Design and Analysis of OFDM System for Powerline Based Communication

by

Miss Noushin Karimian

A thesis submitted in partial fulfilment for the requirements of the degree of MSc (by Research) at the University of Central Lancashire

2011

Abstract

Research on digital communication systems has been greatly developed in the past few years and offers a high quality of transmission in both wired and wireless communication environments. Coupled with advances in new modulation techniques, Orthogonal Frequency Division Multiplexing (OFDM) is a well-known digital multicarrier communication technique and one of the best methods of digital data transmission over a limited bandwidth.

The main aim of this research is to design an OFDM modem for powerline-based communication in order to propose and examine a novel approach in comparing the different modulation order, different modulation type, application of Forward Error Correction (FEC) scheme and also application of different noise types and applying them to the two modelled channels, Additive White Gaussian Noise (AWGN) and Powerline modelled channel. This is an attempt to understand and recognise the most suitable technique for the transmission of message or image within a communication system. In doing so, MATLAB and embedded Digital Signal Processing (DSP) systems are used to simulate the operation of virtual transmitter and receiver.

The simulation results presented in this project suggest that lower order modulation formats (Binary Phase Shift Keying (BPSK) and 4-Quadrature Amplitude Modulation (QAM)), are the most preferred modulation techniques (in both type and order) for their considerable performance. The results also indicated that, Convolutional Channel Encoding **(**CCE)-Soft and Block Channel Encoding **(**BCE)-Soft are by far the best encoding techniques (in FEC type) for their best performance in error detection and correction. Indeed, applying these techniques to the two modelled channels has proven very successful and will be accounted as a novel approach for the transmission of message or image within a powerline based communication system.

Keywords: Digital communication, OFDM, FEC, AWGN, Powerline, DSP, PSK, QAM, CCE and BCE

Acknowledgements

First and foremost, I would like to acknowledge the assistance given to me by my academic supervisor, Dr. Javad Yazdani, and gratefully thank him for kindness and providing me with everyday motivation, persuasion and support, thoughtful suggestions, perceptive comments and observant guidelines.

I would also wish to thank Professor Shark for his enlightening suggestions and advices.

My especial gratitude goes to Dr. Martin Varley for his continuous support, assistance, and guidance in the past 4 years of my studies.

I would also like to express my appreciation to Dr. Bogdan Matuszewski, dean of the school Mr. Rob Wallace, and all members of staff of the School of Computing, Engineering and Physical Sciences who have assisted me in any capacity during past four years.

My special thanks go to my family especially my father, Dr. Hassan Karimian, my mother, Mrs. Frouhandeh Sanai, my dear brother Dr. Shokrollah Karimian and my dear sister Miss Simin Karimian who is a PhD student at University of Leeds, for their help, support, encouragement and patience during my studies.

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Acronyms

ADSL: Asymmetric Digital Subscriber Line

ANN: Artificial Neural Network

APK: Amplitude-Phase Keying

ASK: Amplitude Shift Keying

AWGN: Additive White Gaussian Noise

BCE: Block Channel Encoding

BER: Bit Error Rate

BPSK: Binary Phase Shift Keying

CCE: Convolutional Channel Encoding

CENELEC: Committee for Electro-technical Standardisation/Comité Européen de Normalisation Électrotechnique

CP: Cyclic Prefix

CPFSK: Continuous-Phase FSK

CPM: Continuous Phase Modulation

CS: Complementary Sequences

DAB: Digital Audio Broadcasting

DBPSK: Differential BPSK

DFT: Discrete Fourier Transform

DQPSK: Differential Quadrature PSK

DSP: Digital Signal Processing

DVB: Digital Video Broadcast

ECC: Error Correction Coding

FEC: Forward Error Correction

FFT: Fast Fourier Transform

FSK:	Frequency Shift Keying
FPGA:	Field-Programmable Gate Array
HDV:	High Definition Video
HF:	High-Frequency
HIPERLAN:	High Performance Local Area Network
HOL:	Higher Order Logic
ICI:	Inter-Carrier Interferences
IDFT:	Inverse Discrete Fourier Transform
IFFT:	Inverse Fast Fourier Transform
ISI:	Inter Symbol Interference
IN:	Impulsive Noise
I-Q:	In-phase and Quadrature
ITU-T:	International Telecommunication Union
MAN:	Metropolitan Area Network
MC:	Multi-Carrier
MIMO:	Multiple-Input Multiple-Output
OFDM:	Orthogonal Frequency Division Multiplexing
OOK:	On-Off Keying
O-QAM:	Orthogonal- Quadrature Amplitude Modulation
PAM:	Pulse Amplitude Modulated
PAPR:	Peak to Average Power Ratio
PDF:	Probability Density Function
PLC:	Powerline Communication
PSK:	Phase Shift Keying
QAM:	Quadrature Amplitude Modulation
RLS:	Recursive Least Squares
RMS:	Root Mean Square

SER:	Symbol Error Rate
S-FSK:	Spread-FSK
SGT:	Smart Grid Technology
SNR:	Signal to Noise Ratio
STBC:	Space–Time Block Code
WLAN:	Wireless Local Area Network

Chapter 1

Introduction

1.1. Digital Communication Systems

Digital communication system is a system in which information is conveyed from one point to another by using a finite set of discrete symbols. This system has been the subject of numerous research over the past fifty years of its introduction. As such, during the last three decades, the development and use of digital communication systems, has extensively increased and are still becoming more and more attractive due to the ever increase in demand for data communication, ease of regeneration of digital signals, high flexibility and availability of options for data processing in comparison to analogue transmission [1, 2]. Block diagram of a typical digital communication system is shown in Figure 1.1.

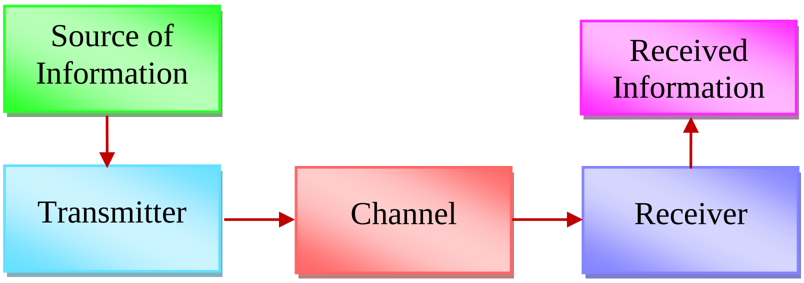


Figure 1.1. A standard digital communication system

When a digital signal or so called ideal binary digital pulse, propagates along a digital transmission line as depicted in Figure 1.2, two basic mechanisms greatly affect the shape of the waveform by degrading the pulse shape as a function of line length [2]: (i) As all transmission lines and circuits have some non-ideal frequency transfer function, there is a distorting effect on the ideal pulse; and (ii) Unwanted electrical noise or other interferences further distort the pulse waveform.

As illustrated in Figure 1.2, whilst the transmitted signal can still be reliably identified, before it is degraded to an ambiguous state, the signal is amplified by a digital amplifier that recovers or regenerates its original ideal shape. Circuits responsible for performing this function at regular intervals along a digital transmission system are known as regenerative repeaters [2].

