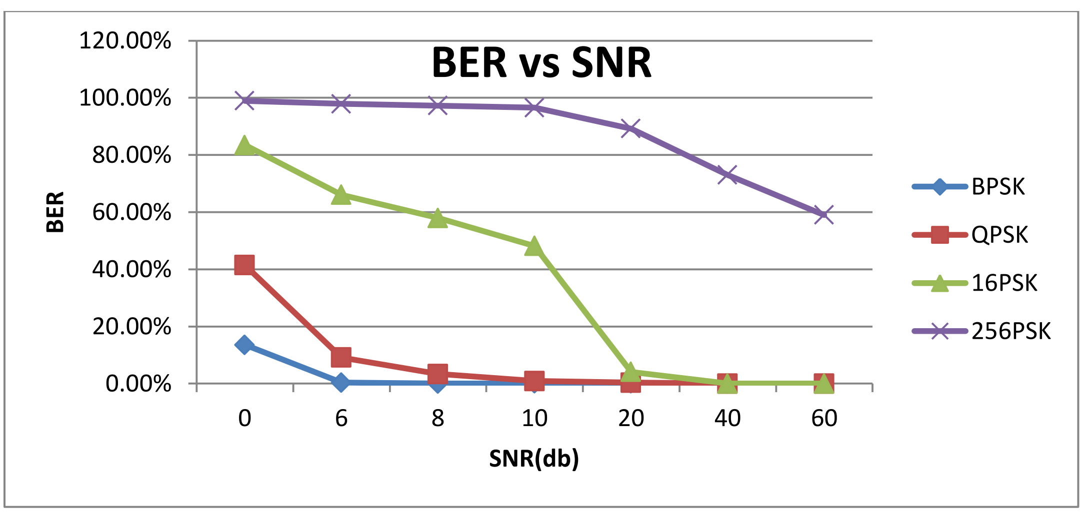
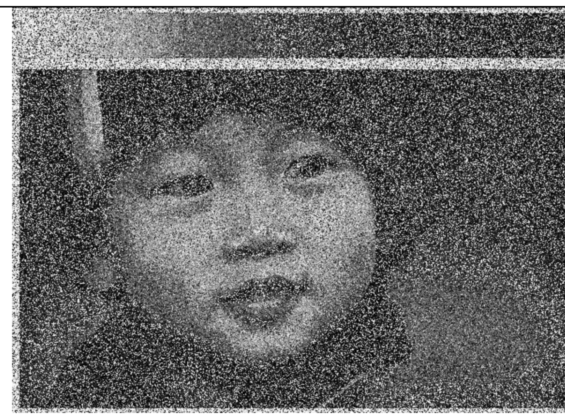


Figure 31: OFDM graph of BER vs SNR

Similarly, as shown in Figures below, 256-PSK and 16-PSK require a relatively large SNR to transmit data with an acceptable percent error. The Figures below show the original image and received images for different orders of PSK with varied SNR

Original Image

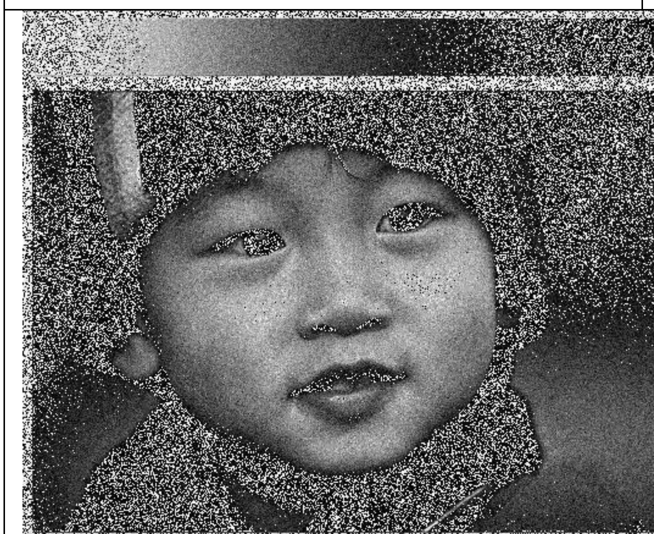
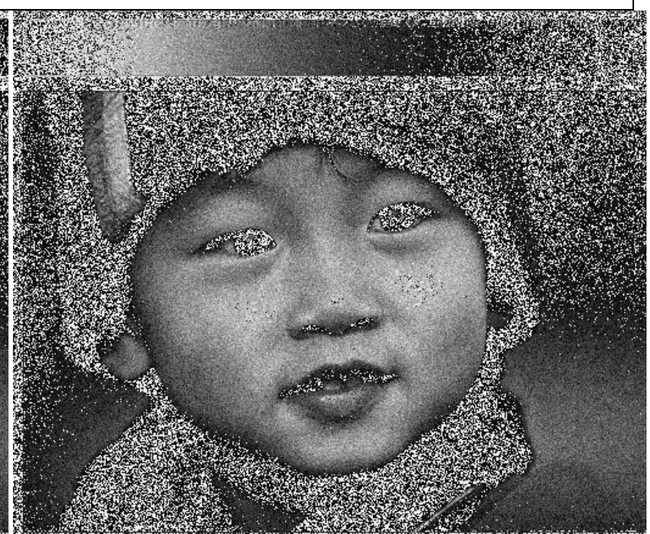
BPSK; SNR =0



