AMIR TIMILEHIN AMODU

A COMPARATIVE ANALYSIS OF ADVANCED DIGITAL MODULATION TECHNIQUES

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

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Approval

We certify that we have read the thesis submitted by AMIR TIMILEHIN AMODU titled **“A COMPARATIVE ANALYSIS OF ADVANCED DIGITAL MODULATION TECHNIQUES**” and that in our combined opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Educational Sciences.

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Declaration

I hereby declare that all information, documents, analysis and results in this thesis have been collected and presented according to the academic rules and ethical guidelines of Institute of Graduate Studies, Near East University. I also declare that as required by these rules and conduct, I have fully cited and referenced information and data that are not original to this study.

Amir Timilehin Amodu

15/12/2021

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Amir Timilehin Amodu

Abstract

A Comparative Analysis of Advanced Digital Modulation Techniques

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Imagine a world without interaction and any form or means of communication, a place where you can’t express yourself, thoughts, intentions, opinion, etc., to anyone at all whether close or far, whether family, friends or acquaintances, imagine such a world! The need or importance of Communication Systems in this present world of ours cannot be over-emphasized as it has finally become an integral and crucial part of the human existence. Communication system has been improved and developed overtime in other to suit and match the unending and seamless demand of this current era for the transmission of information and data via different mediums of communication and at the shortest possible time-frame or period of time across the web and internet throughout the entire globe with little or no congestion.

In this research or thesis work, a thorough comparative study on communication system was carried out with more emphasis placed on one aspect called Digital Modulation Technique. The types of this modulation techniques (e.g., ASK, PSK, FSK, QAM, OFDM etc.) and their individual classification or modulation schemes (e.g., BPSK, BASK, QPSK, BFSK, MSK, GMSK, etc.) advantages and disadvantages, error performance and probability, the required bandwidth and bandwidth efficiency, etc.

Although, modulation techniques are chosen based on the task at hand however, the analysis carried out in this work, shows OFDM is superior to majority of the digital modulation techniques for various task, especially in the mobile communication sector.

Key Words: Communication systems, analog modulation, digital modulation, digital communication systems, digital modulation techniques.

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LIST OF ABBREVATIONS

AC:	Analogue Communication
ACSs:	Analogue Communication Systems
ANN:	Artificial Neural Network
ANSI:	American National Standards Institute
ASDL:	Asymmetric Digital Subscriber Line
AM:	Analog Modulation
APK:	Amplitude Phase Keying
ASK:	Amplitude Shift Keying
BASK:	Binary Amplitude Shift-Keying
BER:	Bit Error Rate
BFSK:	Binary Frequency Shift-Keying
BPM:	Bandpass modulation
BPSK:	Binary Phase Shift Keying
BRAN:	Broadband Radio Access Network
BW:	Bandwidth
CP:	Cyclic Prefix
CT:	Communication Technique
DAB:	Digital Audio Broadcasting
DBBMT:	Digital Baseband Modulation Technique

DC:	Digital Communication
DCSs:	Digital Communication Systems
DCT:	Digital Communication Techniques
DM:	Digital Modulation
DMT:	Digital Modulation Techniques
DPBMT:	Digital Passband Modulation Technique
DPSK:	Differential Phase Shift-keying
DVB – T:	Digital Video Broadcasting – Terrestrial
DVB – H:	Digital Video Broadcasting – Handheld
ECC:	Error Correction coding
ETSI:	European Telecommunications Standards Institute
FFT:	Fast Fourier Transform
FSK:	Frequency Shift Keying
GMSK:	Gaussian Minimum Shift-Keying
ICN:	Inter-Carrier Interference
IFFT:	Inverse Fast Fourier Transform
ISI:	Inter Symbol Interference
ITU:	International Telecommunication Union
LMT:	Linear Modulation Technique
MAN:	Metropolitan Area Network

MSK:	Minimum Shift Keying
MC-MS:	Multi Carrier Modulation Schemes
MT:	Modulation Techniques
NLMT:	Non-Linear Modulation Technique
NN:	Neural Network
OFDM:	Orthogonal Frequency Division Multiplexing
OM:	Orthogonal Modulation
PAPR:	Peak to Average Power Ratio
PM:	Pulse Modulation
PSK:	Phase Shift Keying
QAM:	Quadrature Amplitude Modulation
QPSK:	Quadrature Phase Shift-Keying
RB:	Required Bandwidth
SCS:	Single Carrier System
SNR:	Signal-to-Noise Ratio
SSM:	Spread Spectrum Method
VDSL:	Very High-Bit-Rate Digital Subscriber Line
WBDCSs:	Wideband Digital Communication Systems
WLAN:	Wireless Local Area Network
WMAN:	Wireless Metropolitan Area Network

WPAN: Wireless Personal Area Network.

CHAPTER I
Introduction

1.1 Overview

This chapter consists of introduction, aim & objectives of the thesis, the motivation & contribution of the thesis as well as the organization of the thesis. The introduction section contains, a brief and concise review the subject matter. DCSs was explained and a brief light was beamed on the OFDM system and some of its advantages.

1.2 Introduction

Living in the age where communication is virtually and practically part of the thing's humans cannot live without on a daily basis, it then can be said to be the life wire and backbone of interaction. Hence, the need and its degree of importance cannot be overemphasized. Communication can be in various forms which could be audios, videos or any medium wherewith information can be disseminated from one person to another or one place to another at any moment of time. Any medium of information that takes the form of an electrical signal can be referred to as data. The amount of data transferred via the internet across the World Wide Web either wirelessly or wired, in every single tick and moment of the clock on a daily basis is undoubtedly vast and gigantic. DCSs would be reviewed in the next segment of this section.

1.3 Digital Communication Systems

DCSs is a system that is used to convey information from one place, point or person to the other by transmitting a limited set of discrete symbols. Since its existence for more than five decades, it has been a subject of both intense and numerous researches by various sets and category of persons. It is quite obvious that both the development and use of DCSs has increased extensively beyond leaps and bounds for the past three decades. The fact that it is becoming continually and exponentially attractive owing to the unrelenting surge in demand for data communication cannot be overemphasized coupled with its high flexibility, ability for digital signals to be regenerated with ease as well as the available data processing options compared to its counterpart, the analogue transmission (Sklar, 2001; Peyton & Peebles, 1987). A simple block diagram of a classic DCS is illustrated in Fig 1.1 below.

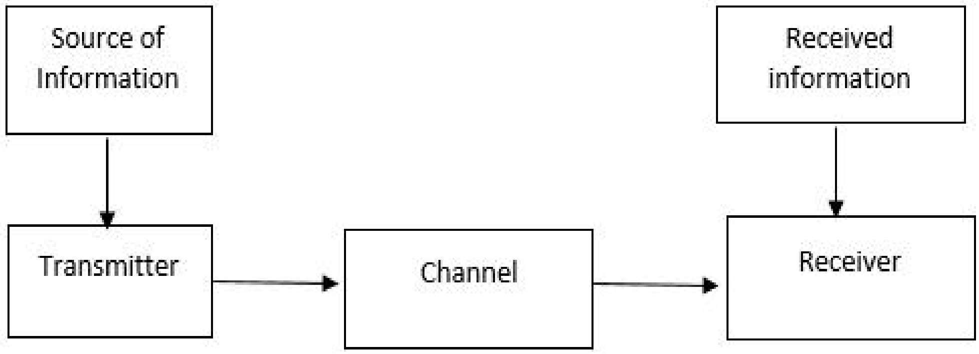


Figure 1.1: Standard block diagram of DCSs.

The shape of a waveform can be greatly affected by two basic mechanisms that degrades the shape of the pulse as a function of line length whenever a digital signal (or ideal binary digital pulse) is propagated along a digital transmission line as illustrated in Fig 1.2. (Sklar, 2001)

(i) The ideal pulse is prone to distortion because all circuits and transmission lines contain some non-ideal frequency transfer function.
(ii) The pulse wave is further distorted by the unwanted electrical noise and other possible interferences.

As shown in Figure 1.2, prior to the degradation of the transmitted signal into an ambiguous state, while it was yet identifiable, a digital amplifier was used to amplify the signal in order to ensure a possible recovery or regeneration of the original signal's ideal shape. The circuits used to perform or carry out this definite operation at regular or certain intervals, along a digital transmission system are referred to as regenerative repeaters (Sklar, 2001).

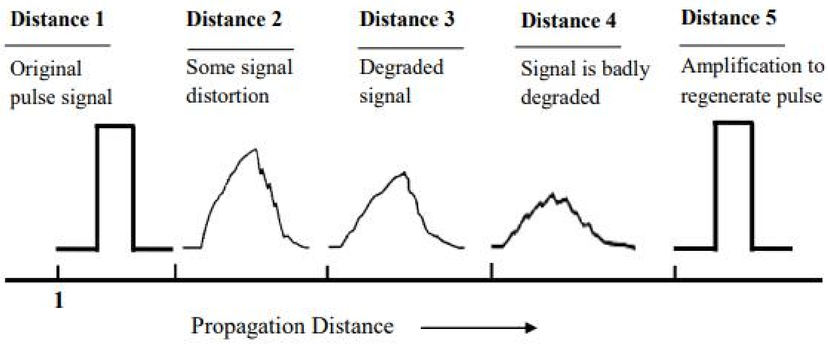


Figure 1.2: Example of signal degradation and regeneration (Sklar, 2001).

One of the primary benefits of DCSs over its counterpart, the analogue communication systems (ACSs) is that it is less prone to interference and distortion. DCSs are circuits which are binary digital based that operate in dual states (i.e., either state 1 or 0) at every point in time and hence, it would take a very large level of disturbance for the circuit operating point to be successfully changed from one state to another. This type of circuits that operates with just two states makes it very easy for any signal to be regenerated thereby preventing the accumulation of noise and other forms of disturbances during transmission. In addition, using digital techniques makes it extremely possible to have low error rates which produces high reliable signals via error correction and detection (Sklar, 2001). In addition to the aforementioned benefits of DCSs, there are yet some important advantages which include:

- The available digital circuits in DCs can be relied on and also manufactured at a very cheap and low cost.
- Digital hardware is very flexible when it comes to implementation
- Digital Communication Techniques (DCTs) are usually protected or less prone to either jamming & interference, or enjoy encryption & privacy because they naturally offer themselves to signal processing functions.
- A large amount of data communication operations can be affected either from one computer to the other computer, or from digital/terminal instruments to computer. Naturally, these types of digital terminations are best served by DC links.

In order for the task of synchronization to be feasible at various levels, a significant share of resources needs to be allocated by DCSs. Despite all the advantages of DCSs, one of the main disadvantages of signal degradation is that whenever the Signal-to-noise ratio (SNR) value drops or dips below a specific threshold, there can be an instantaneous change in the quality of service (QoS) from excellent to terrible. (Sklar, 2001). The transmitter and receiver sub-systems in a classic DCS is depicted in Figure 1.3 below.

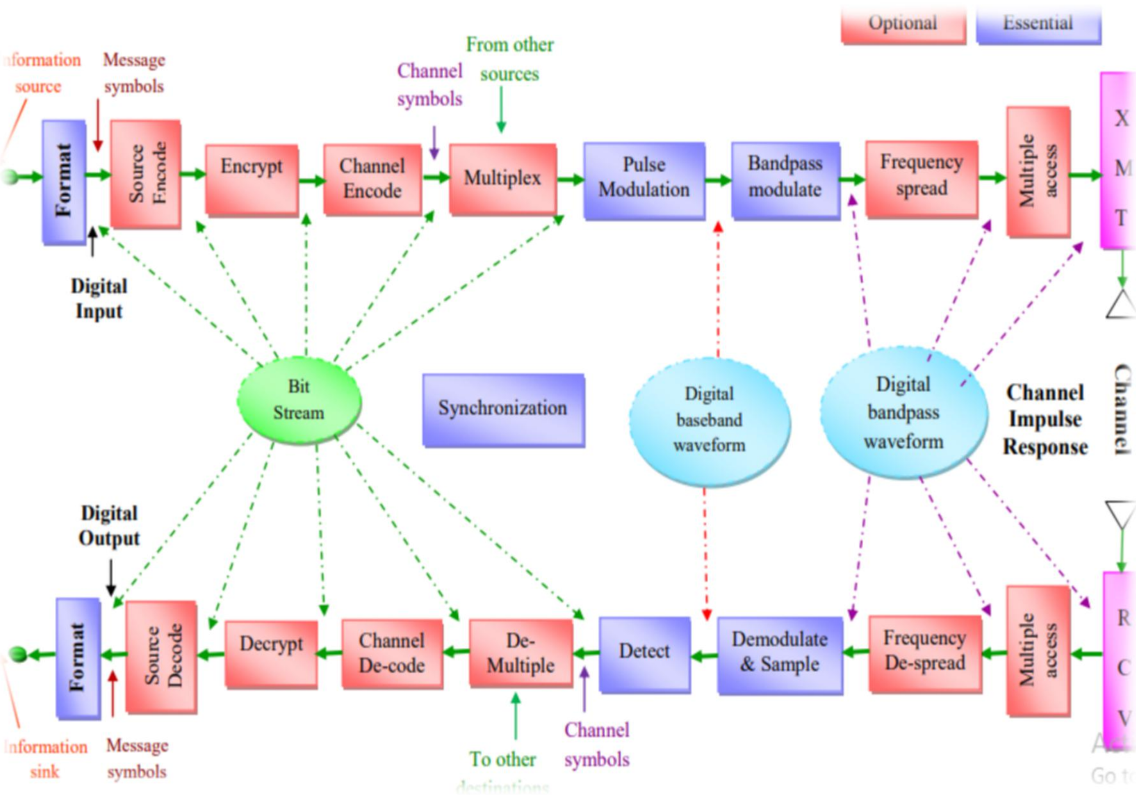


Figure 1.3: Transmitter and receiver sub-systems in DCS (Sklar, 2001).