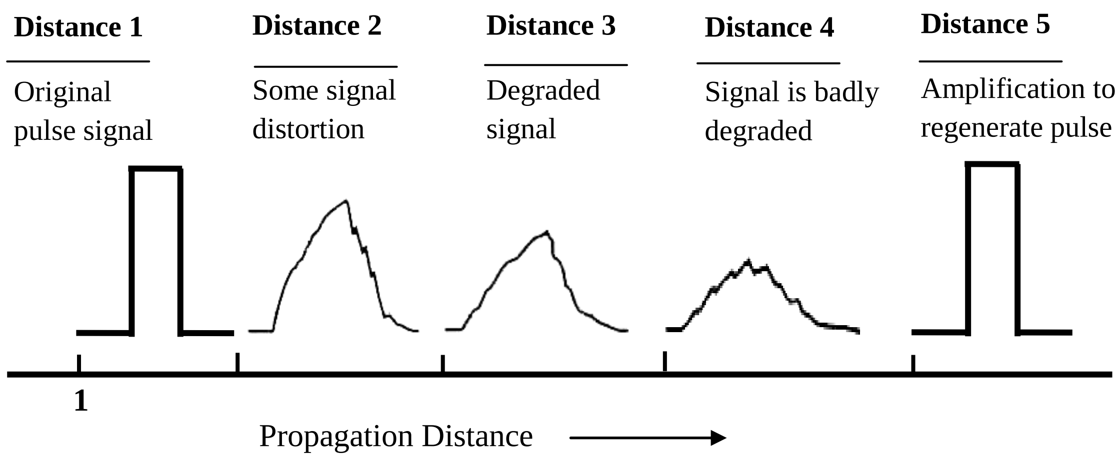


Figure 1.2. Signal degradation and regeneration [2]

One of the main advantages of digital communication systems is that they are less subject to distortion and interference, in comparison to analogue communication systems, as binary digital circuits operate in one of the two states (i.e. state 0 or 1) and hence disturbance must be large enough to change the circuit operating point from one state to the other. Such two-state operating systems ease signal regeneration and thus prevent noise and other disturbances from accumulating in transmission. In addition, with digital techniques, extremely low error rates producing highly reliable signals are possible through error detection and correction [2]. In addition to the mentioned advantages, digital communications has some other important advantages as follows:

- Digital circuits available in digital communications are reliable and can be produced at low cost

- Digital hardware lends itself to flexible implementation
- Digital communication techniques offer themselves naturally to signal processing functions that protect against interference and jamming, or that provide encryption and privacy
- A great deal of data communication can be carried out, from computer to computer, or from digital instruments or terminal to computer. Such digital terminations are naturally best served by digital communication links

Digital communication systems need to allocate a significant share of their resources to the task of synchronisation at various levels. Despite all the advantages, there exist one main disadvantage of facing degradation, as value of Signal-to-Noise Ratio (SNR) drops below a certain threshold, the quality of service can change from very good to very poor [2]. An indication of receiver and transmitter sub-systems in a typical digital communication system is illustrated in Figure 1.3; for which the appropriate blocks used in this project are further discussed in Chapters 3 and 4.

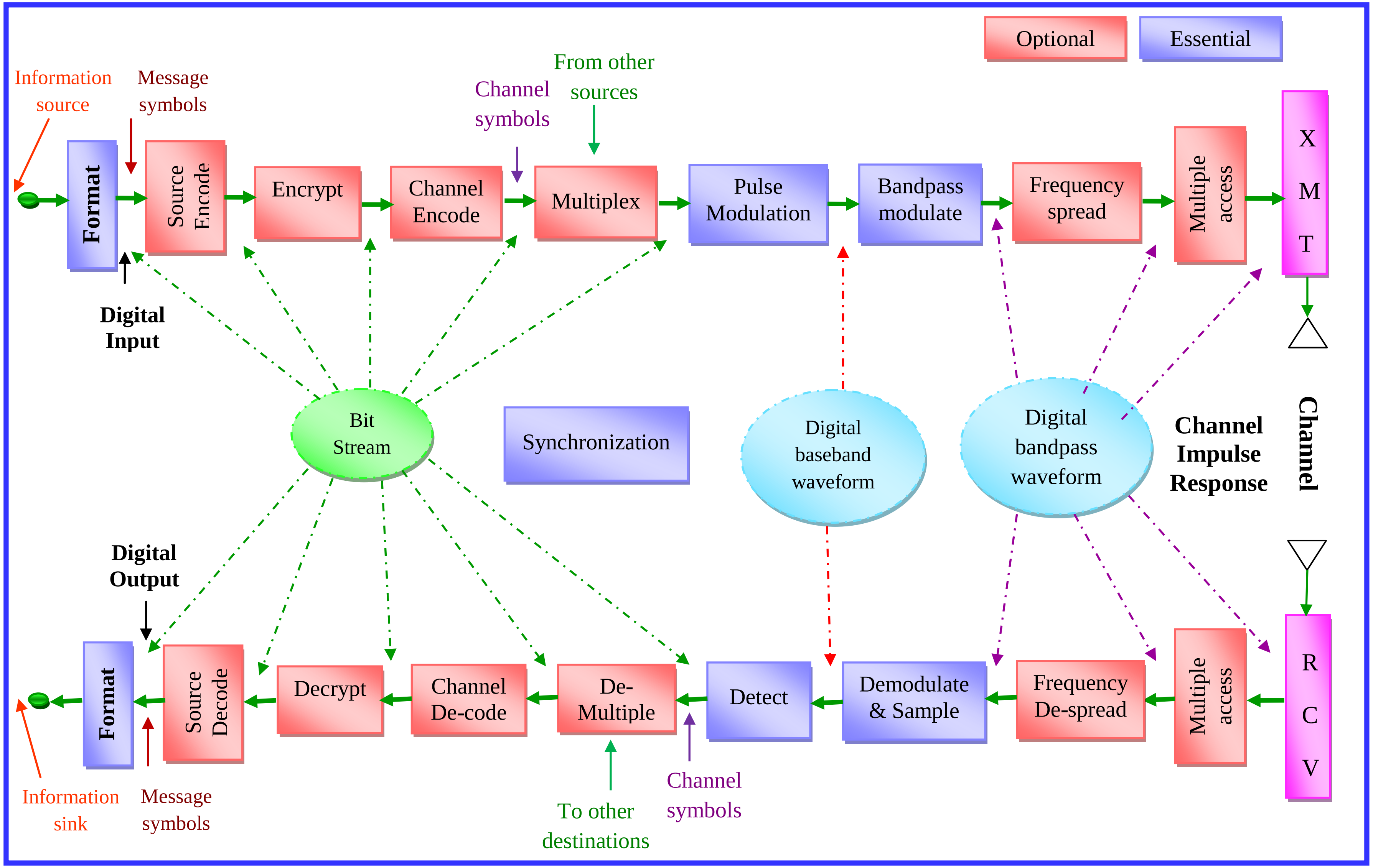


Figure 1.3. An indication of receiver and transmitter sub-systems in a typical digital communication system [2]

1.2. Orthogonal Frequency Division Multiplexing (OFDM) Communication Systems

Among the techniques that have been used to design a digital communication system, Orthogonal Frequency Division Multiplexing (OFDM) has been referred to as one of the most advantageous technique. OFDM systems have been widely recognised as a bandwidth efficient transmission technique for wireless communications. This multi-carrier transmission technique has been gaining more and more interest from communications and signal processing communities [3].

The main idea of these systems is that the whole bandwidth is divided into much smaller sub-bands whilst preserving orthogonality between the bands, using Fast Fourier Transform (FFT) and its inverse (IFFT). The main motivation of this band division is to mitigate the Inter Symbol Interference (ISI) problems associated with the wide-band transmissions available in frequency selective channels [4].These concepts and associated problems will be further explained in Chapters 2 and 3.

OFDM is sometimes referred to as a frequency-domain approach to communications, and has important advantages when dealing with the frequency-selective nature of high data rate communication channels. In addition, it benefits from a high spectral efficiency, simple implementation, strong multipath tolerance, robust against narrow-band co-channel interference and channel fading etc. Moreover, one of the main advantages of using OFDM technique is that the transmission signal is affixed with the cyclic prefix (CP), assisting it in counteracting the effects of delay. However, in addition to its important advantages, OFDM has number of disadvantages, such as the loss of bandwidth due to guard time, large Peak to Average Power Ratio (PAPR) and its prone to frequency and phase offset errors.

Employing the above mentioned benefits, OFDM has extensively been developed into well-admired schemes for wideband digital communication systems including Wireless Local Area Network (WLAN), Asymmetric Digital Subscriber Line (ADSL), International Telecommunication Union (ITU-T) and Metropolitan Area Network (MAN) [5-8]. As the demand for operating with higher data rates is exponentially increasing, OFDM system is now emerged as an effective physical-layer solution in their environment [9].