QPSK; SNR =0

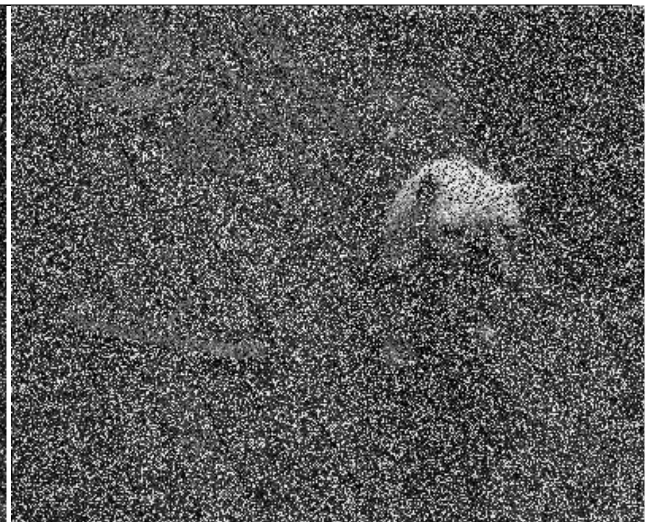
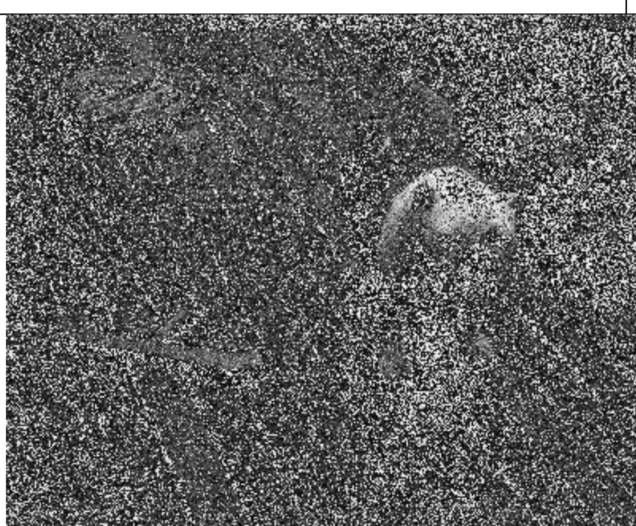
16PSK; SNR =0

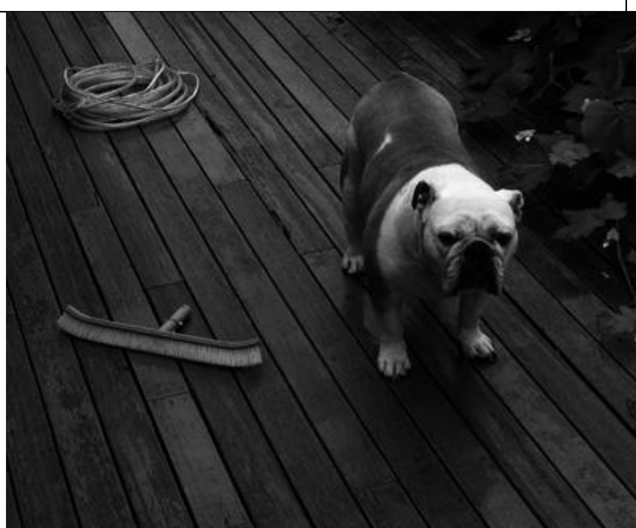
256PSK; SNR =0

	
BPSK; SNR =6	QPSK; SNR =6
	
16PSK; SNR =6	256PSK; SNR =6

	
BPSK; SNR =20	QPSK; SNR =20
	
16PSK; SNR =20db	256PSK; SNR =20db

Original Image

	
BPSK; SNR =0	QPSK; SNR =0
	
16PSK; SNR =0db	256PSK; SNR =0db

	
BPSK; SNR =40	QPSK; SNR =40
	
16PSK; SNR =40db	256PSK; SNR =40db

Even some low SNR received images, especially 256-PSK modulated images, have rather high BER; most of the information in the received images is still observable. For example, at 20dB of SNR, even though the 256-PSK received image has a BER of 93.63%, the image is still observable. This is because for grayscale digital images, if the decoded value of a pixel is off by a small number of gray levels, it's not easily observed by human eye, but will be counted as a bit error. A balanced trade-off between BER-tolerance and desire of data rate needs to be found for the type of data to be transmitted using OFDM.

The selected image varies differently when noise is introduced to it. When we look at the BPSK channel, it gets clearer as the signal to noise levels increase. This scenario is replicated as the channel gets to 256PSK. The change in picture quality can therefore be said to be much better in channels that are able to handle many modulations at a given time. Simulation results indicate that if a channel has a higher SNR then it is better placed to deliver a good signal.

4.6. Performance Comparison with CDMA

According to Khoja, Bredrow and Al-Shalash (2003), CDMA is inherently tolerant to multipath delay spread signals as any signal which is delayed by more than one chip time becomes uncorrelated to the PN code used to decode the signal. This results in the multipath simply appearing as noise. This noise leads to an increase in the amount of interference seen by each user subjected to the multipath and thus increases the received BER. Figure 32 shows the effect of delay spread on the reverse link of a CDMA system. However, OFDM is found to have total immunity to multi-path delay spread provided the reflection time is less than the guard period used in the OFDM signal. In a typical system a delay spread of up to 100 msec could be tolerated, corresponding to multi-path reflections of 30 kms. Considering cellular base, CDMA capacity is limited by multiple access interference (MAI), which results from the imperfection of auto and cross-correlation characteristics of spreading codes. Although, zero cross correlated orthogonal codes could result in no MAI in flat fading channels, the orthogonality will not be guaranteed in frequency selective fading channels because of inter chip interference, which will cause MAI and degrade the system performance. Though CDMA is very good as far as security aspects are concerned, it is found to perform poorly in a single cellular system. Typically, with each cell allowing only10-20 simultaneous users in a cell compared to 128 users for OFDM.

Other Performance Comparisons are shown below:

4.6.1. Multipath Delay Spread Performance

To eliminate ISI the guard period insertion is done in OFDM. For a delay spread that is longer than the effective guard period, BER rises rapidly due to ISI. The maximum BER will occur when the delay spread is greater than the symbol time. See Fig. 32