1.4 Orthogonal frequency division multiplexing (OFDM) Communication systems

Despite the numerous techniques used previously in designing DCS, the digital transmission technique called Orthogonal Frequency Division Multiplexing (OFDM) is considered amongst others as one of the top, with efficient bandwidth and one of the most beneficial modulation techniques. OFDM systems have gained a vast recognition across diverse industries for numerous applications especially in the wireless communications industry as a transmission technique with efficient and reliable bandwidth. It is a multicarrier transmission technique and has been a center of attraction as the number of individuals fascinated and intrigued by the modulation technique in the signal processing and communications sector are growing exponentially (Engels, 2002).

The main idea or primary aim of this particular modulation technique system is to ensure that orthogonality between bands is preserved via Fast Fourier Transform (FFT) as well as its inverse (IFFT) after dividing the entire bandwidth of the transmitted signal into smaller sub-bands. Mitigating the problems of Inter Symbol Interference (ISI) that are associated with the wide-band transmissions existing in selected channels of different frequencies is the major motivation of the band division (Koivo & Elmusrati, 2009). The associated or related problems and concepts will be further reviewed later on in other chapters, mainly chapter two and three.

OFDM is occasionally viewed to be a frequency- domain approach to communications of which it plays a huge role when dealing with communication channels operating with higher data rate and by nature are frequency-selective. In addition, the system benefits and profits from a high spectral efficiency, strong multipath tolerance, simple implementation, channel fading and very robust and stout against narrow-band co-channel interference etc. Furthermore, another main advantage of employing OFDM technique is the fact that the effects of delay can be countered because the transmitted signal is assisted by the cyclic prefix (CP) it is affixed or attached with. Despite all the advantages of OFDM, there are yet a number of disadvantages faced and exhibited by this particular technique some of which are leakage in bandwidth due to guard time, its proneness to phase and frequency offset errors and large Peak to Average Power Ratio (PAPR).

In the verge of harnessing the benefit mentioned above, OFDM has been employed and extensively/widely developed into well-admired schemes for WBDCSs including Asymmetric Digital Subscriber Line (ASDL), International Telecommunication Union (ITU-T), Metropolitan Area Network (MAN) and Wireless Local Area Network (WLAN) (Eklund et al., 2002; Crow et al., 1997; Eklund et al., 2002; Maxwell, 1996). OFDM system has grown to be an effective and real physical layer solution in their immediate environs, seeing the exponential increase in the demand by majority to carry out operations with higher data rates (Narasimhamurthy et al., 2010).

1.5 Aims & Objectives

The aim of this study is to carry out a comprehensively detailed comparison on the types of digital modulation techniques with their various individual classifications or modulation schemes. A thorough comparison will be made based on some important features such as their capacity, advantages, disadvantages, bandwidth efficiency, spectral efficiency, error performance and probability, power required and so on.

1.6 Motivation & Contribution

Although numerous researches have been carried out by various individuals on the use of digital modulation techniques (such as FSK, PSK, ASK, QAM, OFDM, etc.) in the wireless communication industry. Although, when compared to other previous forms of communication technique such as the Analog Modulation Techniques (such as AM, FM, PM, etc.), there are obvious improvements. Nonetheless, these sets of digital modulation techniques still have unsolved weaknesses and shortcomings of its own. Hence, various proposed methods having been put forward by different researches with the aim of solving or strengthening their individual weaknesses such as: loss and reduction in the spectral efficiency, high sensitivity to Doppler swings or shift and high PAPR, etc. In the subsequent chapters of this work, various existing digital modulation techniques, would be comprehensively reviewed and analysed based on their performance analysis and detection (i.e. bit-error rate, SNR, bandwidth, etc.,), advantages and disadvantages and so on.

1.7 Thesis Organization

In this current chapter an attempt and efforts to provide a brief introduction to DCSs has been made with the highlight on OFDM CSs and investigating the request for such a good technology. With some of its advantages briefly explained, which seems to be part of the reasons why it is found interesting by and among many in diverse sectors and industries. This was followed up by the aims & objectives of the research work or study coupled with the motivation & contribution of the project afterwards.

Chapter 2 consists of the literature review which is aimed at providing a general background overview that has been researched in recent years on the topic matter in other to establish an abstract or theoretical framework needed to

In chapter 3, all forms of modulation technique (such as AM, DM, PM and SSM.) were thoroughly explained although, the study focused more on the two best, major or commonly used types of modulation technique which is the AM and DM. The modulation schemes or techniques under the various types of DM were comprehensively researched and explained in details.

In chapter 4, a vast comparison on various forms and schemes or components of DMT was made with respect to their various characteristics and features. Their merits, demerits, error probability and performance, bandwidth efficiency, required bandwidth, power required and so on were comprehensively explained and reviewed in a tabular form.

Finally, the last section which is situated in chapter 5 comprises of the conclusion and possible research direction for future works in the gaps relating to the subject matter.

CHAPTER II

Modulation Techniques

2.1 Overview

In this particular section, various categories of modulation techniques (which are AM, DM, PM and SSM) would be reviewed including the classifications under each individual category with more emphasis on the major modulation techniques namely: AM and DM. The Table below is a summary of the available types of modulation techniques coupled with their individual classifications.

Table 2.1: A tabular representation of types of MT and their individual classifications.

	Modulation Techniques (MT)	Types	Notation
1	Analogue MT	(i) Amplitude Modulation	AM
		(ii) Frequency Modulation	FM
		(iii) Phase Modulation	PM
2	Digital MT	a. Single-carrier Modulation	
		(i) Amplitude Shift-Keying	ASK
		(ii) Phase Shift-Keying	PSK
		(iii) Frequency Shift-Keying	FSK
		(iv) Quadrature Amplitude Modulation	QAM
		b. Multi-carrier Modulation	
		(i) Orthogonal Frequency Division Multiplexing	OFDM
		(ii) Generalized Frequency Division Multiplexing	GFDM
		(iii)Code Division Multiple Access	CDMA

		(iv) Filter Bank Multi-Carrier	FBMC
3	Pulse MT	(i) Pulse Amplitude Modulation	PAM
		(ii) Pulse Position Modulation	PPM
		(iii) Pulse Width Modulation	PWM
		(iv) Pulse Number Modulation	PNM
		(v) Pulse Density Modulation	PDM
4	Spread Spectrum MT	(i)Frequency Hopping Spread Spectrum	FHSS
		(ii) Direct Sequence Spread Spectrum	DHSS
		(iii) Time Hoping Spread Spectrum	THSS
		(iv) Chirp Spread Spectrum	CSS

2.2 Analog Modulation (AM) Technique

AM is simply the process whereby an analog base-band (low frequency) signal (i.e., a TV or audio signal) is transferred over a signal with higher frequency such as a RF band. AM can be basically divided into three types namely: the AM, the FM and PM.

2.2.1 Amplitude Modulation (AM)

This type of analog modulation technique was the earliest form of modulation used for broadcasting and radio transmissions including applications that uses two-way radio communications. It is mainly used for short, medium and long wave broadcasting coupled with some point-to-points communication in the aeronautical sector. In AM, the carrier amplitude is simply modulated and the detector needed at the receiver's end could simply be a diode-based circuit which makes demodulation less complex and executed at a reduced cost. So many years ago, AM was seen as a key requirement for the widespread of radio technology when integrated circuits (ICs) were unavailable. Figure 3.1 below is a simple diagrammatic representation of AM.

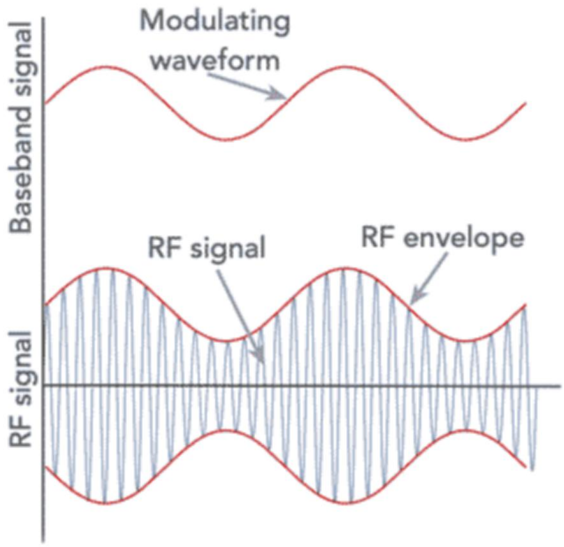


Figure 2.1: AM wave Diagram.

Though AM has numerous advantages and can also be used for various applications but its current degree of usage cannot be compared to that of decades ago because of the emergence of new and diverse other modulation techniques. Some of the area where AM can be applied includes:

(i) Air-band radio: AM is still being used for numerous airborne applications by Very high frequency (VHF) transmissions. AM is used for two-way radio links for ground staff as well as for ground to air radio communication.

(ii) Broadcasting: AM is still vastly used in broadcasting, irrespective of the wave band, could be long, medium or short. AM is simple and easy to demodulate. The radio receiver that has the capacity to demodulate AM are simple and cheap to manufacture. Nonetheless, individuals are trooping to high- and better-quality forms of transmissions such as digital transmissions or FM.

(iii) Single Side-Band (SSB): AM in form of SSB is still currently used in high-frequency radio links. It uses a lower BW and provision for the effective use of the transmitted power is certain. It can be used for numerous high –frequency links that are point-to-point.

(iv) Quadrature Amplitude Modulation (QAM): AM is vastly used for data transmission in practically all things, from wireless links with short range such as Wi-Fi to mobile/cellular telecommunications and beyond. It is formed when two carriers are 90° out of phase.

QAM can be represented by the carrier signal equation below:

$$C(t) = C\sin(\omega_c + \varphi) \tag{2.1}$$

Where:

C: Carrier amplitude

φ: Phase angle of the signal with respect to the reference time

ω_c: Carrier frequency (in Hz) is $\omega/2\pi$

2.2.2 Frequency Modulation (FM)

This is another type of analog modulation where information is encoded in a carrier signal or wave by varying or fluctuating the instantaneous frequency of the signal or wave. This MT is often used in very high frequency applications and above. It is used in radio broadcasting, computing, signal processing and telecommunications. In other for a frequency modulated signal to be generated, the radio carrier's frequency must be changed with respect to the amplitude of audio signal that is incoming. FM can be generated from a variety of diverse methods such as phase locked loop, varactor diode oscillator, etc. The figure 3.2 below is a simple diagrammatic representation of a FM wave.

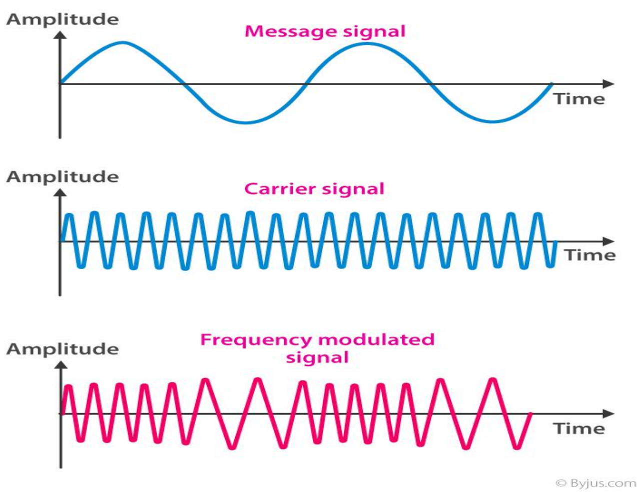


Figure 2.2: FM wave diagram.

FM can be represented by the carrier signal equation below:

$$X_c(t) = A_c \cos (2\pi f_c t) \qquad (2.2)$$

Where:

f_c : Frequency of the base-band signal or carrier wave

A_c: Amplitude of the carrier wave.

2.2.3 Phase Modulation (PM)

This is a type of analog modulation used in the conditioning of communication signals for transmission. The information or message signal is encoded as variations in the carrier's wave instantaneous phase. PM is among the two principle or standard forms of angle modulation coupled with FM. The carrier's signal phase is modulated in a manner where it follows the dynamic and fluctuating amplitude or signal level of the transmitted information or message signal. Both the frequency and the peak amplitude of the carrier signal or wave remains constant but whenever the amplitude of the transmitted message signal changes, the carrier's phases changes likewise simultaneously and in synchronism. PM which is vastly used in the transmission of radio waves is also fundamental in numerous coding schemes that are digital transmitted in nature and covers a massive range of technologies such as satellite television, GSM and Wi-Fi. PM can also be used to generate waveforms and signals in digital synthesizers. The figure 2.3 below is a simple diagrammatic representation of a PM wave.

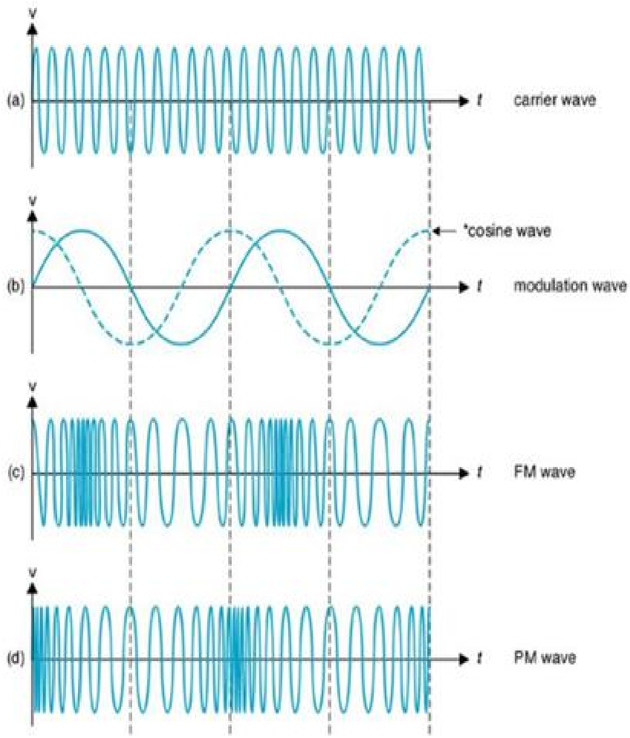


Figure 2.3: Graph (b) is a PM wave.