1.3. Powerline Communication (PLC) Systems

Powerline Communication (PLC) systems are considered to be amongst one of the main technologies that can contribute in formation of Home Networks and recently energy management in Smart Grid Technology (SGT), which uses the existing power cable infrastructure for communication purposes [10, 11]. Although some of the technical challenges in PLC systems are yet unresolved in terms of regulatory bodies and standardisation, however PLC is still considered as one of the strong competitors in the broadband communication market for in-building networking. PLC systems are demanded for wide availability, ability for transmission of high data rate with associated services (internet, high definition video (HDV), video on demand etc.), ease of use, and low infrastructure cost, assuming that the power cables are already installed for energy distribution purposes [12]. It is now rewarding to see that the deployment of PLC in SGT in terms of communication over the National Grid and its associated networks, is being considered by researchers in this area.

However, like all other technologies, PLC systems also face their own set of obstacles and technical challenges. Powerline channel may sometimes appear as a harsh environment for communication signals with high frequency and low power, the medium used is often subjected to many interfering noise such as stationary, cyclo-stationary or impulsive noise generating devices. Bit errors in PLC systems originate from one of the main sources of interference, known as Impulsive Noise (IN). Impulsive noise mainly occurs for a fraction of time and may be characterised by its duration, inter-arrival time and magnitude [13, 14]. In order to overcome these obstacles and interferences, many efforts have been made in characterising and modelling the PLC channels. In this research, PLC channel is modelled with various noise characteristics; further details can be found in both literature review and Chapter 5.

Despite wide use of the OFDM in conjunction with (or without) other techniques, limited cases of its application in powerline networks have been reported. It is believed that there is a great potential for this technique to be employed in PLCs, and as such the main focus of the current research is channelled to this goal. Therefore, the particular concern of the present project is to design an OFDM modem for powerline based communication, by achieving the objectives outlined below.

1.4. Aim and Objectives

The research aim of this project is to design and implement an OFDM communication link for PLC system, using platforms such as MATLAB to simulate the operation of virtual transmitter and receiver. The performance of the system design is then analysed by adding noise (Additive White Gaussian Noise and Powerline Coloured Background Noise) in an attempt to corrupt the signal. The research objectives of this project are as follows:

- **Objective 1:** A basic structure of a modem, using binary Phase Shift Keying (PSK) to be designed and tested to build an understanding of the blocks of modulation and demodulation used in digital modems

- **Objective 2:** Using knowledge gained from objective 1, to design and build a more comprehensive OFDM modem

- **Objective 3:** The functioning of the communication link with respect to OFDM will be investigated by utilising Cyclic Prefix/guard time, to assist in counteracting the effects of delay, ISI and Inter-Channel Interference (ICI)

- **Objective 4:** Analyse the performance of the OFDM modem using Additive White Gaussian Noise channel (AWGN)

- **Objective 5:** To conduct comparative performance studies using the Bit Error Rate (BER) plots from numerous simulations scenarios (i.e. having different modulation types, different modulation orders such as ***n***PSK, ***n***-Quadrature Amplitude Modulation (QAM), different types of channel coding etc.)

- **Objective 6:** Additional analysis to test the performance of the OFDM modem will be conducted to examine the effect of noise, initially using AWGN and subsequently with other types of noise (Powerline coloured background noise)

- **Objective 7:** Full functioning OFDM modem will be used for image transmission

A basic structure block diagram of an OFDM modem for this research project is shown in Figure 1.4.

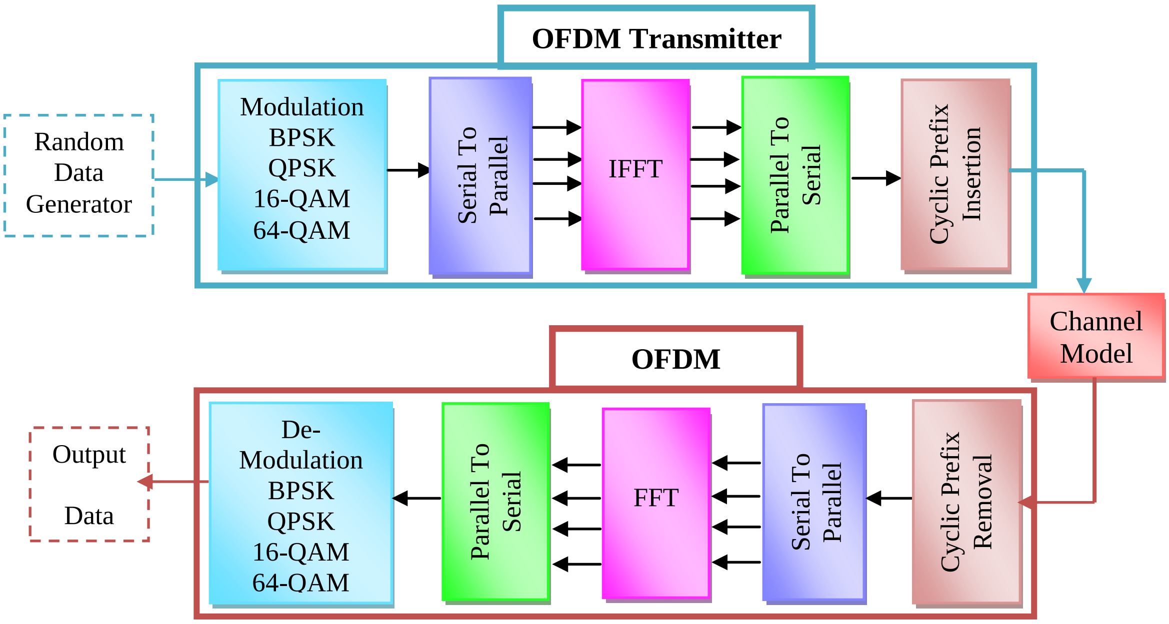


Figure 1.4. OFDM Block diagram

In achieving the stated aims, platforms such as MATLAB will be used to simulate and therefore obtain the required outcome for each of the above objectives. In doing so, initially a fundamental OFDM modem will be designed containing the transmitter, channel and receiver. Later, a more comprehensive OFDM will be designed and simulated, followed by additional analysis to test the performance of OFDM modem in presence of noise. A more detailed methodology and approach in achieving the stated aims and objectives will be explained in Chapter 2.

1.5. Motivation and Contributions of the Thesis

There have been numerous research on the use of OFDM in wireless communication. Methods have also been introduced to improve its weaknesses such as high PAPR, high sensitivity to Doppler shifts and loss in spectral efficiency, many of which will be reviewed in Chapter 2, literature review. Although there have been number of works on employing the OFDM techniques in powerline communication, there still remains many unexplored areas and techniques to be discovered and improved.

This thesis, therefore, focuses on the design and analysis of OFDM system for powerline based communication. Different techniques will accordingly be investigated for achieving better performance. This will be accomplished by initially investigating the performance of the designed OFDM system for different modulation type and order. The next technique for examining the performance of the OFDM system would be the application of different types of Forward Error Correction (FEC) to the best performed modulation types and orders. Following the investigation of the above techniques, powerline modelled channel will be compared against the AWGN modelled channel, employing the best performed FEC type, modulation types and order.

In addition to the transmission of bits and following the comparative performance analysis studies of the OFDM modem different techniques and scenarios will be conducted. Later the transmission of an image using the FEC technique with the best modulation process will be considered.

Comparison of these techniques is a novel approach using different modulation order and type and FEC techniques when applied to the modelled channels such as AWGN and Powerline Coloured background noise. This attempts to understand and recognise the most suitable technique for the transmission of message or images within a communication system.

1.6. Organisation of the Thesis

In the present chapter an attempt has been made to provide a brief introduction to digital communication systems particularly highlighting OFDM communication system, and examining the demand for such technology as well as offering an explanation of the advantages that have given its significant interest. This was followed by an introduction to powerline communication, and later, the aims and objectives together with motivation and contribution of this project were discussed.