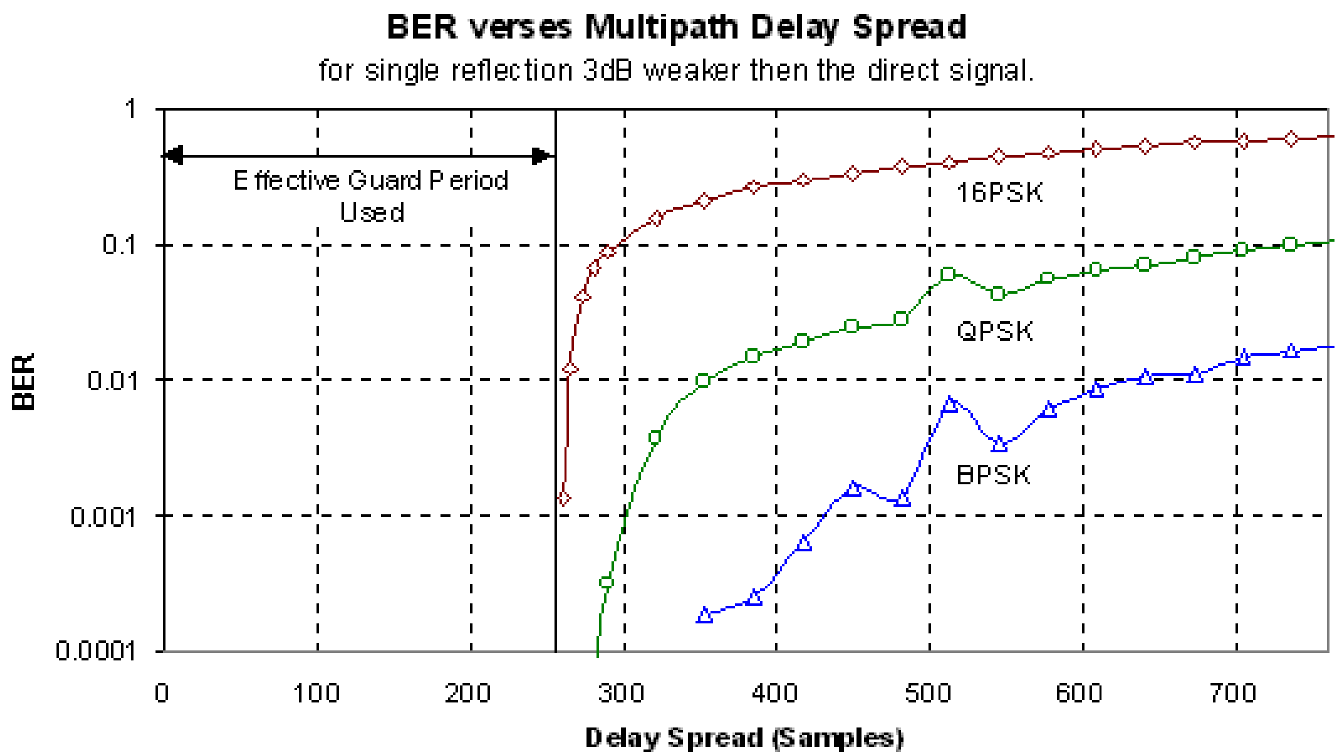


Figure 32: Delay Spread tolerance of OFDM

As shown in Fig.32 CDMA is inherently tolerant to multi-path delay spread signals as any signal delayed by more than one chip time becomes uncorrelated to the PN code used to decode the signal. This results in the multi-path simply appearing as noise. This noise lead to an increase in the amount of interference seen by each user subjected to the multi-path and thus increases the received BER

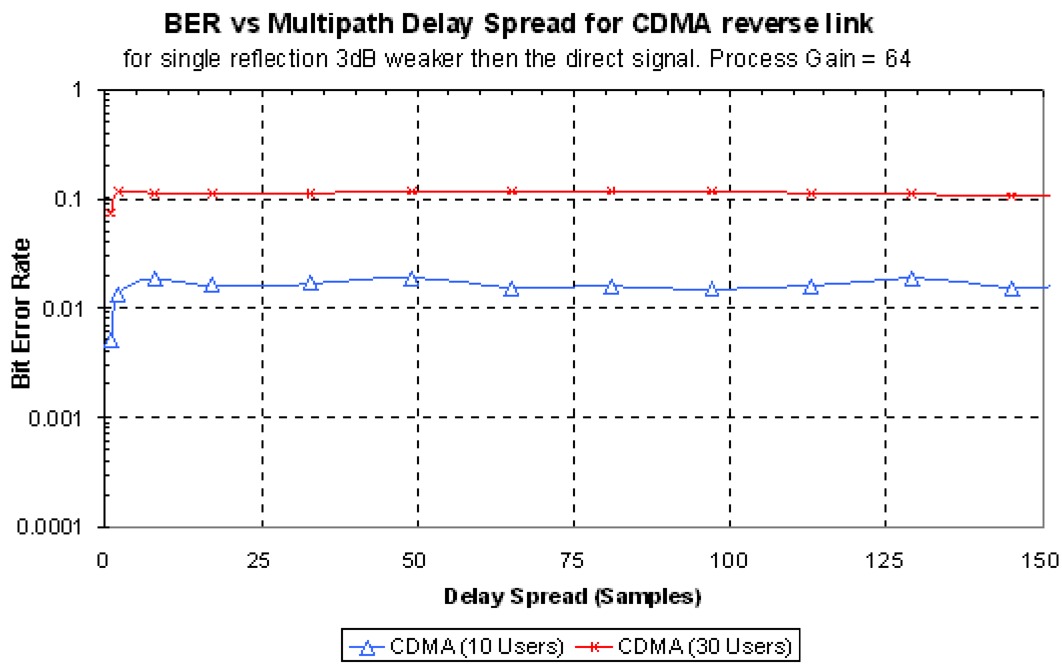


Figure 33: Effect of multi-path delay spread on the reverse link of a CDMA system

4.6.2. Gaussian Noise Tolerance

SNR performance of OFDM is similar to a standard single carrier digital transmission. This is expected, as the transmitted signal is similar to a standard FDM, though it is with closely placed orthogonal multiple carriers. Using QPSK the transmission can tolerate SNR>10-12 dB.

BER gets rapidly poor as the SNR drops below 6 dB. However, BPSK allows BER to be improved in a noisy channel, at the expense of transmission data capacity. Using BPSK the OFDM transmission can tolerate SNR >6-8 dB. If a low noise link and SNR>25 dB, 16PSK mapped OFDM can increase the transmission data capacity.