PM can be represented by the carrier signal equation below:

$$C(t) = A_c \sin(\omega_c t + \phi_c) \tag{2.3}$$

Where:

ω_c: Frequency of the base-band signal or carrier wave

A_c: Amplitude of the carrier wave

ϕ_c: The carrier signal's or wave phase

2.2.4 A Comparison of the three types of Analog Modulation (AM) Technique

These three classifications of AM technique consist of numerous classifications, sub-classification or derivatives as itemized in table- 2.2 below. Amplitude modulation (AM) has quite a lot of derivatives which are distinctly visible from the comparative information in table 2.3 that the Single Side Band Suppressed Carrier (SSB-SC) when compared with the Double Side Band Suppressed Carrier (DSB SC), Double Side Band Full Carrier (DSB FC) and Single Side Band Full Carrier (SSB FC), has the smallest bandwidth and requires smaller power. Nonetheless, for this type of signal to be detected, a sharp cutoff low pass filter (LPF) is required and from a practical point of view, it is not viable. A gradual cutoff LPF can be achieved if the SSB-SC is replaced with the Vestigial Side Band (VSB) technique. However, the VSB technique requires more power and bandwidth compared to the SSB-SC technique but lesser than the DSB-SC and DSB-FC techniques. Hence, SSB-SC is ideally proven to be the best when compared to all other types of AM techniques or schemes but in real time or practically, VSB is proven to be better than all the known and existing AM techniques.

Non-linear amplifiers are used in amplitude modulated signals. However, these types of amplifiers generate spectral components that are spuriously out-of-band and are very difficult to be filtered out. Frequency Modulation (FM) proves to be better when contrasted with AM and PM. Narrow Band Frequency Modulation (NBFM) which is a derivative or component of FM is often employed to override or overcome the problems mentioned above in the CS. Table-2.3 consists of the individual representation of the MTs, the required bandwidth (BW) and also the power requirement features of the available AM techniques. One of the main and major edge that FM has over AM is the capability for the effects of noise to be suppressed at the expense of BW. The major drawback or limitation that makes it difficult for the AM systems to be chosen for communicating over long channels compared to other forms of modulation techniques is the fact that once any form of noise is detected at any place along or across the channel, it must be carried out until the end. This is because all various forms of AM system (AM, AM and PM) are extraordinarily sensitive to existing noise at the receiving (i.e., the receiver) end compared to the digital modulation (DM) technique where the modulated and transmitted signal is massively less sensitive to the noise at the receiver's end. Table 2.2 below shows the classifications and notation/representation of the various types of AM technique while table 2.3 contains the performance analysis and gives more information about the BW, power saving and requirements of the classified signals under the types of AM techniques.

Table 2.2: Classifications of amplitude modulation (AM) techniques.

Serial No.	Modulation Techniques (MT)	Notations	Types
1	Amplitude Modulation Single-Side Band Suppressed Carrier	AM SSB-SC	Linear
2	Amplitude Modulation Double-Side Band Suppressed Carrier	AM DSB-SC	Linear
3	Amplitude Modulation Single-Side Band with Full Carrier	AM SSB-FC	Linear
4	Amplitude Modulation Double-Side Band with Full Carrier	AM DSB-FC	Linear
5	Amplitude Modulation Vestigial- Side Band	AM VSB	Linear

Table 2.3: Performance analysis of AM techniques.

Serial No.	Type of AM	Bandwidth (BW)	Power required	Power saving (%)
1	AM-SSB-SC	ω_m	1/4 P_c	~83.3
2	AM-DSB-SC	$2\omega_m$	5/4 P_c	~66.7
3	AM-SSB-FC	ω_m	1/2 P_c	~16.7
4	AM-DSB-FC	$2\omega_m$	3/2 P_c	Standard
5	AM-VSB	$> \omega_m$	Greater than SSB-SC	Greater than SSB-SC

Where:

ω_m: is the modulating frequency

M_F: is FM modulation index

M_P: is PM modulation index

P_c: is the carrier power

2.3 Digital Modulation (DM) Technique

The fundamental of transmitting data wirelessly is simply modulation, which is a process whereby data required for transmission are impressed on the radio carrier.

Digital modulation is a process whereby digital information signals are encoded into the phase, frequency or amplitude of the transmitted signal. The transmitted signal's bandwidth and its robustness to channel impairments are usually affected by the encoding process. Generally, modulation techniques are used to encode numerous bits into a symbol, the bandwidth of the transmitted signals are determined by the rate of the symbol transmitted. Since the symbol rate is what determines the signal bandwidth, the larger or more the number of bits per symbols the higher the data rate generated for the bandwidth of a given signal. However, the received SNR required for a given target of BER to be achieved is dependent on the number of bits per symbol. Hence, if the number of bits per symbol is larger, then the received SNR required to achieve the BER target would be greater.

Digital modulation techniques can either be nonlinear or linear. In linear modulation, the digital modulating signal can be said to vary linearly with phase and/or amplitude of the transmitted signal, whereas for nonlinear techniques the amplitude of the transmitted signal is constant. Linear modulation techniques, together with all forms or classification of quadrature-amplitude modulation (QAM) as well as phase-shift-keying (PSK), uses less bandwidth compared to nonlinear techniques, with various forms of minimum/frequency-shift-keying (MSK AND FSK) inclusive. Since linear techniques are used in encoding information into the phase and amplitude of linear modulation, this particular type of modulation is undoubtedly extremely susceptible to both phase and amplitude fluctuations triggered by multipath flat-fading. Inclusively, only linear amplifiers must be used for or during linear modulation, though these set of amplifiers are usually less efficient and more expensive than the ones used for nonlinear modulation. Thus, linear modulation bandwidth's efficiency is normally obtained at the cost or expense of power, higher bit error ratio (BERs) in fading and hardware cost. Linear modulation techniques are commonly used in numerous wireless local area network (WLAN) products, while nonlinear techniques are vastly used in numerous wide area wireless data systems and cellular.

Linear modulation techniques are usually detected either differentially or coherently. In coherent detection, the transmitted signal's phase reference must be obtained by the receiver. This is quite tough and challenging to do in an environment that is rapidly fading and the receiver's complexity is increased. In Differential detection, the phase reference of the previously detected symbols is used for the current symbol. Differential detection needs approximately twice the power consumed by coherent detection for the same bit error rate (BER) because the symbol detected is a noisy reference. Besides, the accuracy of differential detection would be low if the channel continually changes rapidly, since the phase of the channel is prone to changing greatly over just one symbol time. Channels that change rapidly with differential detection undoubtedly have undesired error floor, which means that the channel's BER has a lower bound (which is error floor) that is irreducible by increasing the signal-to-noise ratio (SNR) received. Increment in error floor is depending on the rate at which the channel variation (the channel Doppler) increases and the decrement is dependent on the increment in data rate (seeing the higher the data rate, the shorter the bit time, the channel phase will have lesser time to de-correlate between bits). For wireless data with high speed (beyond 1 Mbps), the users will have low floor error when the operating speed is lesser than 60mph, but the error floor turns out to be significant when the data rates are lower, which will prevent the use of differential detection.

Though a greater percentage of data transmitted wirelessly today have been more in digital form than analog, there are yet a number of challenges faced by the communication systems or both modulation technique because of the demand and constant requirement needed to effectively and efficiently carry out the activities daily. Spectral congestion, limitation in available spectrum, co-channel interference issues & several adjacent, data reception being corrupted by noise and so on are part of the challenges faced by the modulation techniques as opposed to one of the main goals of digital modulation which is squeezing as much data as possible into the slightest or minimum amount of spectrum available. That objective can be referred to as spectral efficiency which measures the swiftness of transmitting data in a designated bandwidth having its standard unit of measurement as Bits per seconds per hertz (b/s/Hz). The limitation faced by the modulation technique made it necessary for research that will facilitate new development such as (new encoding & decoding techniques, modulation & demodulation techniques, new transmission channels and so on) to be embraced and employed for the sole aim of improving the spectral efficiency and other essential features. Designing a communication system is based on quite a number of factors and the two most important to be taken into consideration are the type of signal and the fact that it is application oriented (i.e., used for specified purpose). The various types and classifications of DM (LMT/DPBMT and NLMT/DBBMT) will be comprehensively reviewed below especially the linear or passband modulation technique.

2.3.1 Linear Modulation Technique (LMT)/ Digital Passband Modulation Technique (DPBMT)

Bandpass modulation (BPM) is viewed to be among the most common types of DM. This particular DMT converts the information signal into sinusoidal waveform. BPM can either be AM or DM, in which a digital symbol is often used to denote a sinusoidal duration (*T*).

All sinusoidal signals consist of three main features namely: amplitude, frequency and phase which makes it possible for them to be distinguished from one another. BPM can be simply defined as a process where any change in frequency, amplitude or phase of the carrier signal or even a combination of all three features is in line or synchronizes with the data to be transmitted.

The equation 2.4 below is the general equation of the carrier signal

$$s(t) = A(t) cos\theta(\mathrm{t}) \qquad (2.4)$$

Where $\theta(\mathrm{t})$ is considered as a time varying angle and can be denoted or written as the Equation 2.5 below

$$\theta(\mathrm{t}) = \omega_o \mathrm{t} + \varphi(\mathrm{t}) \qquad (2.5)$$

When Equation 2.4 is substituted into Equation 2.5, Equation 3.6 is derived

$$s(t) = A(t)\cos\left[\omega_o \mathrm{t} + \varphi(\mathrm{t})\right] \qquad (2.6)$$

Where:

- A(t): Time varying amplitude
- ω_o: The radian frequency of the carrier signal
- $\varphi(t)$: The phase angles

For clarity purpose, the term ω [which is frequency in radians per seconds (rad/sec)] and f [In hertz (Hz)] are both a representation of frequency and are linked by the equation below:

$$\omega = 2\pi f$$

Some of the types of BPM/LMT were initially indicated or listed out in the digital modulation (DM) technique section would be properly explained in the follow up section below coupled with a tabular representation afterwards.

2.3.1.1 Amplitude Shift- Keying (ASK)

ASK is one of the main types of DBPMT, the general mathematical equation and its analytical expression is as follow (Peyton & Peebles, 1987):

$$S_i(t) = \sqrt{\frac{2E_i(t)}{T}} \cos(\omega_o t + \varphi) \qquad 0 \leq t \leq T \qquad i = 1, 2 \ldots M \qquad (2.7)$$

Where:

- $\sqrt{\frac{2E_i(t)}{T}}$ denotes the amplitude that will contain discrete values of M.
- T represents the duration of symbol time ($0 \leq t \leq T$)
- φ denotes the phase term and is an arbitrary/random constant.

2.3.1.2 Frequency Shift- Keying (FSK)

FSK is another main classification or type of DBMPT, the general mathematical equation and its analytical expression is as follow (Peyton & Peebles, 1987):

$$S_i(t) = \sqrt{\frac{2E}{T}} \cos(\omega_i t + \varphi) \qquad 0 \leq t \leq T \qquad i = 1 \ldots M \qquad (2.8)$$

Where:

- E represents the energy's symbol
- T represents the time duration of the symbol ($0 \le t \le T$)
- $\varphi_i(t)$denotes the phase term and is an arbitrary/random constant
- ω_i is the frequency with M discrete values

In FSK modulation, whenever any change occurs in the binary state of the carrier signal, then automatically the carrier signal's frequency changes alongside. In Table 2. (b), the waveform gently transited from a lower frequency (LF) into a high frequency (HF) and then to a very high frequency (VHF). The category or type of MT that act in such manner are usually classified as Continuous-Phase frequency Shift-Keying (CPFSK). It is essential to note the fact that in a general or classical M-FSK MT, such changes occur suddenly or swiftly because the phase is not expected to be continuous. The value of M in the example shown in Table 3. (b) is 3. This M-value, corresponds or tallies to the number of the available waveform types. Importantly, the values of M are selected or chosen to be non-zero power or multiples of 2 (e.g., 2, 4, 8, 16 etc.) (Peyton & Peebles, 1987).

The vector signal as depicted in Table 2.1 (), is a representation of the Cartesian co-ordinates. Symbolically, the sinusoidal signals of diverse frequencies are represented by the arrangement of the mutually vertical or perpendicular axis.

2.3.1.3 Phase Shift-Keying (PSK)

This is one of the main DBPMTs which was created eon of years ago about the early ages of the outer-space program. This technique is very efficient in terms of signal power and now widely used in numerous systems, industries and applications for various purposes such as commercial communication systems (e.g., wideband microwave radio relay systems, satellite links, etc.), military etc. The phase function is where the digital information is usually encoded, with both the amplitude and frequency remaining constant as the phase changes. The carrier signal's phase needs to be varied to represent/denote digital data (i.e., binary numbers 0 or 1). The phases differ from one another by 180° degrees (e.g., if **phase 0°** is used to represent **bit 0**, before a bit of **value 1** can be sent, the **phase angle** needs to be changed from **0° to 180°**). Compared to ASK AND FSK, PSK is simple to implement because there is no need to repeatedly tune the phase or filter signals of different frequencies unlike FSK and it is not susceptible or prone to noise degradation unlike ASK.