Chapter 2 presents the literature review with the aim of providing a background overview of the research carried out to date to establish a theoretical framework for design and analysis of OFDM system for powerline-based communication. The methodology and approach in achieving the stated aims is also outlined in Chapter 2.

The historical and theoretical background of OFDM, including the theoretical background to each of the OFDM blocks in the transmitter, as depicted in Figure 1.4, will be explained in Chapter 3. This Chapter will also contain the step by step results and discussions for the simulation of OFDM transmitter. Chapter 4 will similarly include the theoretical background and step by step results and discussions for the simulation of the individual building blocks of OFDM in the receiver.

Chapter 5 will include the simulation response of an overall OFDM system. In other words, it will present the comparative performance studies on a more comprehensive OFDM modem, by analysing different techniques and scenarios, theories of which will be explained in the same Chapter. These include the analysis of different modulation order, different modulation type, application of FEC scheme and also application of different noise types.

Finally, Chapter 6 concludes by highlighting the important findings and also provides future works by setting new research directions.

Chapter 2

Literature Review and Methodology

2.1. Literature Review

This section aims to provide a background overview of the research carried out to date, and to establish a theoretical framework for design and analysis of OFDM system for powerline based communication. It also defines research related key terms, definitions and terminologies such as communication system, OFDM, channel, noise and powerline. More specifically, this literature review identifies the already completed studies and models on the design of an OFDM modem or related studies in different environments.

Research conducted to date and publications on OFDM and powerline communication can be studied both chronologically and based on their subject area. In this section, an attempt has been made to introduce the research carried out based on their publication time and later in terms of their topics.

Traditionally communication can be referred to as the ability to send and receive messages. Communication systems, either analogue or digital, are designed to send messages or information from a source that generates the messages to one or more destinations. The field of communication system was originally recognised in the twentieth century, in which the first half of the century is known as the era of the evolution of analogue communication as most of the communication took place in the form of radio communication. This leaves the second half of the twentieth century recognisable as the era of the evolution of digital communication [15]. A block diagram of communication system model is presented in Figure 2.1.

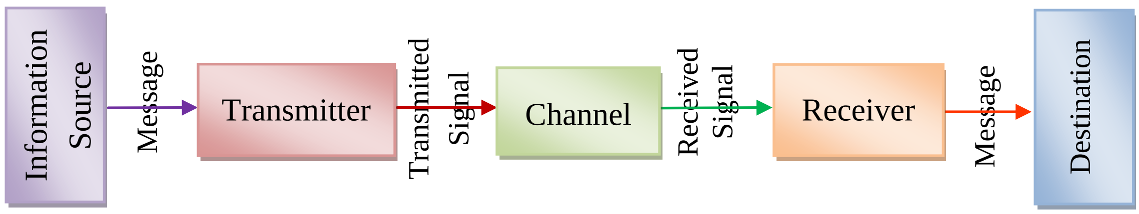


Figure 2.1. Basic model for functional block diagram of communication system

Introduction to such division of communication systems, i.e. the digital systems, has promised a better quality of transmission in both wired and wireless channels. Such communication systems were developed based on number of major needs within the already existing communication systems [15]:

I. A great demand in the transmission for a variety of forms and applications with a growing accuracy requirements
II. Continuous need for a synchronous digital communication with an ability to facilitate the worldwide communications at very high data rates. Evolution of such costly system with its bandwidth and power limitations, impose a major economic incentive on the efficient use of the channel resources [15]
III. The need for data communication network with the ability to provide simultaneous service to many users with variety of rates and requirements, in a situations of which the simple and efficient multiplexing of data and multiple access of the channels is a crucial concern for the economic [15]
IV. With the recent advancement in Digital Signal Processing (DSP), the required digital transmission signals become noise immune and processing of such digital signals become easier

Although the theoretical foundation to the digital communication system was initially laid in 1948 by C. E. Shannon through one of his publications titled "Mathematical Theory of Communication" [16], but in order to support the development of such digital communication systems, the stated requirements and the electronic technology were necessary and therefore were evolved simultaneously and in parallel during the third quarter of the 20^{th} century [15].

As described in Chapter 1, OFDM is a recognised digital multi-carrier (MC) communication technique, which divides the available channel bandwidth into many narrow bandwidth channel, referred to as subcarriers, where the data symbols are modulated and transmitted on each subcarrier simultaneously [8].

In comparison to the other digital communication techniques, OFDM in particular, is known to be one of the best methods for providing high data rates transmission over a limited bandwidth [8, 17]. In other words, OFDM is a bandwidth-efficient signalling scheme for wideband digital communication, which allows the transmission of digital data over channels with particularly harsh characteristic [18, 19]. It is also worth mentioning here that, although OFDM is derived from a multiplexing technique, but it is mainly considered as a modulation technique.

One of the main advantages of such multi-carrier communication technique in comparison to the single carrier system is its robustness against frequency selective fading or narrowband interferences. This is due to the fact that in a single carrier system, a small interference or a single fade causes failure to the entire link, whilst this will only affect a small percentage of the subcarriers in the multicarrier systems, for which the Error Correction Coding (ECC) can be applied in order to correct the few affected subcarriers [20 - 22].

The performance of the OFDM synchronisation between the transmitter and receiver, in particular the accuracy of the frequency and timing error estimations, are of major and crucial importance on the overall OFDM system performance [23, 24]. A wide variety of techniques have been proposed for estimating and correcting both timing and carrier frequency offsets at the OFDM receiver [25, 26]. For instance, in OFDM systems, the task of the frame synchronisation is to align the FFT windows at the correct received samples. If this is not achieved, then the samples from the adjacent OFDM symbol can be included in the FFT block, resulting in ISI, causing distortion to the signals [27].

The idea of using the OFDM systems (sometimes termed as the frequency division multiplexing) and the primary application of OFDM, dates back to 1960s where it was largely used in military communications [28, 29], although some of its early development goes back to 1950s [21, 30]. Some of these military communication based research was completed by Bello [31], Zimmermann [32], Powers and Zimmerman [33], Chang and Gibby [34]. The reason for the use of OFDM in such application was the advantage of having a great potential to combat not only the ISI which was mainly caused by multipath, but also the impulsive noise and narrow band interferences [35]. ISI is an unavoidable consequence of OFDM communication system where at the early attempts of transmission, it was observed that the received signals were getting elongated and smeared into each other [36]. To mitigate and to some extend eliminate ISI almost completely; a guard time is introduced for each OFDM symbol. The guard time is chosen larger than the expected delay spread, such that multipath components from one symbol cannot interfere with the next symbol [37], more detailed background theories to these concepts and terminologies will be explained in Chapter 3.

In the early stages of the evolution of OFDM, many researchers contributed by applying a similar technique in different applications and environment. For example in April 1967, M. Zimmermann and A. Kirsch developed the AN/GSC-10 (KATHRYN)[1] with variable data rate modem for high-frequency (HF) radio [32]. Another study on this multi-carrier system was done in 1967 by Saltzberg. This was achieved by the use of orthogonal time staggered QAM (O-QAM) modulation of the carriers [29].

Other researchers such as Weinstein and Ebert in 1971 [38], Peled, Ruiz and Hirosaki in 1980 - 1981 [39-41], Kolb and Schussler in 1982 - 1983 [42, 43], Preuss in 1984 [44], Ruckriem and Cimini in 1985 [45, 46], Alard and Lassalle in 1987 [47] and Kalet in 1989 [48], largely contributed towards the basis of OFDM in different applications [48]. For instance in 1971, an idea to reduce the implementation complexity of OFDM modems through the use of Discrete Fourier Transform (DFT) was suggested by Weinstein and Ebert. This was achieved by employing the DFT technique in replacing the banks of sinusoidal generators and the demodulators [38]. Later in 1980, an equalisation algorithm approach was suggested by Hirosaki, in an attempt to decrease the number of interferences, explicitly the Inter-Carrier Interferences (ICI) and ISI, caused by either frequency and timing errors or channel impulse [40]. In the same year, an implementation to a simplified OFDM modem was considered by Peled [39]. The Orthogonal-QAM OFDM system studied in 1967 by Saltzberg, was further developed by Hirosaki in 1981, through introduction of the DFT-based implementation [41]. During 1982 to 1985, an additional research on the OFDM application were completed at the Erlangen University (Germany) by the researchers, namely Kolb [42], Schussler [43], Preuss [44] and Ruckriem [45].