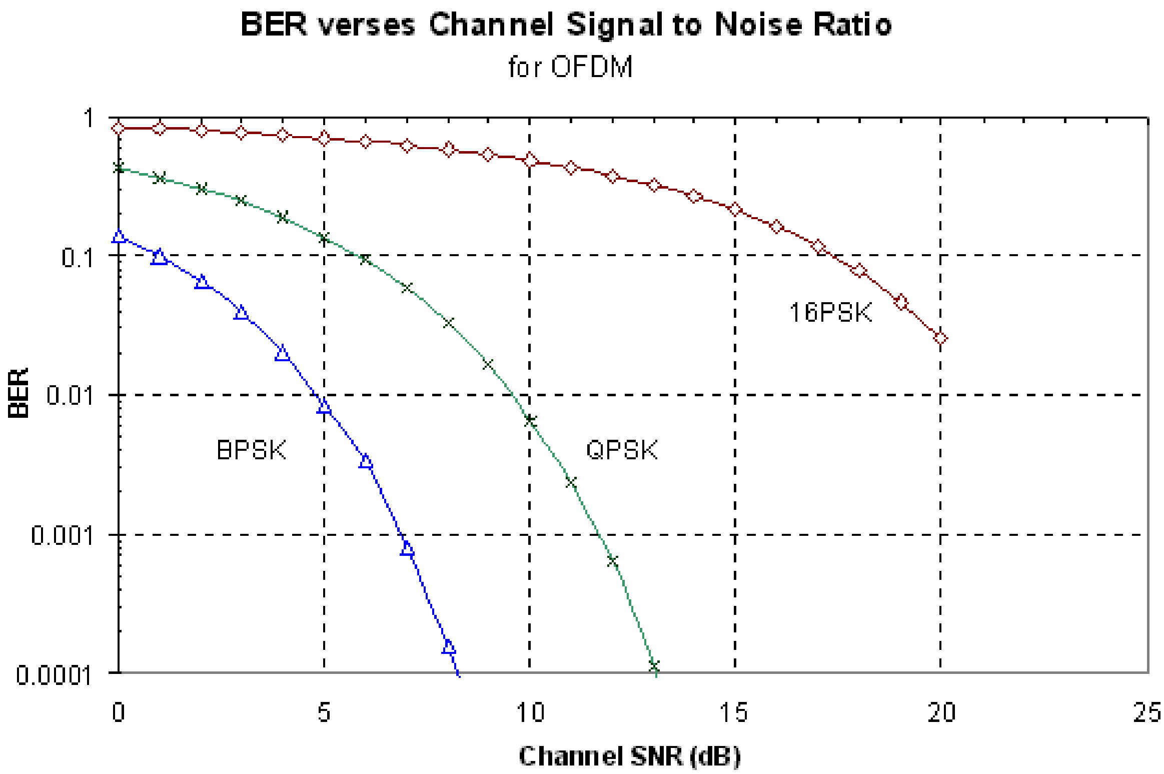


Figure 34: BER vs SNR for OFDM using BSPK, QPSK and 16PSK

The noise performance of the CDMA reverse link shows that the BER rises as the SNR of the channel worsen due to the high level of inter-user interference, the BER of each of the lines (10, 20, 30 users) approaches approximately the same BER at a SNR of 0 dB. At 0 dB the effective noise of the channel is the same as adding 60 users to the cell, thus the difference between 10, 20 and 30 users becomes insignificant. The BER is very bad for more than 10 users regardless of the channel SNR. However, for 10 users the BER becomes greater than the 0.01 (SNR of ~14 dB), which is the maximum BER that can be normally tolerated for voice communications. Refer Fig. 37

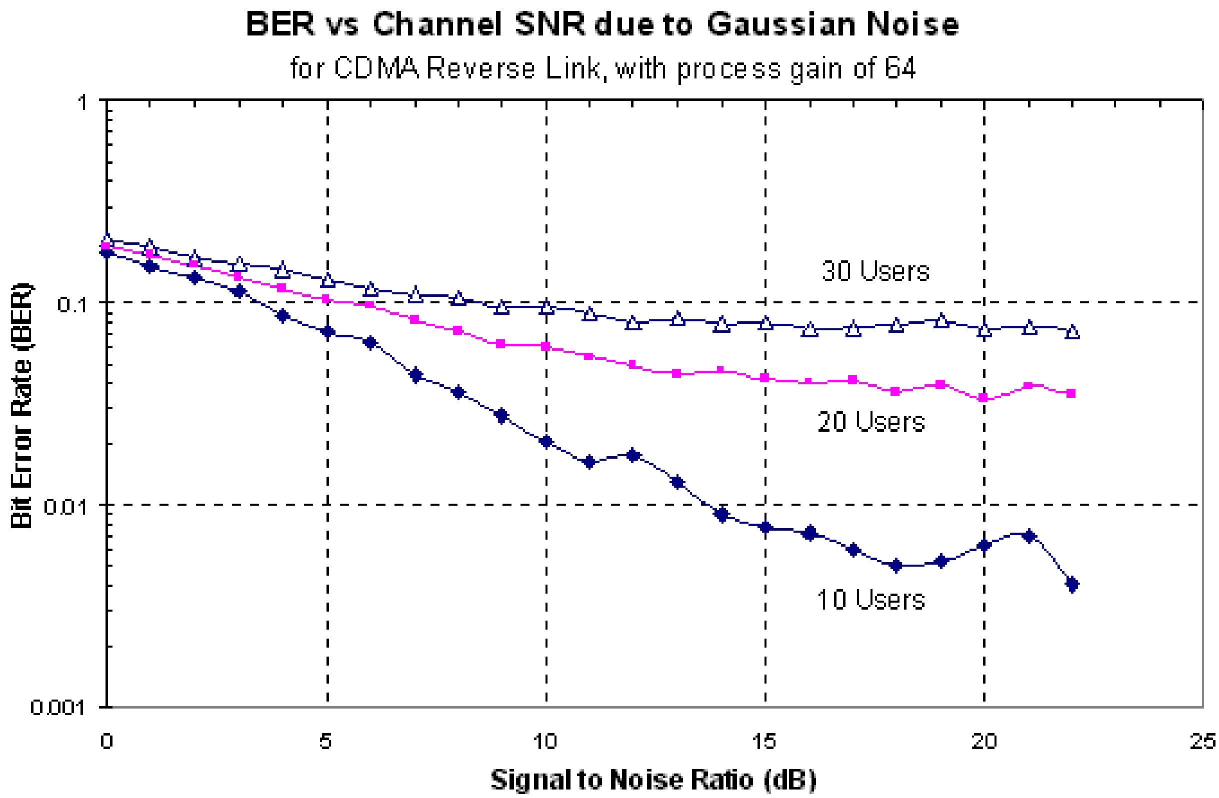


Figure 35: BER verses the radio channel SNR for the reverse link of a CDMA system.