The standard mathematical representation of PSK is (Peyton & Peebles, 1987):

$$S_i(t) = \sqrt{\frac{2E}{T}} \cos\left[\omega_i t + \varphi_i(t)\right]$$

$0 \leq t \leq T \quad i = 1 \ldots M \qquad (2.9)$

Where:

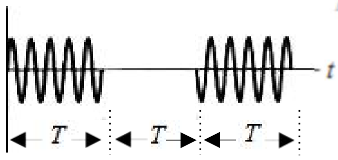
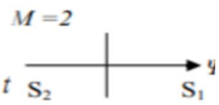
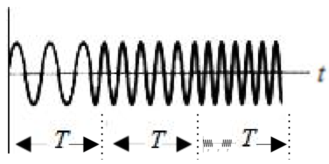
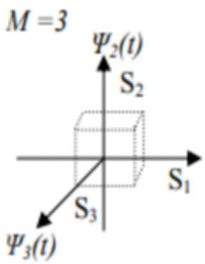
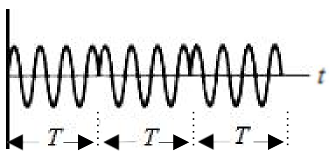
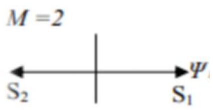
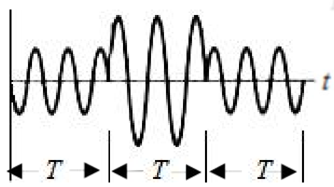
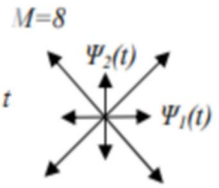
- E represents the symbol energy
- T represents the duration of symbol time ($0 \leq t \leq T$)
- The $\varphi_i(t)$ denotes the phase term and it is expressed as:

$$\varphi i(t) = \frac{2\pi i}{M} \qquad i = 1 \ldots M$$

Binary phase-shift keying (BPSK) is the most common example amongst other types of PSK modulation technique and its M is 2. Typically, in BPSK modulation techniques, as depicted in Table 2.1 (a), the phase of S_i (t) waveform can only be shifted to one amongst the available two states which is either S_1 or S_2 with each representing 0° or 180° respectively following any change in the symbol transitions.

The vector representation of BPSK illustrated in table 2.1 (a) corresponds to a dual opposing vector of 180°. Such sets of signals which that take this type of pattern or form are known as antipodal signals (Peyton & Peebles, 1987).

Table 2.4: Basic information on some DMTs extensions

Sr No	MT	General Mathematical Equation	Sinusoidal Waveform	Vector Representation
i	ASK	$S_i(t) = \sqrt{\frac{2Ei(t)}{T}}\cos(\omega_o t + \varphi)$ $0 \le t \le T \quad i = 1, 2 \ldots M$ (2.4)		
ii	FSK	$S_i(t) = \sqrt{\frac{2E}{T}}\cos(\omega_i t + \varphi)$ $0 \le t \le T \quad i = 1 \ldots M$ (2.5)		
iii	PSK	$S_i(t) = \sqrt{\frac{2E}{T}}\cos[\omega_i t + \varphi_i(t)]$ $0 \le t \le T \quad i = 1 \ldots M$ (2.6)		
iv	PSK/ ASK (APK)	$S_i(t) = \sqrt{\frac{2Ei(t)}{T}}\cos[\omega_o t + \varphi_i(t)]$ $0 \le t \le T \quad i = 1, 2 \ldots M$ (2.7)		

The immediate section will contain a brief review comprising of a few amongst many types or extensions of PSK modulation technique such as Binary Phase-Shift Keying (BPSK), Differential Phase-Shift Keying (DPSK), Quadrature Phase-Shift Keying (QPSK),

2.3.2 Quadrature Amplitude Modulation (QAM)

Asides the 3 basic and major types of DMTs initially explained, QAM is one of the most popular and important modulation techniques that was created by the combination of the three main and basic MTs. QAM is a hybrid system formed by combining both PSK and ASK MT, of which the phase and amplitude are changed simultaneously. QAM MT are often used in numerous radio communications, broadcast or data delivering applications (Zimmermann & Kirsch, 1967). Table 3.1 contains the analytical, mathematical, vector and waveform representation of the QAM MT.

QAM modulation can be implemented using a method called the rectangular constellations. In this implementation method, the rectangular constellation is divided or distributed into Pulse Amplitude Modulated (PAM) components that are independent, namely for the In-phase and also the Quadrature part (I-Q). Figure 3.1 below illustrates an example of the rectangular constellations for QPSK, 16-QAM and 64-QAM of which the constellations are clearly not normalized. In order for the constellations to be normalized to an average power of 1, then there will be a need to multiply them by the normalization factor that are listed in Table 2.5. The table comprises of BPSK (2PSK) modulation which uses just two constellation points out of the available four QPSK (4QPSK)

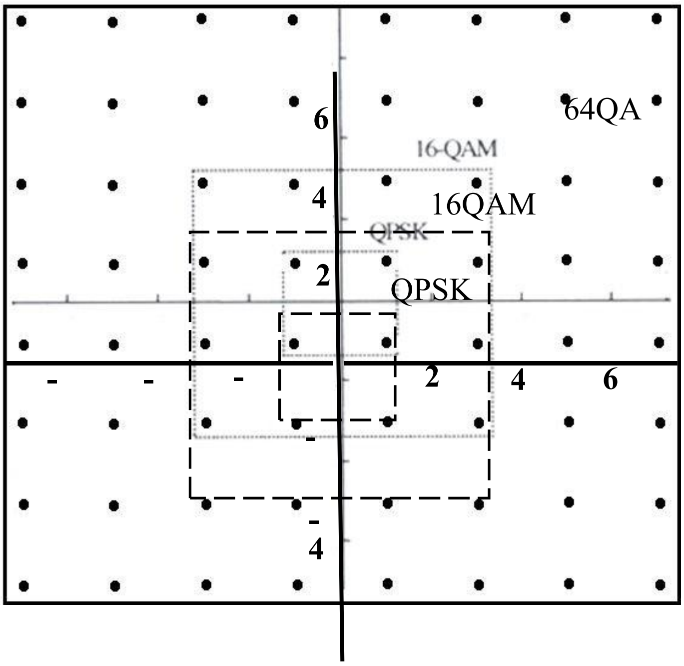


Figure 2.4: Constellation points of QPSK, 16-QAM and also 64-QAM.

Table 2.5: DMTs corresponding symbol rate and loses.

Type of DMT	Maximum E_b/No loss in dB comparative to BPSK	Symbol Rate
QPSK	0	$\frac{1}{2}$
BPSK	0	1
16-QAM	3.98	$\frac{1}{4}$
64-QAM	8.45	$\frac{1}{6}$

Table 2.5 above presents the values required for a certain BER to be achieved for a QAM link (such as the maximum E_b/No loss in decibels comparative to BPSK) that is un-coded. The loss values of E_b/No are undoubtedly accurate for the values of BER that is below 10^{-2} as shown in figure 2.5 below.

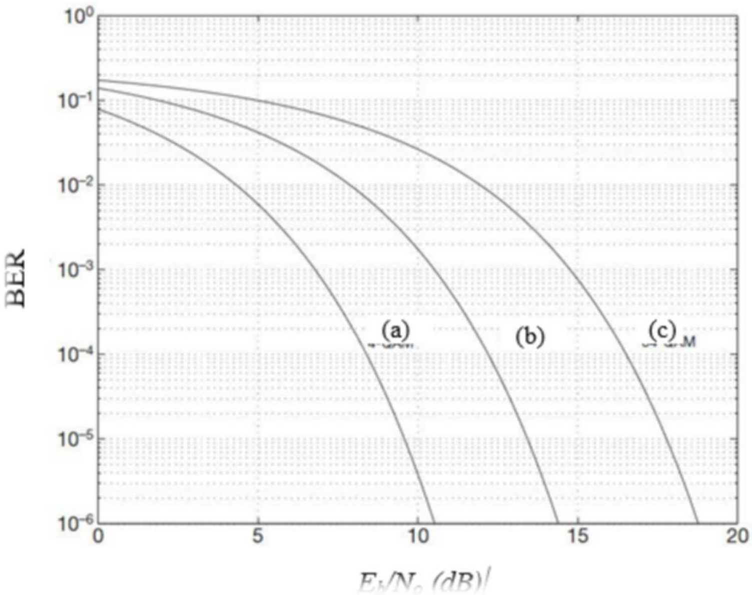


Figure 2.5: BER versus E_b/No for (a) QPSK/BPSK, (b) 16-QAM and (c) 64-QAM..

From Figure 2.5 above, the E_b/No loss values in decibels for QPSK/BPSK, 16-QAM and 64-QAM are 11, 15 and 19.5 respectively. There is a difference of 4dB between 16-QAM and QPSK/BPSK as well as 4.5 dB difference between 64-QAM and 16-QAM. MT of higher order (such as 64-QAM) has a constellation size that creates a penalty for E_b/No whenever the number of bits per symbol is increased of which is convergent from 1dB to 3dB from Figure 2.5 above.

2.4 Extensions of Different Types of Digital Modulation Techniques

The various available extensions (such as BPSK, BASK, BFSK, MSK, GMSK, QPSK and so on) under the types of DMT will be briefly explained in details.

2.4.1 Binary Phase-Shift Keying (BPSK)

The resultant modulation technique or scheme derived by altering the phase of any carrier wave with reference to the modulating signal is called PSK. This DMT is viewed as one of the simplest forms of PM and also referred to as binary because the phase of the transmitted signal can only be represented by two phase states. It is often used in diverse applications such as transferring data at a very high speed, compared to Binary Amplitude Shift-Keying (BASK) MT, BPSK provides a greater power advantage of about 3dB. It is robust as well as simple and easy to implement. However, it often referred to as a nonlinear modulation technique or scheme and it is proven to be inefficient in the usage of the allocated bandwidth. The error rate of BPSK is relatively small, when compared to other types of modulation techniques (MTs). Also, it provides lots of derivatives.

2.4.2 Differential Phase-Shift Keying (DPSK)

For a modulated phase signal to be perfectly detected, it is essential for the receiver to have a coherent reference signal but in a situation whereby both the phase shift keying and differential encoding are incorporated or combined together then the DMT that evolves is known as Differential Phase Shift Keying. For symbol or digit 1 to be transmitted, the phase will be constant or unchanged but for transmitting symbol or digit 0, the phase of the signal will change to 180°. In order to be able to determine any relative change in the phase angle of the symbols or digits transmitted, it becomes essential to have a track information of any or possible phase change. This entire process is centered on the assumption or theory that a change in the phase angle is extremely slow to a point where it is considered to be nearly constant or unchanged over two-bit intervals.

2.4.3 Binary Frequency Shift-Keying (BFSK)

BFSK MT is formed by representing two different symbols with two different frequencies. BFSK can either be a narrow-band or wide-band MT and is known or determined by the level at which the two carrier frequencies are separated. This implementation of BFSK MT is simple and also cost effective, however, its poor bandwidth efficiency and complexities in the receiver design makes it inferior to other MT.

2.4.4 Minimum Shift-Keying (MSK)

MSK MT is a modified form or component of Continuous Phase Frequency Shift Keying (CPFSK). In this MT, the spacing between two different carrier frequencies is equivalent to half (½) of the bit rate and it is the required minimum spacing that makes the orthogonality between the two different frequencies possible.

MSK can be derived or formed either from an FSK signal or alternatively by replacing the square pulse in Offset Quadrature Phase Shift-keying (OQPSK) with ½ co-sinusoidal pulse. MSK MT when compared to QPSK, has equivalent information capacity but with lesser bandwidth requirement because of the co-sinusoidal pulse that was shaped by ½. It has a constant envelope because of the smoothness achieved during the phase transition. When compared to QPSK MT, the out-of-band power of MSK is lower thus, making it spectrally efficient.

The major drawdown of this particular MT is the fact that it is in the class or category of linear modulation coupled with the fact that the compact of the spectrum is not sufficient enough to realize or gather data rate approximating radio frequency channel bandwidth. The representation/notation coupled with the various properties of this MT is summarized in Table 4.2.

2.4.5 Quadrature Phase Shift-Keying (QPSK)

QPSK MT is simply another extension or type of the PSK DMT where the phase of a designed carrier signal is divided by allotting or allocating four equivalently spaced values for the signal's phase angle [1-3] which includes: $\pi/4$, 3 $\pi/4$, 5 $\pi/4$, and 7 $\pi/4$. These phase angles give QPSK an edge by doubling its information capacity when compared to BPSK, i.e.., in the constellation diagram of QPSK, there are four different message points that makes it highly efficient in terms of bandwidth. Considering the receiver design, the possibility for the receiver to retrieve the exact phase of the transmitted signal or message is an extremely important factor to be considered which can eventually result to the detection of erroneous signals if misappropriated. Hence, the receiver design complexity can be increased by this factor. One of the supposed compensation or solution to all these problems is by employing the idea for the modulated carrier signal to be pulse shaped coupled with the root raised cosine pulse shaping to guarantee a better or an optimum performance. However, this leads to the loss of the signal's constant envelope property although considered to be a big disadvantage, but on the other hand, the inter-symbol interference (ISI) performance is remarkably improved.

2.4.6 Gaussian Minimum Shift-Keying (GMSK)

MSK can be easily generated when a square pulse is replaced with half cosine sinusoidal pulse but if a Gaussian pulse shape was rather used then, it would have resulted into a MT known as GMSK which is an improved version of the MSK MT in the area of spectral efficiency and bandwidth. In addition, the major advantage that GMSK has over MSK and QPSK is its narrower main lobe (ML) and sufficient lower-side lobe levels (LSLL).

This MT can be considered to be either a phase or frequency modulation scheme, even though the Gaussian response limits the rate at which the phase changes, yet the phase carrier has the potential to retard or advance up to 90° at the course of the bit period. The grey side or negative effect of pulse shaping is that the Bandwidth time product (BT) can be affected because there can be a minimum of π /2 loss or reduction in the phase change achieved over or at the course of a bit period which automatically will severely affect the BER , although, its bandwidth efficiency is better compared to that of MSK.