Research completed in 1985 to 1987 by Cimini, Alard, B. Hirosaki, S. Hasegawa, A. Sabato and Lassalle presented that OFDM was mainly considered for a high-speed modems [46, 47, 50] and specifically in digital mobile wireless communications [46].

Also in 1985 and 1989, number of research was completed by Cimini [46] and Kalet [48] respectively, in which OFDM modem performance in the mobile communication channels were investigated through the analytical and experimental results [49].

[1] The AN/GSC-10 (KATHRYN) digital data terminal is known as modem equipment for digital data transmission on high-frequency radio circuits [32].

As result of large amount of research on OFDM, and due to unquestionable proof of its reliability and performance, the OFDM technique was standardised as the European Digital Audio and Video Broadcast (DAB - DVB) scheme [49, 51- 54]. In addition, OFDM is now one of the most trusted technique used as part of the IEEE 802.11 Wireless Local Area Network (WLAN) standard as well as being decided as the High Performance Local Area Network's (HIPERLAN) transmission technique [49, 55].

The beginning of last decade (in 1990s and early 2000s), OFDM was enhanced in terms of functionality and performance by many techniques including its combination with other emerging techniques such as Multiple-Input Multiple-Output (MIMO) schemes, etc. [49, 56-63], though MIMO has not been employed in this research. It can therefore be said that, OFDM in conjunction with other diversity of methods such as MIMO and Space–Time Block Code (STBC) has proven to be the logical choice for consideration beyond 3G wireless systems [24, 56, and 63].

In 1995, Pollet, Bladel and Moeneclaey designed an OFDM with the ability to reduce the complexity of tasks such as equalisation and channelling estimation in systems where the bandwidth of the channel is wide, when compared to classical (non-OFDM) approaches [24]. Research on channel estimation was carried out later by several scholars, many of which attempted to use the neural network as an approach to investigate the channel estimation in an OFDM system [64-69].

In 1997, Fazel and Fettweis produced an impressive edited work on some of the recently advanced research on OFDM transmission, completed in different universities of Europe [70]. Two of the main publications from this collection of works are published by Classen and Meyr in 1994 which focuses on the synchronisation algorithms for an OFDM system for both mobile communications [71] and communication over frequency selective fading channels [72]. In addition to some of the already completed research on design of OFDM, its application on different environment and its conjunction with other diversity of methods, it is also worth mentioning that one of the recent important references on the OFDM for Wireless Multimedia Communications was published in 2000, by Nee and Prasad [27].

In 2000, A.J. H. Vinck and J. Haring, G. Lindell have tried to explore the knowledge in coding and modulation for powerline communication [73 - 75].

Following the fundamental research on OFDM, it was then discovered that the orthogonality could be obtained and maintained. This was achieved by mitigating ISI using Inverse Discrete Fourier Transform (IDFT) and adding cyclic prefix, as depicted in Figure 2.2 [37]. These techniques are indeed employed in the present research.

Another research has proposed the CP based block Recursive Least Squares (RLS) algorithm [76] for MIMO-OFDM channel estimation.

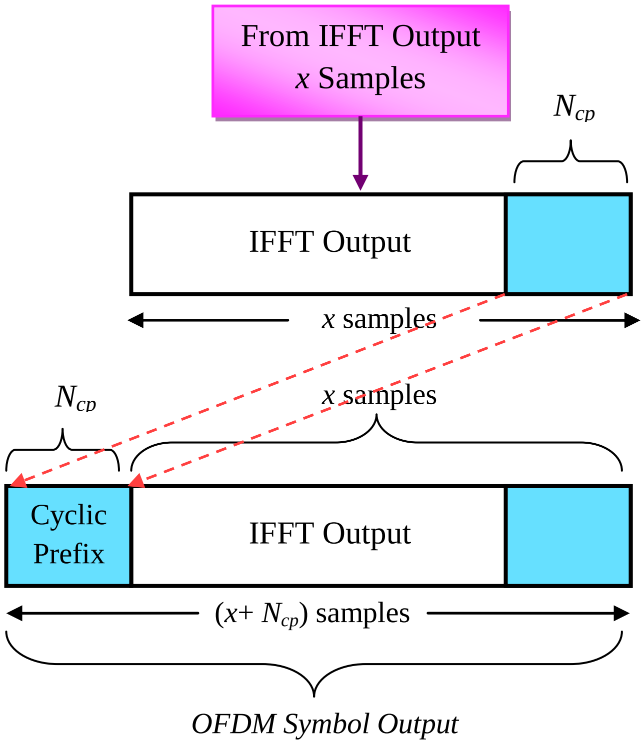


Figure 2.2. Cyclic Prefix addition

Research and publications have exponentially increased up to the present year. As such, some have applied the Artificial Neural Network (ANN) to an OFDM system with the aim of improving the performance of the system [77 - 84]. It is important to note that in the recent years, there have been many OFDM based standards. Further details and review of milestone and some of the important stated contributions on OFDM are illustrated in Table 2.1.

Table 2.1. Summary of milestone and some of the important stated contributions on OFDM [49]

Year	Name of Contributors	Milestones and Some of the Contributions on OFDM	References
1966	Chang	Presented the first OFDM scheme for the dispersive fading channels.	[28]
1967	Saltzberg	Considered the first ‘Orthogonal QAM (O-QAM).	[29]
1968	R. Chang and R. Gibby	Investigated a theoretical study of performance of an orthogonal multiplexing data transmission scheme.	[34]
1970	_	U.S. patent on OFDM issued.	[85]
1971	Weinstein and Ebert	Applied DFT to OFDM modems.	[38]
1980	Hirosaki	A sub-channel-based equaliser was designed for an orthogonally multiplexed QAM system.	[40]
	Keasler et al.	Illustrated the OFDM modem for telephone networks.	[86]
1981	Hirosaki	Designed an orthogonally multiplexed QAM system using the discrete Fourier transform.	[41]
1985	Cimini	Investigation on the viability of OFDM in mobile communications was carried out.	[46]
1986	B. Hirosaki, S. Hasegawa, A. Sabato	Worked on advanced group-band data modem using orthogonally multiplexed QAM technique.	[50]
1987	Alard and Lasalle.	The OFDM for digital broadcasting was used.	[47]
1991	_	ANSI ADSL standard.	[87]
1994	_	ANSI HDSL standard.	[88]
	Classen and Meyr	Focused on the synchronisation algorithms for an OFDM system for mobile communications.	[88]

	Classen and Meyr	Investigated the frequency synchronisation algorithms for OFDM systems suitable for communication over frequency selective fading channels.	[72]
1995	T. Pollet, M. Van Bladel, and M. Moeneclaey	Investigated the BER sensitivity of OFDM systems to carrier frequency offset and wiener phase noise.	[24]
	_	ETSI DAB standard: The first standard for OFDM in digital broadcasting systems.	[53]
1996	_	ETSIWLAN standard.	[55]
1997	Fazel and Fettweis	Produced an impressive edited work on some of the recently advanced research on OFDM transmission.	[70]
	_	ETSI DVB-T standard.	[54]
1998	_	ANSI VDSL and ETSI VDSL standards.	[89, 90]
	_	ETSI BRAN standard.	[91]
1999	_	IEEE 802.11a WLAN standard.	[92]
2000	B. Muquet, M.de Courville, P.Duhame and G. Giannakis	investigated on equalisation using the cyclic prefix concept.	[93]
	A.J. H. Vinck and J. Haring, G. Lindell	Tried to explore the knowledge in coding and modulation for powerline communication’.	[73 – 75]
2002	_	IEEE 802.11g WLAN standard.	[94]
2003	S. Aghajeri, H. Shafiee	Investigated the synchronisation for OFDM communication systems.	[95]
	_	ETSI DVB-H standard.	[96]
	_	IEEE 802.16 WMAN standard.	[97]
2004	_	In this year OFDM was selected as a candidate for IEEE 802.11n standard for next generation WLAN.	[98]