4.7. Drawbacks

The problems associated with OFDM is frequency selective fading, which results in carriers being heavily attenuated due to destructive interference at the receiver. This may result in the carriers being lost in the noise. Another weak point is it is very sensitive to frequency and phase errors between the transmitter and the receiver. The main sources of these errors are frequency stability problems, phase noise of the transmitter and any frequency offset errors between the transmitter and the receiver, due to moving-mobiles and Doppler Effect. This may lead to error in finding the start time of the FFT symbol. This problem can be overcome by synchronizing the clocks between the transmitter and the receiver, by designing the system appropriately or by reducing the number of carrier users. The noise performance of OFDM is found dependent on the modulation technique used for mapping each carrier of the signal. The performance of the OFDM signal is found to be the same as for a single carrier system, using the same modulation-mapping. The minimum SNR required for BPSK is ~8 dB, where for QPSK

~12 dB and for 16PSK ~25 dB is the SNR requirements for better performance same is for CDMA. OFDM signal is contaminated by non-linear distortion of transmitter power amplifier, because of its combined amplitude-frequency modulation and it is necessary to maintain the linearity. The main problem associated with CDMA is near-far problem, limited users in a cell and complex rake receiver design.

5. Chapter 5 - Conclusion and Recommendations

OFDM appears to be a suitable technique as a powerful modulation technique used for high data rate, and is able to eliminate ISI. It is computationally efficient due to the use of FFT techniques to implement modulation and demodulation functions. It is observed from M-PSK BER plot that BER is less in case of 4-PSK for low E_b/N_o as compared to 8- PSK and 256-PSK. Hence, high value of M-ary is easily affected by noise. So OFDM system with QPSK scheme is suitable for low capacity, short distance application. While the OFDM with higher M ary modulation scheme is used for large capacity, long distance application at the cost of slight increase in E_b/N_o.

OFDM appears to be a suitable technique as a modulation technique for high performance wireless telecommunications. An OFDM link has been confirmed to work by using computer simulations, and some practical tests performed on a low bandwidth baseband signal. So far only two main performance criteria have been tested, which are OFDM's tolerance to multipath delay spread and channel noise. Several other important factors affecting the performance of OFDM have only been partly measured. These include peak power clipping, start time error, the effect of frequency stability errors on OFDM and impulse noise effects.

One important major area, which hasn't been investigated here, is the problems that may be encountered when OFDM is used in a multi-user environment. One possible problem is that the receiver may require a very large dynamic range in order to handle the large signal strength variation between users. However, COFDM with forward error correction may solve many problems improving the BER.

6. References

1. K. Fazel and S. Kaiser, (2003), Multi-Carrier and Spread Spectrum System, 2nd edition, New York: John Wiley and Sons Ltd.
2. Schulze Henrik and Christian Luders, (2005), Theory and Applications of OFDM and CDMA John Wiley & Sons Ltd.
3. 3GPP, "Physical layer - General description (Release 9)," 3GPP, Technical Specification TS 25.201 v9.0.0, 2009.
4. L.P. Linde, L Staphorst, and J.D. Vlok, "Performance of a quisi-synchronous fourdimentional super-orthogonal WCDMA modulator for next generation wireless applications," South African journal of Science, vol. 1, no. 103, pp. 459-464, November 2007.
5. Kenya Country Strategy Paper , National Indicative Programme, 2008-2013, (Accessed February2012) http://ec.europa.eu/development/icenter/repository/scanned_ke_csp10_en.pdf
6. Souter, David, et al. (2005), The Economic Impact of Telecommunications on Rural Livelihoods and Poverty Reduction: a study of rural communities in India (Gujarat), Mozambique and Tanzania, DFID KaR Project 8347, London
7. Dr. Sassan Ahmadi, (2006), Introduction to mobile WiMAX Radio Access Technology: PHY and MAC Architecture, Wireless Standards and Technology Intel Corporation.
8. Trieu, K. & Ajiboye, O., (2007), Performance Analysis of Adaptive Array System and Space-Time Block Coding in Mobile WiMAX (802.16e) Systems , Blekinge Institute of Technology , Karlskrona, Sweden.
9. Rappaport T.S., (1996), Wireless Communications Principles and Practice, New York: Prentice Hall.
10. M. A. Masud, M. Samsuzzaman, M. A.Rahman, (2010), Bit Error Rate Performance Analysis on Modulation Techniques of Wideband Code Division Multiple Access *Journal of Telecommunications, Volume 1, Issue 2.*
11. Understanding an OFDM transmission(2008) (Accessed in June 2012):

http://www.dsplog.com/2008/02/03/understanding-an-ofdm-transmission/

12. Yuan-Pei Lin, See-May Phoong, P. P. Vaidyanathan, (2011), Filter Bank Transceivers for OFDM and DMT Systems, Cambridge University Press.
13. Fourth Generation wireless (2012), (Accessed in June 2012) http://en.wikipedia.org/wiki/4G#Background.
14. Holly Moore, (2011), MATLAB for Engineers 3rd ed., Salt Lake City, Utah, Pearson.
15. Khalid Sayood, (2007), Learning Programming using MATLAB, Nebraska, USA, Morgan & Claypool Publishers
16. K. Fazel and S. Kaiser, (2008), Multi Carrier and Spread Spectrum, 2nd Edition, UK, Wiley
17. S.R. Otto & J.P. Denier, (2005), An Introduction to Programming and Numerical Methods in MATLAB, London, Springer
18. Howard B. Wilson, Louis H. Turcotte and David Halpern, (2003), Advanced Mathematics and Mechanics Applications Using MATLAB, 3rd Edition, CHAPMAN & HALL/CRC
19. Theory of Frequency Division Multiplexing (Accessed in June 2012) http://zone.ni.com/devzone/cda/ph/p/id/269
20. Khoja, Bredrow and Al-Shalash (2003), Simulation of CDMA systems using dynamic simulator, pp 31-34
21. IET-UK International Conference on Information and Communication Technology in Electrical Sciences (ICTES 2007), Dr. MG.R. University, Chennai, Tamil Nadu, India. Dec. 20-22, 2007. pp. 684-687