The relationship or affiliation between the bit period (T_B) and the pre-modulation filter bandwidth is what defines or can be said to be the determinant factor of the GMSK's bandwidth. Hence, the BT value and data rate are vital with the view that there should be a trade between the out-of-band interference and BER as signal power will be enormously reduced if the ISI is affected by the narrow filter.

The process of generating a GMSK signal is similar to the methods used in generating MSK signals, the FSK modulation method. The only difference is that the ½ root raised co-sinusoidal pulse is replaced with the Gaussian pulse shaping.

2.5 Orthogonal Frequency Division Multiplexing (OFDM)

This modulation scheme has multi-carrier transmission techniques and the spectrums available in this MT are divided into numerous carriers which are modulated individually and differently at a data rate with low stream. The carriers are closely spaced and also orthogonal to one another. The orthogonality helps to prevent the carriers from interfering with one another seeing they are closely spaced. Hence, OFDM can be said to be a combination of multiplexing and modulation techniques. The symbol rate in OFDM is low because each of the carriers in the system has a very narrow bandwidth which makes the signal highly tolerant to multi-pathing and thereby, decreasing the possibility of ISI which can be said to be among the main requirement of the modern-day communication systems.

The higher the rate of transmission, the larger the bandwidth of the signals when compared to the coherence bandwidth of the propagating channel. However, the various spectral components available in the signal will pass through or experience diverse fading characteristics. For an acceptable error rate to be achieved in the output or detection end, the appropriate techniques must be used to characterize the various frequency selective fading. Partitioning the signals into different bands of frequencies that is narrower than the channel's coherent bandwidth will help in achieving the characterization needed in frequency selective fading. Subsequently, each and every components of the signal are eventually modulated into distinct sub-carriers and then sent or transmitted parallel across the channel. Afterwards, each of the signal component will no longer experience frequency selective fading because the serial high data rate sequence is now converted or turned into parallel low data sequences with each of them being modulated into a sub-carrier and can solely be achieved by OFDM. Table-4.2 contains the essential modulation parameters and it is reliant on the used data rate.

CHAPTER 3
Literature Review

3.1 Overview

This section comprises of the literature review. A theoretical and comprehensive review that is centered on OFDMA, a type of digital modulation technique amongst many other existing ones that is used in the telecommunication industry would be analyzed.

3.2 Literature Review on OFDM Modulation Technique

In this particular section, up to date researches that has been carried out on the OFDM modulation technique would be explained and a possible theoretical framework for the design and investigation of BER in the signal transmitted via OFDM modulation technique. Definitions and terminologies on key terms such as communication system (CS), channel, OFDM, noise and BER relating to the subject matter would be explained. Most importantly, the literature review would be written around studies that have been completed coupled with models that are available and could be used in designing a modem for OFDM or studies related in different environs.

Current and existing researches that were conducted coupled with numerous publications on BER and OFDM system can be reviewed either chronologically or individually based on their respective subject area. Efforts have been taken in introducing some of the researches already done based on the time of publication with respective to their various topic of focus.

Sending and receiving information or messages is conventionally referred to as communication. CSs which could either be digital or analogue, are distinctively built to send information or messages from the source where the messages are generated to a singular or more destinations. In the 20th century, CS was recognized as a field on its own. Prior to the introduction, evolution and dominance of DC in the second half of the 20th century, the first half was known or was seen as the evolutionary era of AC as a vast majority of communication that were transmitted took the form of radio communication (Viterbi & Omura, 1979). The figure 3.1 below is a simple block diagram representation of CS model.

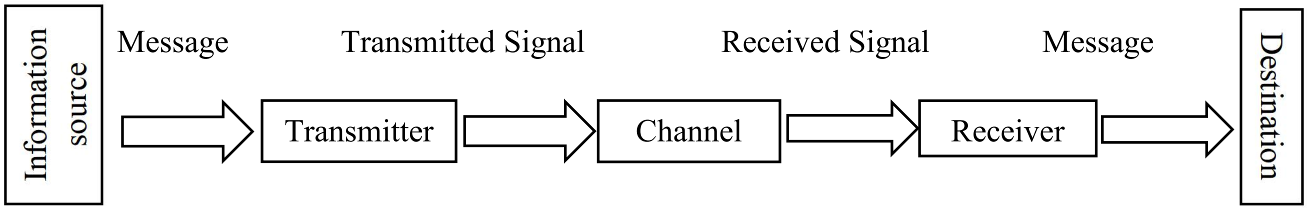


Figure 3.1: Block diagram of a CS

The introduction of such division in CSs, i.e., the digital systems when compared to the analogue systems, possess a better quality of transmission for wired and wireless channels. The digital systems were developed to be an improved version of the already existing analogue systems that had a lot of limitations and couldn't match up with the demands of which some are listed below (Viterbi & Omura, 1979):

I. The need for messages or information to be transmitted in various forms and for different applications with a very high accuracy level is required.

II. A synchronous DCS that has the capacity to continuously facilitate communication worldwide at a very high data rate is needed. The evolution of these systems with its power and bandwidth limitations enforces a major economic or cost-effective incentive for the channel resources to be efficiently used (Viterbi & Omura, 1979).

III. With the current advancement in the field of Digital Signal Processing (DSP), the digital transmission signals required will eventually become insusceptible to noise hence, processing such kinds of digital signals will be easy.

IV. Data Communication Network that has the capacity to deliver simultaneous and multiple services to numerous users at various rates when needed, most especially in circumstances where an efficient and simple multiplexing of data coupled with multiple access of the channels is obviously a serious concern for the current economy (Viterbi & Omura, 1979).

Although in 1948, the theoretical footing/foundation to DCS was first laid by C.E. Shannon via one of the research articles he published named "Mathematical Theory of

Communication" (Shannon, 1948). However, for such DCSs already proposed to be functionally implemented, the requirements stated coupled with the electronic technology were extremely essential, hence, both evolved together at the same time and in parallel about the 3rd quarter in the 20th century (Viterbi & Omura, 1979).

As it was initially described in the 1st chapter, OFDM is known as a digital multi-carrier communication technique, used in dividing the bandwidth of any available channel into numerous channels with narrow bandwidth which are called subcarriers. Data symbols can be modulated and transmitted simultaneously on each individual sub carrier (Eklund et al., 2002).

In contrast to other DCTs, OFDM is particularly regarded to be among the best methods of communication because it has the capacity to provide high data rates for transmission across a limited bandwidth (Eklund et al., 2002; Cavalcanti & Andersson, 2009). In addition, OFDM is a signal-ling scheme with efficient bandwidth for WBDCS, which makes it feasible for digital data to be transmitted over certain channels with harsh and tough characteristics (Eklund et al., 2002; Isabona & Ekpeyong, 2010). Even though OFDM was formed from a multiplexing technique, it is generally viewed to be a modulation technique.

One amongst many benefits provided by such multi-carrier CT in contrast to its counterpart, the single carrier system (SCS), is simply the robustness against narrow band interferences or frequency selective fading. This is based on the fact that any single fade or small level of interference that occurs in a SCS can cause the entire link to collapse or fail, while in the multi carrier systems, only a little percentage of the subcarriers will be affected of which can still be easily corrected when the Error Correction Coding (ECC) is applied (Noh et al., 2006; Intini, 2000; Raphaeli & Bassin, 1999)

For the entire OFDM system to perform optimally, the synchronization performance between the transmitter and receiver, most importantly estimating the time error coupled with the accuracy of the frequency between the transmitter and receiver and is key and very crucial (Hanzo et al., 2003; Pollet et al., 1995).A vast number of techniques have been suggested for the estimation and correction of the carrier frequency offsets and timing at the receiver\receiving end of the OFDM (Nikookar & Prasad, 1996; Chen, 2005). For example, the frame synchronization in OFDM systems has a task of aligning the FFT windows at the samples that were received correctly. If this is not done appropriately, the probability for the FFT block to contain some samples meant for the adjacent OFDM symbol is extremely high which will eventually result in ISI, causing distortion to the transmitted signals (Nee & Prasad, 2000)

OFDM is sometimes referred to as frequency division multiplexing (FDM). The idea of using this particular MT and system coupled with its first primary application or implementation could be traced as far back as the 1960s where it was mainly and vastly used by the military for communication purposes (Chang, 1966; Saltzberg, 1967), although a part of its early development dates back to the year 1950 (Intini, 2000; Mosier & Clabaugh, 1958). Bello (Bello, 1965), Chang and Gibby (Chang & Gibby, 1968), Powers and Zimmermann (Powers & Zimmermann, 1968) and Zimmermann (Zimmermann & Kirsch, 1967), were part of the persons who completed some of the researches relating to how this system was used for military communication. One of the reasons why OFDM was employed and used for such sensitive and crucial application was because it seemingly offered a very great potential in combatting not just the ISI which was primarily caused by multi-pathing, but the narrow band interferences and impulsive noise as well (Liu, 2004).

ISI is one of the inevitable consequences associated with the OFDM CS. Observations were carried out and it was discovered that during the early attempts of transmitting the signals, the signals received were elongated as well as smeared into one another (Schulze & Luders, 2005). The aim of mitigating and endeavoring to eliminate ISI to a particular extent if not completely, led to the addition of guard time to every single symbol of OFDM. The chosen guard time are usually larger than the estimated delay spread, which prevents the interference of the multipath components from a particular symbol with the immediate or next symbol (Prasad, 2004). Further comprehensive theories relating to these terminologies and concepts will be discussed in the third chapter.

In the early phases of the development of OFDM, numerous researchers made their various contributions by applying techniques that are similar in nature but in diverse applications and environment. For instance, in the 4th month of the year 1967, A. Kirsch and M. Zimmerman jointly created the AN/GSC-10 (KATHRYN)[1] with data rate modem that is variable for radio with high-frequency (HF) (Zimmermann & Kirsch, 1967). In 1967, Saltzberg carried out a study on MCS and he achieved it by using orthogonal time staggered quadrature amplitude modulation (O-QAM) of the carriers (Saltzberg, 1967). Researchers like Weinstein & Ebert (1971) (Weinstein & Ebert, 1971), Peled, Ruiz & Hirosaki (1980 – 1981) (Peled & Ruiz, 1980; Hirosaki, 1980; Hirosaki, 1981), kolb & Schussler (1982 – 1983) (Kolb, 1982; Schussler, 1983), Preuss (1984) (Preuss, 1984), Ruckriem & Cimini (1985) (Ruckriem, 1985; Cimini, 1985), Alard & Lassalle in 1987 (Alard & Lassalle, 1987) and Kalet (1989) (Kalet, 1989), all vastly contributed to the basis of OFDM in various application. For example, in the year 1971, Weinstein and Ebert both proposed an idea of reducing the complexity situated or involved in the implementation of OFDM models by using Discrete Fourier Transform (DFT). The idea was achieved using the DFT technique to replace the banks of both the sinusoidal generators and demodulators [33]. Years later, precisely in 1980, with the aim of decreasing the number of interferences, more importantly the ISI and Inter-Carrier Interferences (ICI), caused by either channel impulse or timing error and frequency, an approach called equalization algorithm was suggested by Hirosaki. Peled in the same year, considered the implementation to a simplified modem of OFDM. In 1981, Hirosaki via introducing the DFT- based implementation, developed the Orthogonal-QAM (O-QAM) OFDM system initially studied by saltzberg in 1967. Between the years of 1982 to 1985, four different researchers named Kolb, Preuss, Schussler and Ruckriem from Erlangen University in Germany, completed an additional research on the application of OFDM.

From the year 1985 to 1987, the researches completed by six different researchers named: Cimini, B. Hirosaki, Alard, Lassalle, S. Hasegawa and Sabato, all presented and focused on OFDM being considered for modems with high-speed and precisely in digital mobile wireless communications.

Cimini and Kalet in 1985 and 1989 respectively, completed a number of researches where the performance of OFDM modem in cellular communication channels were reviewed via results gotten from analysis and experiments.

The Europeans standardized the OFDM technique as their Video Broadcast and Digital Audio (DVB – DAB) scheme because of the unquestionable proofs on both its performance and reliability after numerous researches that were carried out. In addition to this, OFDM has established itself to be one among the most trusted MT that is used in the standard IEEE 802.11 Wireless Local Area Network (WLAN) coupled with being selected to be the transmission technique used in High Performance LAN (HIPERLAN) (Hanzo & Keller, 2006; ETSI, 2006).

In the beginning of the last two decades (in the 1990s as well as early 2000s), the performance and functionality of the OFDM MT was enhanced by numerous techniques as well as diverse emerging MT schemes such as Multiple-Input Multiple-Output (MIMO), etc. (Blum et al., 2001; Blum et al., 2001; Huang & Letaief, 2002; Li et al., 2001; Li et al, 2001; Iserte et al., 2002; Sampath et al., 2002; Suthaharan et al., 2002), although MIMO was not employed in this particular study/research. The combination of OFDM MT with diverse other methods or modulation schemes such as Space-Time Block Code (STBC) and MIMO has emerged as the logical/best pick to be considered for wireless systems beyond 3G (Pollet et al., 1995; Blum et al., 2001; Suthaharan et al., 2002).

In 1995, T. Pollet, M. Van Bladel and M. Moeneclaey jointly designed an OFDM system that has the capacity to decrease the complexities of tasks. Tasks which include equalization as well as channel estimation in systems where the channel's bandwidth is wide, in contrast to classical approaches that are not OFDM centered (Pollet et al., 1995). Later on, several scholars carried out different researches regarding channel estimation. Majority of these scholars tried using neural network approach as a methodological approach for investigating the channel estimation in various OFDM systems (Nawaz et al., 2009; Taspmar & Seyman, 2010; Omri et al., 2010; Ozen et al, 2004; Moustafa & El-Ramly, 2009; Hua & X-hui, 2010).