	_	It was again selected as a candidate for IEEE 802.15.3a standard for WPAN (using MB-OFDM).	[99]
	S. Kunaruttanapruk and S. Jitapunkul	Investigated on the channel equalisation by using ‘feedback equalisation’.	[100]
	T. Han and X. Li	Worked on the channel equalisation by using ‘blind adaptive equalisation’.	[101]
	S. Lerkvaranyu, K. Dejhan and Y. Miyanaga	Have applied the Artificial Neural Network (ANN) to an OFDM system.	[77]
2005	_	It was selected as a 4G standard candidate in China, Japan and South Korea (CJK).	[102]
2006	L.V. Ninh, T.A. Vu, H.T.Huynh and P. Fortier	Investigated the synchronisation for OFDM communication systems.	[103]
	E. Chen, R. Tao, X. Zhao	Worked on the channel equalization for OFDM System based on the Back Propagation Neural Network (BPNN)	[104]
	Qi Lu, Lin Gui, and Xiang-Zhong Fang	Used neural network for the channel equalisation of OFDM Systems.	[105]
2007	B. Naeeni, H. Amindavar	Used neural network for the channel equalisation of OFDM Systems.	[106]
	N. Rodriguez and C. Cubillos	Worked on the Orthogonal Neural Network Based Predistortion for OFDM Systems	[78]
2008	M. Jiang, C. Li, H. Li and D. Yuan	Studied the Channel Tracking Based on Neural Network and Particle Filter in MIMO-OFDM System	[79]
2009	J. Kassab and Dr. S. Nagaraj	Examined the adaptive modulation in an OFDM communications system with artificial neural networks.	[80]
	Qingyi Quan	Studied the Multilevel Hopfield Neural Network for OFDM System with Phase Noise,	[81]

2010	H. Yigit and A. Kavak	Worked on the Adaptation using Neural Network in Frequency Selective MIMO-OFDM Systems	[82]
	R. Zayani, R. Bouallegue and D. Roviras	Studied the Crossover Neural Network Predistorter for the Compensation of Crosstalk and Nonlinearity in MIMO OFDM Systems	[83]
2011	F. Meucci, L. Pierucci and N. Prasad	Researched on the Identity Theft Detection Based on Neural Network Non-Linearity Identification in OFDM System	[84]

As illustrated in Table 2.1, most of the research was carried out on the methods of modulation and improvements on the weakness of OFDM systems since 1966. It is therefore believed that there is a great potential for these techniques to be employed in a well- recognised communication systems such as PLC system.

The powerline network is a well-established, large pervasive infrastructure covering most parts of the inhabited areas, and has been used as a communication medium, providing the ability of transferring data over the powerline for many years [107, 108].

In the last twenty years, the powerline technology has gained an enormous interest for the power communications, due to an increase in demand for better services for both residential and industrial [109]. Lately, applications such as home automation, home LAN and Internet access have drawn more attention to the use of in-building powerlines. Since, powerline cables are not specifically designed for the communication use, they therefore, provide challenges for modem designers. As a result, frequency selectivity and time variation of the powerline channel, high levels of noise and regulatory issues have become some of the main concerns [40, 110].

In addition, like all other communication systems, PLC systems are also at risk of internal or external noise and disturbances. Powerline noises can be classified into 5 categories of [11]:

I. Coloured background noise

II. Narrow band noise

III. Periodic impulsive noise asynchronous

IV. Periodic impulsive noise synchronous

V. Asynchronous impulsive noise

Other communication systems might also disturb the communication, thus introducing noise at the receiver. Some of the noise measurement techniques and challenges that have been dealt within this project can be found in [111 – 117].

The particular concern of the present project is an OFDM modem design, as it is a necessary component of the communication system. A modem may be referred to as a communication device that converts binary signal into analogue signals for transmission over communication channel, as illustrated in Figure 2.3, and converts these signals back into binary form at the receiving end. Conversion to analogue signal is known as modulation; conversion back to binary signal is known as demodulation; hence the word modem [118].

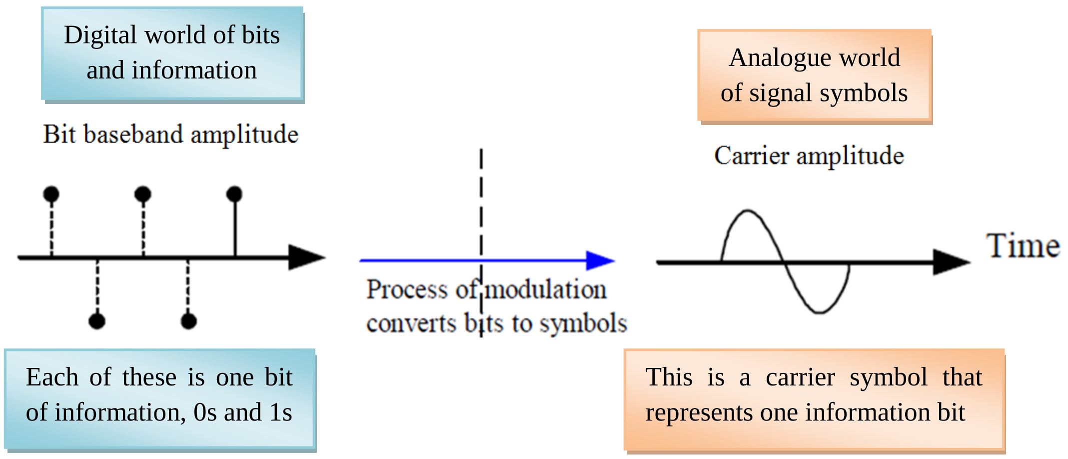


Figure 2.3. Modulation process of converting binary signal into analogue signals for transmission over communication channel

There have been a number of studies performed over the years that have attempted to design or analyse an OFDM modem for various applications and under different conditions. For instance, in [119] an integrated PLC-modem based on OFDM has been designed which contains mostly a digital circuit with an analogue front end. Another research [120] involves design of a high speed OFDM modem system for powerline communications. The designed modem is compatible with Home-Plug standards. The research has investigated the modulation of subcarriers by means of Binary Phase Shift Keying (BPSK), Differential BPSK (DBPSK) or Differential Quadrature PSK (DQPSK).

An idea that will be valuable for the current research project is the demodulation techniques that are used in [120], where the demodulation of BPSK is done by the use of constellation position, and the demodulation of DBPSK and DQPSK is done using [120]:

$$Z_s(k) = X_s(k).\ X^*_{s-1}(k) \tag{2.1}$$

Where:

- $Z_s(k)$ = Demodulated signal of the kth subcarrier in the sth symbol
- $X_s(k)$ = Modulated signal of the kth subcarrier in the sth symbol
- X^* = The conjugate of the modulated signal

As it can be seen from Equation 2.1, the s^{th} modulated symbol is multiplied by the conjugated $(s\text{-}1)^{th}$ modulated symbol, thus resulting in the demodulating the s^{th} symbol.