7. Appendix - Source Code

**************MAIN SIMULATION FILE***********************

```
warning('off','MATLAB:dispatcher:InexactMatch');
clear all;
close all;
fprintf('#*********** Simulation ************#\n')
ofdm_parameters;
save('ofdm_parameters');
x = imread(file_in);
h = size(x,1);
w = size(x,2);
x = reshape(x', 1, w*h);
baseband_tx = double(x);
baseband_tx = ofdm_base_convert(baseband_tx, word_size, symb_size);
save('err_calc.mat', 'baseband_tx');
% ****************** TRANSMITTER ***************** %
tic;
f = 0.25;
header = sin(0:f*2*pi:f*2*pi*(head_len-1));
f=f/(pi*2/3);
header = header+sin(0:f*2*pi:f*2*pi*(head_len-1));
frame_guard = zeros(1, symb_period);
time_wave_tx = [];
symb_per_carrier = ceil(length(baseband_tx)/carrier_count);
fig = 1;
if (symb_per_carrier > symb_per_frame)
power = 0;
while ~isempty(baseband_tx)
frame_len = min(symb_per_frame*carrier_count,length(baseband_tx));
```

```
frame_data = baseband_tx(1:frame_len);
baseband_tx = baseband_tx((frame_len+1):(length(baseband_tx)));
time_signal_tx = ofdm_modulate(frame_data,ifft_size,carriers,...
conj_carriers, carrier_count, symb_size, guard_time, fig);
fig = 0;
time_wave_tx = [time_wave_tx frame_guard time_signal_tx];
frame_power = var(time_signal_tx);
end
power = power + frame_power;
time_wave_tx = [power*header time_wave_tx frame_guard power*header];
else
time_signal_tx = ofdm_modulate(baseband_tx,ifft_size,carriers,...
conj_carriers, carrier_count, symb_size, guard_time, fig);
power = var(time_signal_tx);
time_wave_tx = ...
[power*header frame_guard time_signal_tx frame_guard power*header];
end
peak = max(abs(time_wave_tx(head_len+1:length(time_wave_tx)-head_len)));
sig_rms = std(time_wave_tx(head_len+1:length(time_wave_tx)-head_len));
peak_rms_ratio = (20*log10(peak/sig_rms));
fprintf('\nSummary of the OFDM transmission and channel modeling:\n')
fprintf('Peak to RMS power ratio at entrance of channel is: %f dB\n', ...
peak_rms_ratio)
% **************** Adding AWGN to the CHANNEL **************** %
clipped_peak = (10^(0-(clipping/20)))*max(abs(time_wave_tx));
time_wave_tx(find(abs(time_wave_tx)>=clipped_peak))...
= clipped_peak.*time_wave_tx(find(abs(time_wave_tx)>=clipped_peak))...
./abs(time_wave_tx(find(abs(time_wave_tx)>=clipped_peak)));
power = var(time_wave_tx); % Gaussian (AWGN)
```

```
SNR_linear = 10^(SNR_dB/10);
noise_factor = sqrt(power/SNR_linear);
noise = randn(1,length(time_wave_tx)) * noise_factor;
time_wave_rx = time_wave_tx + noise;
peak = max(abs(time_wave_rx(head_len+1:length(time_wave_rx)-head_len)));
sig_rms = std(time_wave_rx(head_len+1:length(time_wave_rx)-head_len));
peak_rms_ratio = (20*log10(peak/sig_rms));
fprintf('Peak to RMS power ratio at exit of channel is: %f dB\n', ...
peak_rms_ratio)
save('received.mat', 'time_wave_rx', 'h', 'w');
fprintf('#******** OFDM data transmitted in %f seconds ********#\n\n', toc)
% ******************** RECEIVER ****************** %
disp('Press any key to let OFDM RECEIVER proceed...')
pause;
clear all;
tic;
load('ofdm_parameters');
load('received.mat');
time_wave_rx = time_wave_rx.';
end_x = length(time_wave_rx);
start_x = 1;
data = [];
phase = [];
last_frame = 0;
unpad = 0;
if rem(w*h, carrier_count)~=0
unpad = carrier_count - rem(w*h, carrier_count);
end
num_frame=ceil((h*w)*(word_size/symb_size)/(symb_per_frame*carrier_count));
```

```
fig = 0;
for k = 1:num_frame
if k==1 || k==num_frame || rem(k,max(floor(num_frame/10),1))==0
fprintf('Demodulating Frame #%d\n',k)
end
if k==1
time_wave = time_wave_rx(start_x:min(end_x, ...
(head_len+symb_period*((symb_per_frame+1)/2+1))));
else
time_wave = time_wave_rx(start_x:min(end_x, ...
((start_x-1) + (symb_period*((symb_per_frame+1)/2+1)))));
end
frame_start = ...
ofdm_frame_detect(time_wave, symb_period, envelope, start_x);
if k==num_frame
last_frame = 1;
frame_end = min(end_x, (frame_start-1) + symb_period*...
(1+ceil(rem(w*h,carrier_count*symb_per_frame)/carrier_count)));
else
frame_end=min(frame_start-1+(symb_per_frame+1)*symb_period, end_x);
end
time_wave = time_wave_rx(frame_start:frame_end);
start_x = frame_end - symb_period;
if k==ceil(num_frame/2)
fig = 1;
end
 [data_rx, phase_rx] = ofdm_demod...
(time_wave, ifft_size, carriers, conj_carriers, ...
guard_time, symb_size, word_size, last_frame, unpad, fig);
```

```
if fig==1
fig = 0; %
end
phase = [phase phase_rx];
data = [data data_rx];
end
phase_rx = phase;
data_rx = data;
data_out = ofdm_base_convert(data_rx, symb_size, word_size);
fprintf('#********** OFDM data received in %f seconds *********#\n\n', toc)
% ********************** DATA OUTPUT ******************** %
if length(data_out)>(w*h)
data_out = data_out(1:(w*h));
elseif length(data_out)<(w*h)
buff_h = h;
h = ceil(length(data_out)/w);
% if one or more rows of pixels are missing, show a message to indicate
if h~=buff_h
disp('WARNING: Output image smaller than original')
disp(' due to data loss in transmission.')
end
if length(data_out)~=(w*h)