Both Fazel and Fettweis in 1997, jointly produced a work though edited but remarkable on a number of advanced researches that were recently carried out and completed in various universities across Europe on OFDM transmission (Fazel & Fettweis, 1997). Classen and Meyr published two of the core publications relating to this particular work collection in 1994. The focal point of these publications was on synchronization algorithms for OFDM systems for mobile communication (Classen & Meyr, 1994) as well as communication across channels with frequency selective fading (Classen & Meyr, 1994). Adding to some of the researches that have been completed on designing an OFDM system, coupled with its application in different sectors and also its combination with diverse methods or modulation schemes, it is necessary to state that in 2000, Nee and Prasad published a research work on OFDM for Wireless Multi-media communication (Nee & Prasad, 2000).

A.J.H. Vinck and J. Haring, G. Lindell explored the knowledge in modulation and powerline communication coding inclusive in 2000 (Vinck & Haring, 2000; Lindell, 2000; Raphaeli & Grauer, 2000)

After a fundamental research was carried out on OFDM, the possibility for orthogonality to be obtained as well as maintained was discovered by employing Inverse Discrete Fourier Transform (IDFT) to mitigate ISI afterwards adding Cyclic Prefix (CP) as illustrated in Figure 2.2 below (Prasad, 2004). These particular techniques can be applied in present/current researches.
Using the algorithm of CP based recursive least squares for channel estimation in MIMO OFDM systems was proposed in another research.

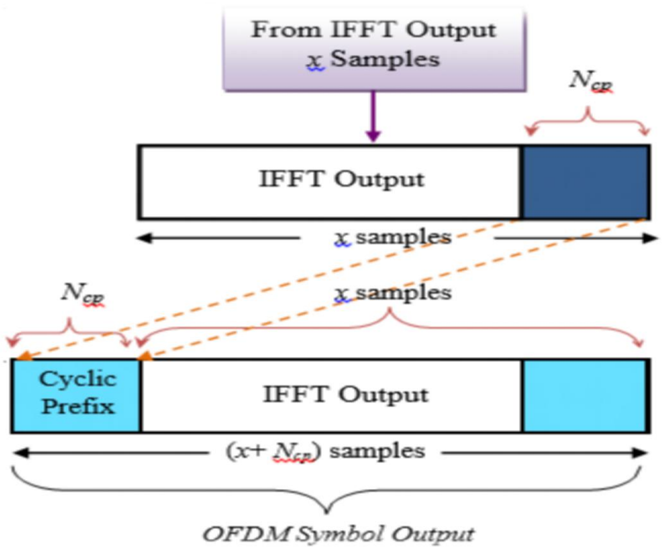


Figure 3.2: Cyclic Prefix Addition

Up until now, there have been an exponential increase in both research and publications on this particular subject matter. Some researchers that aimed on improving the performance of OFDM system employed the Artificial Neural Networks (ANN) as an approach. It is essential to know that numerous standards relating to OFDM have emerged in recent years of which the details and milestone would be further reviewed and illustrated with some of its significant contributions in Table 3.1 below.

Table 3.1: Important milestone and contributions on OFDM

Year of Publication	**Names of the Authors/Contributors**	**Some important contributions and Milestones on OFDM**	**References**
1966	Chang	The first person to present the dispersive fading channels for OFDM scheme	(Chang, 1966)
1967	Saltzberg	The first Orthogonal Quadrature Amplitude Modulation (O-QAM) was considered by the author.	(Saltzberg, 1967)
1968	R. Chang & R. Gibby	An abstract study for investigating data transmission in orthogonal multiplexing scheme was carried out by the author.	(Chang & Gibby, 1968)
1970	---	Issued the U.S patent on OFDM	(Chang, 1970)
1971	Weinstein & Ebert	The author applied Discrete Fourier Transform (DFT) to OFDM Modems	(Weinstein & Albert, 1971)
1980	Keasler, Bitzer & Tucker	The modem of OFDM used in telephone networks was illustrated by the author.	(Keaseler et al., 1980)
	Hirosaki	The author designed an	(Hirosaki, 1980)

		equalizer that is sub-channel based for an orthogonal multiplexed Quadrature Amplitude Modulation system.	
1981	Hirosaki	The author used DFT to design an orthogonal multiplexed Quadrature Amplitude Modulation system	(Hirosaki, 1981)
1985	Cimini	The author carried out an investigational research on the viability or feasibility of OFDM MT in mobile communications.	(Cimini, 1985)
1986	B. Hirosaki, S. Hasegawa & A. Sabato	The Orthogonal multiplexed Quadrature Amplitude Modulation technique was used by the authors to work on group band data modem that are advanced.	(Hirosaki et al., 1986)
1987	Alard & Lasalle	The OFDM used for digital propagation and broadcasting was employed by the authors	(Alard & Lasalle, 1987)
1991	Cioffi	was approved by ANSI to be the standard for ADSL	(Cioffi, 1991)
1994	Classen & Meyr	The authors focused on the algorithms that can help in the synchronization of an OFDM system for cellular or	(Classen & Meyr, 1994)

		mobile communication.	
	---	was approved by ANSI to be the standard for ADSL	(ANSI, 1994)
	Classen & Meyr	The authors investigated the suitable algorithms that can help in synchronizing the frequency for OFDM systems for communication across channels that has selective frequency fading.	(Classen & Meyr, 1994)
1995	T. Pollet, M.Van Badel & M. Moeneclaey	The authors investigated the BER's sensitivity in OFDM systems to wiener phase noise and offset of the carrier frequency.	(Pollet et al, 1995)
	--	DAB was the first OFDM standard to be employed and approved by ETSI for digital broadcasting systems.	(ETSI, 1995)
1996	---	ETSI employed and approved OFDM as the standard for WLAN.	(ETSI, 1996)
1997	---	ETSI also employed and approved OFDM as the standard for DVB -T.	(ETSI, 1997)
	Fazel & Fettweis	The authors jointly produced an edited but yet impressive	(Fazel & Fettweis, 1997)

		work on a number of advanced and recent researches carried out on transmission in OFDM systems.	
1998	---	ETSI employed and approved OFDM as the standard for BRAN.	(ETSI, 1998)
	---	Both ETSI and ANSI employed and approved OFDM as the standard for VDSL.	(ETSI, 1998; ANSI, 1998)
1999	---	OFDM was employed and approved as a WLAN standard for IEEE 802.11a.	(IEEE, 1999)
2000	A.J. H. Vinck, J. Haring & G. Lindell	The authors tried exploring the knowledge in modulation and coding powerline communication	(Vinck et al., 2000; Lindell, 2000; Raphaeli et al., 2000)
	B. Muquet, M, De Courville, P. Duhame & G. Giannakis	The authors used the CP concept to investigate the equalization in OFDM systems.	(Muquet et al., 2000)
2002	---	OFDM was employed and	(IEEE, 2002)

		approved as a WLAN standard for IEEE 802.11g.	
2003	S. Aghajeri & H. Shafiee	Synchronization for OFDM CS was investigated by the authors	(Aghajeri & Shafiee, 2003)
2004	---	OFDM was employed and approved as a WMAN standard for IEEE 802.16	(IEEE, 2004)
	---	ETSI employed and approved OFDM as the standard for DVB-H.	(ETSI, 2004)
	---	OFDM was selected as the standard for the next generation WLAN for IEEE 802.11n in this particular year.	(IEEE, 2004)
	---	OFDM was again selected in the same year as the standard for WPAN for IEEE 802.11n using Multi-Band OFDM (MB-OFDM)	(IEEE, 2004)
	T. Han & X. Li	The authors used the blind adaptive equalization to work on the channel equalization of an OFDM system.	(Han & Li, 2004)

	S. Kunaruttanapruk & S. Jitapunkul	Feedback equalization was employed by the authors when they were investigating the channel equalization in an OFDM system	(Kunaruttanapruk & Jitapunkul, 2004)
	S. Lerkvaranyu, K. Dejhan & Y. Miyanaga	ANN was applied by the authors to an OFDM system.	(Lerkvaranyu et al., 2004)
2005	M. Yabusaki	OFDM MT was selected by Japan, South Korea and China as the standard candidate for 4G network.	(Yabusaki, 2005)
2006	E.Chen, R. Tao & X. Zhao	The Back Propagation Neural Network (BPNN) was used by the authors to work on equalizing the channel for OFDM system	(Chen et al., 2006)
	Qi Lu, Lin Gui & Ziang-Zhong Fang	NN was used by the authors for equalizing the channel of OFDM systems.	(Lu et al., 2006)
	L.V. Ninh, T.A. Vu, H.T. Huynh & P. Fortier	The synchronization needed for OFDM CSs was investigated by the authors.	(Ninh et al., 2006)
2007	N. Rodriguez & C.	The authors work was	(Rodriguez &

	Cubillos	focused on the Orthogonal NN centered pre-distortion for OFDM systems.	Cubillos, 2007)
	B. Naeeni & H. Amindavar	NN was employed by the authors for equalizing the channel in OFDM system.	(Naeeni & Amindavar, 2007)
2008	M. Jiang, C. Li, H. Li & D.Yuan	Tracking of channel via NN and Particle Filter in an OFDM systems with MIMO was studied by the authors.	(Jiang et al., 2008)
2009	Qingyi Quan	The Multi-level Hopfield NN for an OFDM system coupled with Phase Noise was examined by the authors.	(Quan, 2009)
	J. Kassab & Dr. S. Nagaraj	Adaptive modulation was examined by the authors in an OFDM CS with ANN	(Kassab & Nagaraj, 2009)
2010	R. Zayani, R. Bouallegue & D. Roviras	The crossover NN Pre-distorter needed to compensate the Non-linearity and Crosstalk in an OFDM systems with MIMO was studied by the authors.	(Zayani et al., 2010)
	H. Yigit & A. Kavak	The Adaptation in an OFDM system with MIMO having selective frequency was worked on by the authors using NN.	(Yigit & Kavak, 2010)

2011	F. Meucci, L. Pierucci & N. Prasad	The detection of identity theft in an OFDM system which is NN Non-linearity identification based was researched by the authors.	(Meucci et al., 2011)

From Table 3.1 above, it is visible that majority of the researches done on the various MTs, its extensions as well as significant improvements on the drawdowns and limitations on the OFDM system started from 1966. It is obvious that this particular MT has a great potential to be employed or applied in a well-recognized CSs such as Mobile or cellular systems.

CHAPTER 4

Comparison of the Various Types of Digital Modulation Techniques

4.1 Overview

This particular chapter and section comprise of a detailed comparison made on different types of digital modulation techniques and their individual classification (such as BASK, BPSK, QPSK, QAM, DPSK etc.,) based on their advantages, disadvantages, classifications, bandwidth efficiency, required bandwidth (R_B), bit-error-rat (BER), error performance and probability, demodulation performance, ISI status and so on.

4.2 Comparison of different schemes of various types of DMT

The Binary Amplitude Shift-Keying (BASK) MT is simpler and economical in terms of implementation. Though the technique is less prone to error but its bandwidth efficiency is less coupled with the fact that it only operates in the linear region, makes it quite an inefficient technique to be applied in the area of wireless communication systems. The Binary Frequency Shift-Keying (BFSK) MT likewise is similarly less susceptible to errors and its required bandwidth (BW) is similar to BASK (Table-4.1), however, it is a technique with poor bandwidth efficiency. Although, it has a better error performance parameter than BASK (Table-4.7, 4.8). For demodulation, a matched filter detection is required however, this increases the receiver's design complexities thereby making this technique occasionally or rarely used in some applications related to mobile or wireless communications.

The Binary Phase Shift-Keying (BPSK) is pretty much better than the other two MTs mentioned earlier. It is a coherent MT and can be used for diverse applications such as transferring data at a higher speed. The basic advantage of BPSK when compared to BASK and BFSK is its capacity to carry double or dual information (Table-4.5). The technique is useful for satellite communication because of its robustness and simple implementation even though it is inefficient in the area of bandwidth usage and it is classified as part of the non-linear MTs (Table-4.9). The error performance is quite better and can be optimized to achieve the minimum error rate ever possible (Table- 4.4, 4.5). This technique is not useful for the mobile or wireless communication application because of phase shift detection which makes the receiver design complex (Table-4.6).

The information capacity provided by Differential Phase Shift-Keying (DPSK) MT is similar to that of BPSK though more viable and can be classified as a non-coherent OM (Table-4.1, 4.9). The receiver complexities in DSPK when compared to BPSK is very much because the system requires a memory in other to be able to keep consistent and reliable track of the relative phase difference.

Quadrature Phase Shift-Keying (QPSK) MT is a widely used modulation scheme with its information capacity twice that of BPSK (Table-4.1) over similar or equivalent bandwidth and needs coherent detection. The bandwidth efficiency is very high and it is considered to be spectrally efficient since it has a constant modulation envelope. Hence, QPSK doesn't only provide major merits or advantages when compared to BPSK but likewise has overcome the major setbacks or limitations displayed by BPSK.

Detecting the exact phase shift is a criterion that is absolutely essential in other for a QPSK signal to be detectable. Howbeit, the receiver design complexities will surely increase because of the need for the phase shift to be detected and for the further improvement of this particular modulation technique to be achieved, the modulated carrier must be pulse shaped. Pulse shaping the modulated carrier by ½ co-sinusoidal pulse shaping will provide a new and well improved performance MT called Minimum Shift-Keying (MSK). This particular MT known as MSK comprises of two Continuous Phase Frequency Shift-Keying (CPFSK) signals. One of the major advantages of MSK over QPSK is its significantly low out-of-band power (Table-4.5) coupled with the fact that it has a constant envelope and 99% of its overall power is 1.2 T_B makes it spectrally efficient. When compared to QPSK, MSK has proved to be a better MT because its deviation ratio and signal coherence are largely unaffected by the varying input rates (Table-4.2). However, one of the basic disadvantages (Table-4.5) of MSK MT is that higher data rates cannot be realized because the spectrum is not compact enough.