In 1999, Vinck and Haring provided an application of coding and modulation for PLC systems. In doing so, number of aspects of communication was discussed, followed by M-tone signalling modulation scheme, Spread-FSK (S-FSK) and the error control coding for packet transmission [121]. In the same year, Goffart and Boscand presented the result of an integrated PLC modem developed using S-FSK modulation [122] in an attempt to support communication on the powerline. The employed method in their design has allowed hardware and software to simulate in parallel to each other, which has resulted in a drastic reduction in the design lead time for this modem. There have been number of other studies, one of which considers the transmission of M-PSK and M-QAM modulated OFDM signals over an AWGN channel [24]. The degradation of the BER, caused by the presence of carrier frequency offset and carrier phase noise is also presented. This study has evaluated that OFDM is very sensitive to frequency offset and phase noise as:

- Sensitivity increases with the number of symbols
- Sensitivity increases with the number of symbols with the constellation size
- Higher sensitivity of OFDM as compared to for example single carrier, is caused by the *N* times longer duration of an OFDM symbol and by the ISI due to loss of the carrier orthogonality

The present idea of investigating the sensitivity of the OFDM will be taken forward from this research [24], and applied to the current research through the use of different constellation size; the result of which will be presented by the use of BER graphs.

A different research study has presented a frequency domain approach in order to characterise and model the statistical variation of powerline noise [11]; where it considers both the background noise and the impulsive noise. In the extensive study of [11], noise amplitude spectrum which describes the general trends of the noise with respect to time, and the probability distribution of the time-domain noise amplitudes (resembling the Nakagami-m distribution) have been explained. The Nakagami Probability Density Function (PDF) can be written as Equation 2.2:

$$p(r) = \frac{2}{\Gamma(\mathrm{m})}\left(\frac{m}{\Omega}\right)^{m} r^{2m-1} e^{-\frac{mr^2}{\Omega}} \tag{2.2}$$

Where:

- r: Random Variable
- p: The probability of the corresponding random variable
- $\Gamma(.)$: The Gamma function
- m: Ratio of the moments i.e. the closeness between the Nakagami and Rayleigh distribution

Simulation response of this research shows that the Nakagami PDF is exactly the same as the Rayleigh PDF when m = 1. However, when m > 1, the Nakagami PDF has smaller variance and larger mean than the Rayleigh PDF, and reverse is true when m <1. In the power network environment, although the average amplitude of the noise coming from a single source remains mostly unchanged, but as a result of its complex scattering in the network, the resultant noise at the receiver can be roughly regarded as the Rayleigh distribution [11]. Since the background noise is a combination of the Rayleigh distributed noise from multiple sources, it is reasonable to use the Nakagami PDF to represent the noise amplitude distribution. Therefore Equation 2.2 can be used for modelling and analysis of the effect of background noise in this research.

Another valuable idea which will also be reflected in the current research is the use of FFT operation in the OFDM receiver, in order to randomise the powerline noise, resulting in Gaussian distributed axis-PDFs [11]; proving the better performance of OFDM system when subjected to noise.

One method of modelling the powerline communication channels is presented by Holger Philipps in 1999, in which three different approaches have been suggested; namely the echo model, the series resonant circuit model and the noise model, details of which can be found in [123]. An additional research study [124] has used statistical analysis method to analyse the performance of OFDM system through an impulsive noise to corrupt the channel. In order to derive the impulsive noise model, an assumption that a large number of statistical independent interferers contribute to the noise has been taken into account. According to the bandwidth associated with each noise emitted by different interferers, Middleton classifies the noise in three general classes of A, B and C [125].

There have been number of studies performed based on the practical measurements, identifying the important parameters to be accounted when modelling a noise for a powerline environment. For instance, in 2003 a research study has identified that for a practical measurement of the residential powerline, three sets of statistical values are obtained [126]. Therefore these three parameters can be accounted as an important parameter when modelling a noise for the powerline environment.

- Noise Amplitude
- Noise Duration
- Time Interval

Another study has presented an experimental OFDM modem for the European Committee for Electro-technical Standardisation/Comité Européen de Normalisation Électrotechnique (CENELEC) B-Band, for which a concept of powerline communication system is presented, utilising the CENELEC B-band for a bidirectional transmission to achieve a maximum bit rate of 190 kbps [127]. This system uses the OFDM transmission technique which is known for its good performance in frequency selective channels as found in the powerline environments. Pem and Darnel have also used OFDM through Complementary Sequences (CS) for data transmission over non-Gaussian channels [128]. This study has shown that this method provides a capable way of designing modems.

In other studies, formal analysis and verification of OFDM modem design using Higher Order Logic (HOL) have been carried out; in which implementation of the IEEE802.11a standard physical layer based on OFDM modem have been verified [120]. Similarly, as part of the on-going research that is carried out on the use of OFDM in wireless communication systems, an increasing number of studies have been conducted to investigate the design of an OFDM modem in different environments [126, 129 - 131].

The author has noticed that, despite wide use of the OFDM in different environments and in conjunction with (or without) other techniques, limited cases of its application in powerline networks have been reported. Based on the research conducted to date, it is believed that there is a great potential for this technique to be employed in PLCs, and therefore has directed the main objectives of the current research to achieving this goal. The main focus of the present project is to design an OFDM modem for powerline based communication, employing the specified techniques drawn from the literature.

As it was stated above, research and publications related to the OFDM and powerline communication system can also be considered based on their topic as follow:

- Researches on the use of OFDM in wireless communication carried out to improve efficiency of the systems [3,4,5, 9, 19, 21, 27, 35-37, 46, 56 - 63, 126, 130, 131]
- Research on the methods of modulation and improvement on the weakness of OFDM systems [23 - 26, 34, 38, 40, 41, 47, 50, 70 - 85, 126, 129]
- Researches on employing the OFDM techniques in powerline communication [11, 119, 120, 121, 122, 124, 127, 128]

2.2. Methodology and Approach

This section provides the key tools, methods and strategies selected for achieving the stated aims. In doing so, researches and publications related to the OFDM and powerline communication systems have been classified into three groups based on their topics. Such classification of the publications provides assistance in selecting the best methods for the current project. Although the above presented research and publications, by some means, follow the same method or technique, but most of the valuable help and support for the current project can be obtained from the second, but largely from the third group of publications.

In order to achieve the stated aim and objectives, a high-level technical computing language called MATLAB® is used in order to design and implement the outlined OFDM communication system. The codes for these algorithms are written using the guidelines provided in [132-135]. The codes for design and its implementation employed in this project are provided in both the appendices and the enclosed CD.

MATLAB® is very powerful software that is widely used across all engineering disciplines, supporting various graphical input and outputs. Therefore producing efficient codes and making the simulation results easily illustratable in different graphical formats. MATLAB is also known an interpreted language for numerical computation as it allows one to perform numerical calculations without the need for complicated and time consuming programming. Another important advantage of using MATLAB is that it supports several file formats and extensions (for either Image or audio files). This will greatly help and validate the judgments with respect to the achieved results. Future work will enhance using this software in the form of its Simulink representation; it provides visual graphical control with easy changeability mechanism allowing parameters to be altered and outcomes can be graphically compared.

Beside all the stated advantages, MATLAB software has other advantages, in comparison to other programming languages such as C or C++, making it a better programming platform to use for this research. Unlike C or C++ programming, MATLAB uses standardised built-in routines, allowing it to be simulated on any MATLAB installation. In C programming, loops are often used, whereas MATLAB uses vectors which reduces the code lines and makes the codes simpler and easier to read. MATLAB is a good platform for developing algorithms from scratch, allowing the user to write the code and analyse it line by line.

The main research aim of this project is to design and implement an OFDM system for powerline based communication, by simulating the operation of virtual transmitter and receiver. The performance of the system design is then analysed by adding additive AWGN and Powerline Coloured noise, in an attempt to corrupt the signal. This principal aim can be achieved by considering and completing seven objectives which are methodically explained below.