for k=1:(w*h-length(data_out))
mend(k)=data_out(length(data_out)-w+k);
end
data_out = [data_out mend];
end
data_out = reshape(data_out, w, h)';
data_out = uint8(data_out);
```

```
imwrite(data_out, file_out, 'bmp');
% ****************** ERROR CALCULATIONS ***************** %
load('err_calc.mat');
fprintf('\n#**************** Summary of Errors ****************#\n')
if length(data_rx)>length(baseband_tx)
data_rx = data_rx(1:length(baseband_tx));
phase_rx = phase_rx(1:length(baseband_tx));
elseif length(data_rx)<length(baseband_tx)
fprintf('Data loss in this communication = %f%% (%d out of %d)\n', ...
(length(baseband_tx)-length(data_rx))/length(baseband_tx)*100, ...
length(baseband_tx)-length(data_rx), length(baseband_tx))
end
errors = find(baseband_tx(1:length(data_rx))~=data_rx);
fprintf('Total number of errors = %d (out of %d)\n', ...
length(errors), length(data_rx))
fprintf('Bit Error Rate (BER) = %f%%\n',length(errors)/length(data_rx)*100)
phase_tx = baseband_tx*360/(2^symb_size);
phase_err = (phase_rx - phase_tx(1:length(phase_rx)));
phase_err(find(phase_err>=180)) = phase_err(find(phase_err>=180))-360;
phase_err(find(phase_err<=-180)) = phase_err(find(phase_err<=-180))+360;
fprintf('Average Phase Error = %f (degree)\n', mean(abs(phase_err)))
x = ofdm_base_convert(baseband_tx, symb_size, word_size);
x = uint8(x);
x = x(1:(size(data_out,1)*size(data_out,2)));
y = reshape(data_out', 1, length(x));
err_pix = find(y~=x);
fprintf('Percent error of pixels of the received image = %f%%\n\n', ...
length(err_pix)/length(x)*100)
fprintf('#******** END of OFDM Simulation ********#\n')
```

```
% ************* FUNCTION: ofdm_base_convert() ************* %
function data_out = ofdm_base_convert(data_in, base, new_base)
if new_base>base
data_in = data_in(1:...
floor(length(data_in)/(new_base/base))*(new_base/base));
end
for k=1:base
binary_matrix(k,:) = floor(data_in/2^(base-k));
data_in = rem(data_in,2^(base-k));
end
newbase_matrix = reshape(binary_matrix, new_base, ...
size(binary_matrix,1)*size(binary_matrix,2)/new_base);
data_out = zeros(1, size(newbase_matrix,2));
for k=1:new_base
data_out = data_out + newbase_matrix(k,:)*(2^(new_base-k));
end
```

```
% ************* FUNCTION: ofdm_frame_detect() ************* %
function start_symb = ofdm_frame_detect(signal, symb_period, env, label)
signal = abs(signal);
idx = 1:env:length(signal);
samp_signal = signal(idx);
mov_sum = filter(ones(1,round(symb_period/env)),1,samp_signal);
mov_sum = mov_sum(round(symb_period/env):length(mov_sum));
apprx = min(find(mov_sum==min(mov_sum))*env+symb_period);
idx_start = round(apprx-1.1*symb_period);
mov_sum = filter(ones(1,symb_period),1,...
signal(idx_start:round(apprx+symb_period/3)));
mov_sum = mov_sum(symb_period:length(mov_sum));
null_sig = find(mov_sum==min(mov_sum));
start_symb = min(idx_start + null_sig + symb_period) - 1;
start_symb = start_symb + (label - 1);
```

```
% ************* PARAMETERS INITIALIZATION ************* %
file_in = [];
while isempty(file_in)
file_in = input('source data filename: ', 's');
if exist([pwd '/' file_in],'file')~=2
fprintf ...
('"%s" does not exist in current directory.\n', file_in);
file_in = [];
end
end
file_out = [file_in(1:length(file_in)-4) '_OFDM.bmp'];
disp(['Output file will be: ' file_out])
ifft_size = 0.1; % force into the while loop below
while (isempty(ifft_size) || ...
(rem(log2(ifft_size),1) ~= 0 || ifft_size < 8))
ifft_size = input('IFFT size: ');
if (isempty(ifft_size) || ...
(rem(log2(ifft_size),1) ~= 0 || ifft_size < 8))
disp('IFFT size must be at least 8 and power of 2.')
end
end
carrier_count = ifft_size; % force into the while loop below
while (isempty(carrier_count) || ...
(carrier_count>(ifft_size/2-2)) || carrier_count<2)
carrier_count = input('Number of carriers: ');
if (isempty(carrier_count) || (carrier_count > (ifft_size/2-2)))
disp('Must NOT be greater than ("IFFT size"/2-2)')
end
end
```

```
symb_size = 0; % force into the while loop below
while (isempty(symb_size) || ...
(symb_size~=1 && symb_size~=2 && symb_size~=4 && symb_size~=8))
symb_size = input...
('Modulation(1=BPSK, 2=QPSK, 4=16PSK, 8=256PSK): ');
if (isempty(symb_size) || ...
(symb_size~=1&&symb_size~=2&&symb_size~=4&&symb_size~=8))
disp('Only 1, 2, 4, or 8 can be choosen')
end
end
clipping = [];
while isempty(clipping)
clipping = input...
('Amplitude clipping introduced by communication channel (in dB:');
end
SNR_dB = [];
while isempty(SNR_dB)
SNR_dB = input('Signal-to-Noise Ratio (SNR) in dB: ');
end
word_size = 8; % bits per word of source data (byte)
guard_time = ifft_size/4; % length of guard interval for each symbol period
symb_per_frame = ceil(2^13/carrier_count);
symb_period = ifft_size + guard_time;
head_len = symb_period*8;
envelope = ceil(symb_period/256)+1;
spacing = 0;
while (carrier_count*spacing) <= (ifft_size/2 - 2)
spacing = spacing + 1;
end
```

```
spacing = spacing - 1;
midFreq = ifft_size/4;