The GMSK MT is simply just a variation of MSK MT which is formed when Gaussian pulse shaping is used to replace the modulated carrier's co-sinusoidal pulse shaping in MSK MT. In addition, both the spectral efficiency and envelope of GMSK is improved (Table-4.4, 4.5). GMSK MT with a BT of 0.3 is more popular when compared to other existing variations because it provides better error performance as well as bandwidth at this value when optimized. The main disadvantage of this particular MT is the fact that its narrow symbol shape makes it highly susceptible to ISI especially at higher data rates (Table-4.5). This MT is highly and vastly used in GSM mobile or cellular communication.

The average bit error probability of both the decoder and demodulator output is a combination of the demodulator coupled with the decoder performance measure. The error probability is precisely a function of waveforms, code characteristics, the power transmitted, the transmission channel characteristics, with a combination of both the decoder and demodulation. Therefore, the signal that was reconstructed at the receiver's end will be approximately the same or close to the signal that was initially transmitted. The function of the existing differences between the transmitted and reconstructed signal is used as a mark to measure the performance in relation to distortion in a DCS. The bit-error-rate (BER) equations of the various types of DMTs is summarized in (Table-4.8).

The various researches carried out by different individuals in the communication sector led to the emergence of new modulation and coding techniques, improved spectral efficient MT, performance analysis on error rate, etc. but the untamable demand for a faster CS with larger bandwidth requirements has once more resurrected a fresh quest in developing newer techniques which led to the emergence of various MTs such like BASK, BPSK, BFSK, DPSK, GMSK, MSK, M-ary QAM. For any developed, existing or yet to be developed MT, one of the features to take into consideration is that the detection performance when compared to the existing ones should have a better BER performance although, many methods have been created for the same or improved bit-error-rate (BER) performances of the MTs.

One of the primary objectives of a designed or developed CS is ensuring that it has the capacity of transmitting messages as swift as possible with minimal error probability. Fast communication can be ensured when:

(i) The time allocated for each message is reduced which eventually increases the bandwidth.
(ai) Simultaneously transmitting different messages over one particular physical channel is termed Multiplexing. Hence, OFDM can be selected to be the best candidate over all other types of DMTs.

Table 4.1: DMTs extensions and their performance analysis.

Serial No	**Modulation Technique (MT)**	**Notation**	**Type**	**Required Bandwidth (BW)**
	Binary Modulation Schemes			
1	Binary Frequency Shift-Keying	BFSK	Non-Coherent	$2R_B$
2	Binary Amplitude Shift-keying	BASK	Non-Coherent	$2R_B$
3	Differential Phase Shift-Keying	DPSK	Non-Coherent	$2R_B$
4	Binary Phase Shift-Keying	BPSK	Coherent	$2R_B$
	Quadrature Modulation Schemes			
1	Minimum Phase Shift-Keying	MSK	Coherent	< QPSK
2	Quadrature Phase Shift-Keying	QPSK	Coherent	$2R_B$
	M-ray Modulation Schemes			Where: M= 2^N, N
1	M-ary Quadrature Amplitude Shift Modulation	M-ary QAM	Coherent	$2\ R_{b\,/\,N}$
2	M-ary Frequency Shift-Keying	M-ary FSK	Coherent	$M\ 2\ R_{b\,/\,N}$

3	M-ary Phase Shift-Keying	M-ary PSK	Coherent	$2\ R_{b\ /\ N}$
	Orthogonal Frequency Division Multiplexing	OFDM	Coherent	
1	Quadrature Amplitude Modulation Orthogonal Frequency Division Multiplexing	QAM-OFDM	Coherent	Lesser than (<) all other techniques
2	Binary Phase Shift-Keying Orthogonal Frequency Division Multiplexing	BPSK-OFDM	Coherent	Lesser than (<) all other techniques
3	16-Quadrature Amplitude Modulation Orthogonal Frequency Division Multiplexing	16-QAM-OFDM	Coherent	Lesser than (<) all other techniques
4	64-Quadrature Amplitude Modulation Orthogonal Frequency Division Multiplexing	64-QAM-OFDM	Coherent	Lesser than (<) all other techniques

Table 4.2: Modulation parameters of DMTs in MC MS.

Serial No.	**Modulation Technique Representation**	**Data Rate (Mbps)**	**Coded bits per sub-carrier (N_{CBPS-C})**	**Coding Rate ®**	**Data bits per OFDM symbol (N_{DBPS})**	**Coded bits per OFDM symbol (N_{CBPS})**
1	BPSK	6	1	½	24	48
2	BPSK	9	1	¾	36	48
3	QPSK	12	2	½	48	96

4	QPSK	18	2	¾	72	96
5	16-QAM	24	4	½	96	192
6	16-QAM	26	4	¾	144	1192
7	64-QAM	48	6	2/3	192	288
8	64-QAM	54	6	¾	216	288

Table 4.3: OFDM MC MS parameters.

Serial No.	Parameters	Notation/Formula	Value
1	Sampling rate	$f_s = 1/T$	f= 20MHz, T= 0.05 μSec
2	Duration of Cyclic Prefix	$\mathbf{T}_{CP}$ **=** 16T (Mandatory) $\mathbf{T}_{CP}$ **=** 8T (Optional)	16T = 16(0.05) =0.8 μSec 8T = 8(0.05) =0.4 μSec
3	Duration of the useful Symbol Part	$\mathbf{T}_U = 64T$	64T = 64(0.05) =3.2 μSec
4	Symbol Interval	$\mathbf{T}_S = 80T$ $\mathbf{T}_S = 72T$	80T = 80(0.05) =4 μSec, ($\mathbf{T}_U + \mathbf{T}_{CP}$) 72T = 72(0.05) =3.6 μSec, ($\mathbf{T}_U + \mathbf{T}_{CP}$)
5	No. of Pilot Sub-Carrier	$\mathbf{N}_{SP}$	48
6	No. of Data Sub-Carrier	$\mathbf{N}_{SD}$	4
7	Total No. of Sub-Carrier	$\mathbf{N}_{ST} = (\mathbf{N}_{SP} + \mathbf{N}_{SD})$	48 + 4 =52
8	Fast Fourier (FFT) Transform Size	$\mathbf{N}_{FFT}$	64
9	Spacing of the Sub-carriers	$\delta_F = (1/\ \mathbf{T}_U)$	(1/3.2 μSec) = 0.3125Mhz
10	The index of Sub-Carrier used		{-26 to -1, +1 to +26}

11	The Spacing between the 2 outmost Sub-Carriers	**(N**$_{ST}$ x δ_F)	(52 x 0.3125) = 16.25Mhz

Table 4.4: Parameters DMTs extensions.

Sr. No	Type of DMT	Envelope Type	No. of Symbols	Capacity Of Information	The required BW	BW Efficiency	Message Point No.	Shaping the Symbol
1	BPSK	Constant	2	Twice of BFSK	2R_B	Used for transferrin g data that requires high speed	2	Not needed
2	BASK	Not Constant	1	Poor	2R_B	poor	1	Not needed
3	BFSK	Constant	1	Better than BASK	2R_B	Not efficient	1	Not needed
4	DPSK	Constant	2	Equivalent with BPSK	2R_B	Used for Communi cation that requires Medium speed	1	Not needed

5	MSK	Constant	4	Equivalent with QPSK	< QPSK	When compared to QPSK, the out-of-band power is significantly lower and 99% of MSK's total power is 1.2 T_a	4 [This is expressed in the terms of the Signal's energy / symbol]	Needed for half the Co-Sinusoidal pulse
6	GMSK	Constant	4	Equivalent with MSK	Narrow BT-0.3	Excellent	4	Needed for the Gaussian Pulse
7	QPSK	Constant	4	Twice of BFSK	$2R_B$	Highly efficient	4 [This is expressed in the terms of the Signal's energy / symbol]	Needed for the Rectangular pulse
	OFDM BPSK-			Higher than	Lesser	More		Better

8	OFDM	Not Constant	2	all the modulation techniques listed above	(<) than all other techniques	Excellent tan all the modulation techniques listed above	2	than all other modulation schemes
	QAM-OFDM		4				4	
	16-QAM		16				16	
	64-QAM		64				64	

Table 4.5: Advantages & Disadvantages of DMTs extensions.

Serial No.	**Type of DMT**	**Derived or Formed from**	**Merits (Advantages)**	**Demerits (Disadvantages)**	**Main Side Lobe Level (MSLL)**
1	BPSK	PSK	i) It is robust ii) Simple and easy to implement iii) Vastly and Majorly used for satellite communication	i) it is a non-linear modulation scheme ii) poor bandwidth efficiency	-13db

			iv) Compared to BASK, BPSK power advantage is about 3db		
2	BASK	ASK	i) Low cost ii) Simple and easy to implement	i) It is not Bandwidth efficient ii) Easily prone to noise iii) Its operation is mainly in the linear region	-13db
3	BFSK	FSK	i) Low cost ii) Simple and easy to implement	i) The design received is complex	-13db
4	DPSK	PSK	i) It reduces the complexity of the design to be received by the receiver for non-coherent scenarios	i) it has a lesser efficiency compared to the coherent PSK	-13db

5	MSK	The square pulse in OQPSK is replaced with ½ Co-Sinusoidal pulse	i) The envelope remains constant ii) The out of band power is minimal or lower. iii) Two frequencies is allowed to be orthogonal to one another because of the available minimum spacing. iv) It is easy to generate and also spectral efficient	i) It is a linear modulation scheme ii) The spectrum is not sufficiently compact to realize the data rate and hence, the bandwidth of the rf channel is approximated	-13db

6	GMSK	The ½ Co-Sinusoidal pulse in FSK is replaced with a Gaussian pulse	i) The envelope remains constant ii) It is spectral efficient iii) It is vastly and majorly used in GSM mobile or cellular communication with a BT of 0.3	i) It promotes inter-symbol interference (ISI) during the transmission of higher bit	A fast roll with 0.3 BT factor, lower side lobe (LSL), narrow main lobe (NML)
7	QPSK	PSK	i) It is bandwidth efficient and has the capacity to transmit twice the data in the same bandwidth ii) It has more spectral efficiency than BPSK	i) Shaping the pulse wave is necessary and during this process, the constant envelope characteristic or property is lost ii) The designed received by the receiver is often complex	-13db
	OFDM BPSK-	Multi-carrier	i) It is robust to ISI &ICI.	i) It is very sensitive to Doppler shift	

8	OFDM QAM-OFDM 16-QAM 64QAM	modulation schemes	ii) It highly spectral efficient iii) It uses FFT for efficient implementation iv) Its sensitivity to error in the area of time synchronization is low. v) Single Frequency network such as complex equalization is facilitated vi) Filters used in tuning the sub channel are not needed by the receiver.	ii) Sensitive to synchronization problems relating to frequency (is). iii) It uses linear power amplifiers that makes the transmitter inefficient in terms of power consumption.	-----

Table 4.6: Analysis of DMTs Performance detection.

Serial No.	Type of DMT	Derivatives	The Detection Performance of Demodulation	Combination with other MT
1	BPSK	OQPSK, QPSK, BPSK, 16-PSK, π/4PSK, MPSK, In-coherent detection, QAM,	The Rx is complex because of the phase shift detection	ASK-QAM
2	BASK	QAM (This is extensively used in Digital Micro-wave links of M-ary ASK)	Simple to demodulate	PSK
3	BFSK	M-ary FSK	Simple to demodulate with matched filter detection	The special cases of Orthogonal modulation
4	DPSK	π/4 DPSK	A memory is needed for the receiver to be able to measure the relative difference in the phase angle between the transmitted waveforms received in	Considering a Non-coherent Orthogonal modulation over two-bit interval

			successive intervals.	
5	MSK	GMSK	NRZ data is directly injected into the frequency modulator with 0.5 as the modulation index	Replacing the ½ Co-Sinusoidal pulse with Gaussian Pulse to obtain GMSK
6	GMSK	GMSK (BT= 0.3) GMSK (BT= 0.5)	BT which is a product of bandwidth time is an essential factor performance and is measured by Signal-to-noise ratio (SNR) versus Bit Error Rate (BER)	----
7	QPSK	a channel of OQPSK-Q that is shifted by ½ symbol of QPSK to OQPSK and then to MSK, π /4 DQPSK is the representation	Phase shift detection is essential	Diverse phase variation. Replacing the square pulse with ½ Sinusoidal pulse to obtain or derive MSK

		of a differentially decoded $\pi/4$ QPSK		
8	OFDM	QAM, BPSK, 16-QAM, 64-QAM	BT which is a product of bandwidth time is an essential factor performance and is measured by Signal-to-noise ratio (SNR) versus Bit Error Rate (BER)	QAM, BPSK, 16-QAM, 64-QAM

Table 4.7: Characteristic performances of DMTs.