first_carrier = midFreq - round((carrier_count-1)*spacing/2);
last_carrier = midFreq + floor((carrier_count-1)*spacing/2);
carriers = [first_carrier:spacing:last_carrier] + 1;
conj_carriers = ifft_size - carriers + 2;
```

```
% ************* FUNCTION: ofdm_modulation() ************* %
function signal_tx = ofdm_modulate(data_tx, ifft_size, carriers, ...
conj_carriers, carrier_count, symb_size, guard_time, fig)
carrier_symb_count = ceil(length(data_tx)/carrier_count);
if length(data_tx)/carrier_count ~= carrier_symb_count,
padding = zeros(1, carrier_symb_count*carrier_count);
padding(1:length(data_tx)) = data_tx;
data_tx = padding;
end
data_tx_matrix = reshape(data_tx, carrier_count, carrier_symb_count)';
carrier_symb_count = size(data_tx_matrix,1) + 1;
diff_ref = round(rand(1, carrier_count)*(2^symb_size)+0.5);
data_tx_matrix = [diff_ref; data_tx_matrix];
for k=2:size(data_tx_matrix,1)
data_tx_matrix(k,:) = ...
rem(data_tx_matrix(k,:)+data_tx_matrix(k-1,:), 2^symb_size);
end
 [X,Y] = pol2cart(data_tx_matrix*(2*pi/(2^symb_size)), ...
ones(size(data_tx_matrix)));
complex_matrix = X + i*Y;
spectrum_tx = zeros(carrier_symb_count, ifft_size);
spectrum_tx(:,carriers) = complex_matrix;
spectrum_tx(:,conj_carriers) = conj(complex_matrix);
if fig==1
figure(1)
stem(1:ifft_size, abs(spectrum_tx(2,:)),'b*-')
grid on
axis ([0 ifft_size -0.5 1.5])
ylabel('Magnitude of PSK Data')
```

```
xlabel('IFFT Bin')
title('OFDM Carriers on designated IFFT bins')
figure(2)
plot(1:ifft_size, (180/pi)*angle(spectrum_tx(2,1:ifft_size)), 'go')
hold on
grid on
stem(carriers, (180/pi)*angle(spectrum_tx(2,carriers)),'b*-')
stem(conj_carriers, ...
(180/pi)*angle(spectrum_tx(2,conj_carriers)),'b*-')
axis ([0 ifft_size -200 +200])
ylabel('Phase (degree)')
xlabel('IFFT Bin')
title('Phases of the OFDM modulated Data')
end
signal_tx = real(ifft(spectrum_tx'))';
if fig==1
limt = 1.1*max(abs(reshape(signal_tx',1,size(signal_tx,1)...
*size(signal_tx,2))));
figure (3)
plot(1:ifft_size, signal_tx(2,:))
grid on
axis ([0 ifft_size -limt limt])
ylabel('Amplitude')
xlabel('Time')
title('OFDM Time Signal (one symbol period in one carrier)')
figure(4)
colors = ['b','g','r','c','m','y'];
for k=1:min(length(colors),(carrier_symb_count-1))
plot(1:ifft_size, signal_tx(k+1,:))
```

```
plot(1:ifft_size, signal_tx(k+1,:), colors(k))
hold on
end
grid on
axis ([0 ifft_size -limt limt])
ylabel('Amplitude')
xlabel('Time')
title('Samples of OFDM Time Signals over one symbol period')
end
end_symb = size(signal_tx, 2); % end of a symbol period without guard
signal_tx = [signal_tx(:,(end_symb-guard_time+1):end_symb) signal_tx];
signal_tx = signal_tx'; % MATLAB's reshape goes along with columns
signal_tx = reshape(signal_tx, 1, size(signal_tx,1)*size(signal_tx,2));
```

```
% ************* FUNCTION: ofdm_demod() ************* %
function [decoded_symb, decoded_phase] = ofdm_demod...
(symb_rx, ifft_size, carriers, conj_carriers, ...
guard_time, symb_size, word_size, last, unpad, fig)
symb_period = ifft_size + guard_time;
symb_rx_matrix = reshape(symb_rx(1:...
(symb_period*floor(length(symb_rx)/symb_period))), ...
symb_period, floor(length(symb_rx)/symb_period));
symb_rx_matrix = symb_rx_matrix(guard_time+1:symb_period,:);
rx_spectrum_matrix = fft(symb_rx_matrix)';
if fig==1
limt = 1.1*max(abs(reshape(rx_spectrum_matrix',1,...
size(rx_spectrum_matrix,1)*size(rx_spectrum_matrix,2))));
figure(5)
stem(0:ifft_size-1, abs(rx_spectrum_matrix(ceil...
(size(rx_spectrum_matrix,1)/2),1:ifft_size)),'b*-')
grid on
axis ([0 ifft_size -limt limt])
ylabel('Magnitude')
xlabel('FFT Bin')
title('Magnitude of Received OFDM Spectrum')
figure(6)
plot(0:ifft_size-1, (180/pi)*angle(rx_spectrum_matrix(ceil...
(size(rx_spectrum_matrix,1)/2),1:ifft_size)'), 'go')
hold on
stem(carriers-1, (180/pi)*angle(rx_spectrum_matrix(2,carriers)'),'b*-')
stem(conj_carriers-1, (180/pi)*angle(rx_spectrum_matrix(ceil...
(size(rx_spectrum_matrix,1)/2),conj_carriers)),'b*-')
axis ([0 ifft_size -200 +200])
```

```
grid on
ylabel('Phase (degrees)')
xlabel('FFT Bin')
title('Phase of Receive OFDM Spectrum')
end
rx_spectrum_matrix = rx_spectrum_matrix(:,carriers);
rx_phase = angle(rx_spectrum_matrix)*(180/pi);
rx_phase = rem((rx_phase+360), 360);
if fig==1
figure(7)
rx_mag = abs(rx_spectrum_matrix(ceil(size(rx_spectrum_matrix,1)/2),:));
polar(rx_phase(ceil(size(rx_spectrum_matrix,1)/2),:)*(pi/180), ...
rx_mag, 'bd')
title('Received Phases')
end
decoded_phase = diff(rx_phase);
decoded_phase = rem((decoded_phase+360), 360);
decoded_phase = reshape(decoded_phase', ...
1, size(decoded_phase,1)*size(decoded_phase,2));
base_phase = 360/(2^symb_size);
decoded_symb = ...
floor(rem((decoded_phase/base_phase+0.5),(2^symb_size)));
decoded_phase = rem(decoded_phase/base_phase+0.5, ...
(2^symb_size))*base_phase - 0.5*base_phase;
if last==1
decoded_symb = decoded_symb(1:(length(decoded_symb)-unpad));
decoded_phase = decoded_phase(1:(length(decoded_phase)-unpad));
end
```