Serial No	**Type of DMT**	**Probability of Error**	**Status of ISI**	**Error Performance**	**Dimensions**	**No. of Primary/ Basic functions**
1	BPSK	$\frac{1}{2}\text{erfc}\sqrt{\frac{E_B}{N_o}}$	Minimal or Less prone	Though it has the smallest error rate when compared to other system but there is a restriction	2	2

				of AWGN on single or 1 bit decoding. The fact that it achieves minimal possible error rate makes it optimum		
2	BASK	$\frac{1}{2}\exp(-\frac{A^2}{8N_o})$, for $A^2 \geq N_o$ Where: A: Amplitude $N_o = \eta B_T$, η: Noise-power B_T: Bandwidth	---	It is only efficient in regions that linear	1	1
3	BFSK	$\frac{1}{2}\exp(-\frac{E_B}{2N_o})$, Where: N_o : is Noise E_B: Bit density	---	When the values of E_B/N_O are high, the performance of BFSK is very well as FSK & PSK for same signal as	1	1

				well as bit rate		
4	DPSK	$\frac{1}{2}\text{erfc}\,(-\frac{E_B}{2N_o})$	Minimal or Less prone	For the same error rate, GMSK requires a 3dB less E_B/N_O compared to BFSK	2	2
5	MSK	$\frac{1}{2}\,\text{erfc}\,(\sqrt{\frac{E_B}{N_o}}) - \frac{1}{4}\,\text{erfc}^2\,(\sqrt{\frac{E_B}{N_o}})$	Minimal or Less prone compared to QPSK	The variations or change in the imputed data rate doesn't affect the deviation ratio and coherent signal.	2	2
6	GMSK	$P_e = Q\,(\sqrt{\frac{2\delta E_B}{N_o}})$, Where: BT=0.25, δ=0.68 BT=∞, δ=0.85,	More prone compared to MSK	Over a bit period, the carrier lags or leads by 90° with respect to BT resulting into BER	2	2
7	QPSK	$\frac{1}{2}\,\text{erfc}\,(\sqrt{\frac{E_B}{N_o}}) - \frac{1}{4}\,\text{erfc}^2$	It is ISI Prone	It gives a better	2	2

		$(\sqrt{\frac{E_B}{N_o}})$		performance than BFSK & BPSK but its major setback is the use of square wave which can be enhanced by using an improving ISI root raised cosine to sharpen the pulse		
8	OFDM	$\int_{\pi}^{\pi}\int_{-\pi}^{\pi}\int_{-T/2}^{T/2}\frac{1}{2}erfc$ $P_\tau(\tau)P_\alpha(\alpha)P_\phi$ $\frac{\mu W_0 W_P W_T}{\sqrt{2(\sigma^2+\sigma_{ISI}^2)}}$ $(\phi)d\tau d\alpha d\phi$	---	Quite minimal when compared to other modulation schemes	4 in QPSK 2 in BPSK 16 in 16-QAM	4 in QPSK 2 in BPSK 16 in 16-QAM

Table 4.8: BER equations of DMTs.

Serial No	**Type of DMT**	**Pe**	**M=2^N**	**BW**

1	QPSK	½ erfc $\sqrt{(E_b \mid N_o)}$	4,2	R_b /2
2	BPSK	½ erfc $\sqrt{(E_b \mid N_o)}$	2,1	R_b
3	MSK	½ erfc $\sqrt{(E_b \mid N_o)}$	4,2	R_b /2
4	SQPSK	½ erfc $\sqrt{(E_b \mid N_o)}$	4,2	R_b /2
5	M-PSK	erfc $\sqrt{\langle NE_b \mid N_o Sin^2 \pi \mid M\rangle}$	M,N	R_b/N
6	M-QAM	2[1-1/N]erfc $\sqrt{\langle(3 \mid \{ N^2-1\})E_b \mid N_o\rangle}$	M,N	R_b/N
7	M-FSK	(M-1)/2erfc $\sqrt{(N \mid 2) * (E_b \mid N_o)}$	M,N	M, R_b/L
8	16-QAM	2erfc $\sqrt{(0.4E_b \mid N_o)}$	16,4	R_b /4
9	QPR	½ erfc $\sqrt{(\pi^2 E_b \mid 16N_o)}$	L levels	R_b /4
10	OFDM-BPSK	$P_b(m)=\frac{1}{2}-\int_o^\infty \frac{\sin\left(\sqrt{E}\omega c_0^I\right)}{\pi\omega} e^{-\frac{1}{2}\omega^2\sigma^2} \times \prod_{\substack{k\neq m\\k=0}}^{N-1}\cos\left(\sqrt{E}\omega c_{k-m}^I\right)d\omega$ $where - c_{k-m}^I = \mathrm{P}\left(\frac{k-m}{\mathrm{T}}+\Delta f\right)\times\cos(\pi[k-m+\Delta f][1+\alpha])$.	2	The BW required is lesser than other schemes
11	LQPR	$2[1-1/L^2]erfc\sqrt{[\pi/4(\log_2 L)^{1/2}(6/\{L^2-1\})^{1/2}E_b/N_o]}$	L levels	R_b /L
12	OFDM-16-QAM	$\mathrm{P}_{il}(m)=\frac{1}{2}-\int_0^\infty \cos(2\omega dc_0^Q)\cos(\omega dc_0^Q)\times\sin(2\omega dc_0^I)\cos(\omega dc_0^I)\beta(\omega)d\omega$	16	The BW required is

		$\mathrm{P}_{i2}(m)=\frac{1}{2}-\int_{0}^{\infty}2\sin(2\omega d)\sin\left(2\omega dc_{0}^{1}\right)\sin\left(\omega dc_{0}^{1}\right)\times\cos\left(2\omega dc_{0}^{Q}\right)\cos\left(\omega dc_{0}^{Q}\right)\beta(\omega)d\omega.$ $\beta(\omega)=\frac{e^{-\frac{1}{2}\omega^{2}\sigma^{2}}}{\pi\omega}\prod_{\substack{k\neq m\\k=0}}^{\mathrm{N}-1}\cos\left(2\omega dc_{k-m}^{1}\right)\cos\left(\omega dc_{k-m}^{1}\right)\times\cos\left(2\omega dc_{k-m}^{Q}\right)\cos\left(\omega dc_{k-m}^{Q}\right).$		lesser than other scheme s
13	OFDM -QPSK	$\mathrm{P}_{b}(m)=\frac{1}{2}-\int_{0}^{\infty}\sin\left(\omega\sqrt{\mathrm{E}}c_{0}^{\mathrm{I}}\right)\cos\left(\omega\sqrt{\mathrm{E}}c_{0}^{Q}\right)\times\eta(\omega)d\omega.$ $where-\eta(\omega)=\frac{e^{-\frac{1}{2}\omega^{2}\sigma^{2}}}{\pi\omega}\coprod_{\substack{k\neq m\\k=0}}^{\mathrm{N}-1}\cos\left(\omega\sqrt{\mathrm{E}}c_{k-m}^{\mathrm{I}}\right)\times\cos\left(\omega\sqrt{\mathrm{E}}c_{k-m}^{Q}\right)$	4	The BW require d is lesser than other scheme s

Table 4.9: Mathematical representation of DMTs.

Serial No	Type of DMT	Type	Mathematical Representation	Compo nents	Signal Correl ation	Q-Compon ents
1	BPSK	Coherent	$X_1(t) = \sqrt{\frac{2E_B}{T_B}}\cos(2\pi f_c t)$ & $X_2(t) = \sqrt{\frac{2E_B}{T_B}}\cos(2\pi f_c t+\pi)$ $X_1(t)$ for Bit 1 & $X_2(t)$ for Bit 0	None	None	None
2	BASK	Non-Coherent	$X(t) = Am(t)\cos 2\pi f_c t$ for $0 \leq 1 \leq T_B$, $m(t) = 1$ for Bit 1 & 0 for Bit 0 Signal energy representation $X(t) = \sqrt{\frac{2E_B}{T}}\cos 2\pi f_c t$	None	None	None

3	BFSK	Non-Coherent	$X_i(t) = \sqrt{\frac{2E_B}{T}}\cos(2\pi f_c t)$ for $0 \le t \le T_B$, $i = 1,2$ $\quad f_c = \frac{n_c + i}{T_B}$ $X_1(t) = 1, (f_1)$ & $X_2(t) = 0, (f_2)$ and	None	None	None
4	DPSK	Non-Coherent	$X_1(t) = \begin{cases} \sqrt{\frac{E_B}{2T_B}}\cos(2\pi f_c t)\ for\ 0 \le t \le T_B \\ \sqrt{\frac{E_B}{2T_B}}\cos(2\pi f_c t)\ for\ T_B \le t \le 2T_B \end{cases}$ $X_2(t) = \begin{cases} \sqrt{\frac{E_B}{2T_B}}\cos(2\pi f_c t)\ for\ 0 \le t \le T_B \\ \sqrt{\frac{E_B}{2T_B}}\cos(2\pi f_c t + \pi)\ for\ T_B \le t \le 2T_B \end{cases}$ It is a special case of Non coherent Orthogonal Modulation for $T_B = 2T_B$ & $E_B = 2E_B$ $X_1(t)$ for Bit 1 and $X_2(t)$ for Bit 0	None	Exists	None
5	MSK	Coherent	$X_i(t) = \cos\left[2\pi f_c t - \frac{AB\pi t}{T_B} + 0\right]$ Where the value of $\theta = 0$ for A = 1 and the value of $\theta = \pi$ for A = -1. Thus the above expression can be of the form (1) $X_i(t) = \cos\left[2\pi f_c t \mp \frac{\pi t}{T_B}\right]$ for A = 1 & B = ± 1 (2) $X_i(t) = \cos\left[2\pi f_c t \mp \frac{\pi t}{T_B} + \pi\right]$ for A = -1 & B = ± 1	$X_I(t)=$ $\pm\sqrt{\frac{2E_B}{T_B}} *$ $\cos\left(\frac{\pi}{2T_B}t\right)$ $Q \le 1 \le$ T_B	Exists	$X_Q(t)=$ $\pm\sqrt{\frac{2E_B}{T_B}} *$ $\sin\left(\frac{\pi}{2T_B}t\right)$ $Q \le 1 \le$ T_B
6	GPSK	Coherent	$G(t) = \frac{1}{2T}\left[\begin{array}{l} Q(2\pi B_{ban})\left(\frac{t - 0.5T_B}{\sqrt{\log_e 2}}\right) \\ -Q(2\pi B_{ban})\left(\frac{t - 0.5T_B}{\sqrt{\log_e 2}}\right) \end{array}\right]$ $Q(t) = \int^{\infty} \frac{1}{\sqrt{2}}\exp\left(\frac{-x^2}{2}\right)dx$, B_{ban} is the bandwidth of the filter	I(t) = cos[C(t)] For C to be a constant i.e..,	Exists	Q(t) = Sin[c(t)]

				$\int_{-T}^{T} CG(t)dt = \frac{\pi}{2}$		
7	QPSK [45°, 135°, 225°, 315°]	Coherent	$X_o(t) = \begin{bmatrix} \sqrt{\frac{2E_B}{T_B}}\cos(2n-1)\frac{\pi}{4}\cos(2\pi f_c t) \\ -\sqrt{\frac{2E_B}{T_B}}\sin(2n-1)\frac{\pi}{4}\sin(2\pi f_c t) \end{bmatrix}$ for $0 \le t \le T_B$, Where n = 1`,2,3,4 and for Bit 10 00 01 11 Phase $\pi/4$ $3\pi/4$ $5\pi/4$ $7\pi/4$	$X_t(t) = \sqrt{E_B}\cos(2n-1)*(\frac{\pi}{4})$ Where: n=1, 2, 3, 4	Exists	$X_Q(t) = -\sqrt{E_B}\sin(2n-1)*(\frac{\pi}{4})$ Where: n=1, 2, 3, 4
8	OFDM	Non-Coherent	$X(t)=\frac{1}{\sqrt{N}}\sum_{K=0}^{N-1}X_K\exp(j2\pi Kt/T);0\le t\le T.$ T = Signal Duration, N = N-Point IDFT, $\frac{1}{\sqrt{N}}$ =Scale factor, Signal samples $X_N = X\left(\frac{nT}{N}\right); n=0,1,2,.........,N-1.$ Sub carrier frequency = $f_K = \frac{K}{T}; K=0,1,2,...K-1$ = Sub-carriers. E_B = Energy of the Bit, T_B = Time duration of the Bit, f_c = Carrier Frequency, m(t) = Modulation Index, A = Amplitude, n_c = Noise	None	None	None
9	OFDM (QAM, BPSK, 16-QAM, 64-QAM)	Non-Coherent	$X(t)=e^{j2\pi f_c t}\sum_{k=0}^{N-1}a_k g(t)\exp(j2\pi f_k t);$ $a_K, k=0,1,2,....,N-1,$ is complex data symbol, T = OFDM block duration, $g(t)$ = pulse shape, f_c = carrier frequency.	None	None	None

CHAPTER V

Conclusion and Recommendations

The analysis carried out in this study on the various types and schemes of DMTs reveals the fact that selecting a DMT is solely and especially dependent on specific and various application. One of the reasons is because some of these MTs provides lesser difficulties or complexities when designing the modulation as well as demodulation systems coupled with the fact that they have proven to be economical. MTs like BPSK, BASK, BFSK and DPSK can be visualized and employed for applications that does not really need high amount or level of precisions, or probably when considering the economical aspect since the performances with respect to BER can be tolerated.

Importantly, whenever any system designer is solely considering to employ MTs like BPSK, BASK, BFSK and DPSK for some particular reasons like cost and implementation he should not neglect considering the fact that there are better and more reliable MTs like GMSK, QPSK and MSK, where GMSK has been proven to be far much better than MSK & GMSK in terms of performance in the area or field of mobile communication as a result of its high spectral efficiency though still inferior when compared to OFDM.

On the other hand, it is important to note that the earnest pursuit for a better MT is not just the criterion or standard for higher data rate communication which is taking the frontline in virtually almost all areas of communication but the realization of ISI and BER also should be taken into consideration as it is an aspect that is very crucial and important especially for the future of any DMT.

When the facts listed above are taken into consideration, designing a DCS can be extremely trivial and rather more highly application oriented. In terms of data reception, there are some applications that may demand higher precision whilst some others may compromise regarding this particular aspect but might be extremely rigid on other aspects such as available power or bandwidth. Hence, parameters like power, modulation bandwidth, BER and channel noise becomes extremely important parameters to be taken into consideration when designing wireless or digital CS.

Future Works/Recommendations

OFDM has proven to be a good multi-carrier multiplexing modulation technique especially in the GSM and cellular networks, it is yet limited and has a number of defects that can be possibly improved on. Other promising modulation techniques and multiplexing multi-carrier systems such Universal Filtered Multi-Carrier (UFMC), Filter Bank Multi-carrier (FBMC) as well as many others can be examined and investigated regarding their application in the mobile or cellular communication system.

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