In objective 1, a basic structure of an OFDM modem using the binary Phase Shift Keying (PSK) will be designed, containing three main elements of transmitter, channel and receiver. Figure 2.4 illustrates these three main elements as well as the two other important sub-units, modulation/ de-modulation and IFFT and FFT, in the transmitter and receiver respectively. The method of modulation and demodulation of the BPSK demonstrated by K.L. Heo, S.M. Cho, J.W. Lee, M.H. Sunwoo, and S.K. Oh in [120] and illustrated in Equation 2.1, will be taken forward and applied in this step of OFDM modem design

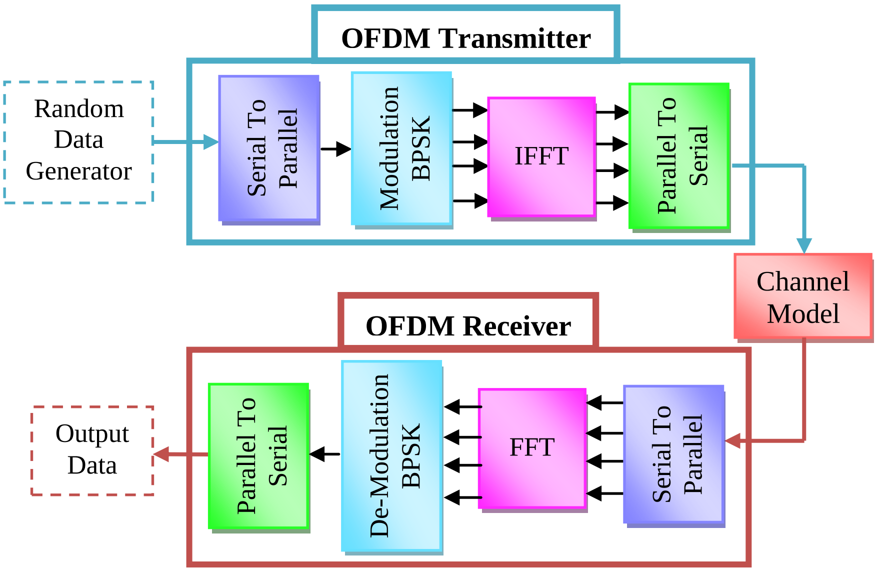


Figure 2.4. Block diagram of a basic structure OFDM transceiver

Following the design of a basic structured OFDM modem, it will be tested in order to understand the fundamental blocks of modulation and demodulation used in such digital modems. It is important to state that this research project will be based on a general assumption of having a perfect timing synchronisation between the transmitter and receiver. Subsequent to obtaining an exact replica of transmitted signal in the receiver unit, and using the knowledge gained from objective 1, a more comprehensive OFDM modem, as shown in Figure 2.5, can be designed and simulated (objective 2).

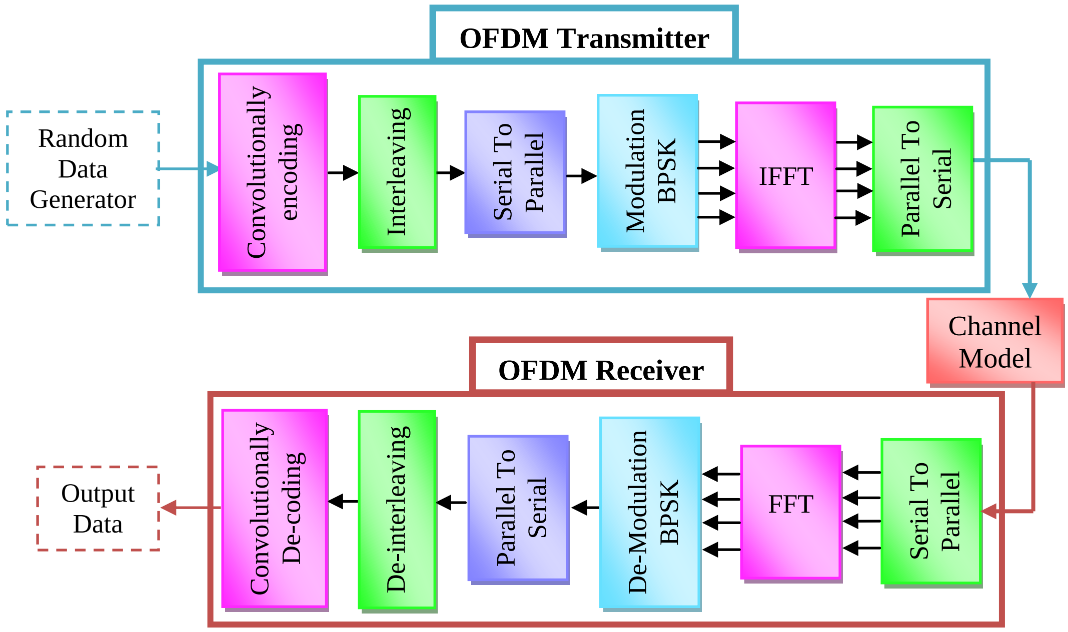


Figure 2.5. Block diagram of a more comprehensive OFDM transceiver

In objective 2, a more comprehensive structure of an OFDM modem using the BPSK will be designed, containing the three main elements of transmitter, channel and receiver. Figure 2.5 illustrates these three main units containing the important sub-units of modulation/ de-modulation and IFFT and FFT, Convolutional encoding/decoding, interleaving and de-interleaving in the transmitter and receiver respectively.

In objective 3, the functioning of the communication link with respect to OFDM will be investigated by utilising Cyclic Prefix to assist in counteracting the effects of delay, ISI and ICI. As it can be observed from Figure 2.6, a cyclic prefix has been inserted in the transmitter and then removed in the receiver part. A more detailed theoretical background to the Cyclic Prefix will be provided in Chapter 3.

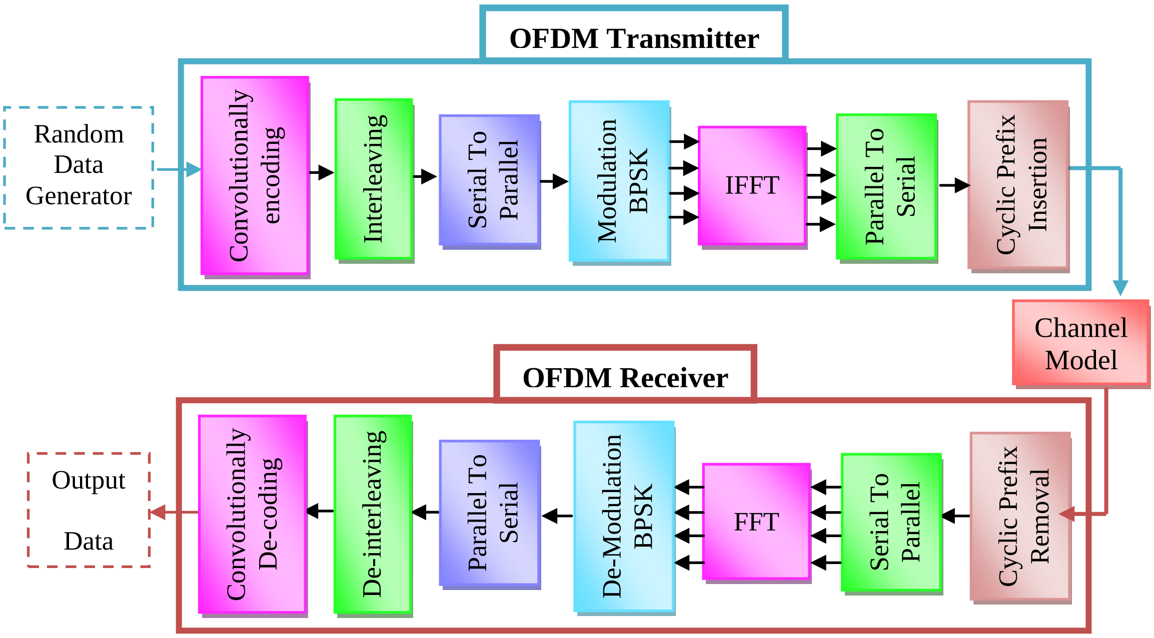


Figure 2.6. Block diagram of a more comprehensive OFDM transceiver with the Cyclic Prefix

In Objective 4, performance of the OFDM modem will be analysed by using AWGN. In other words, AWG noise will be modelled and applied to the channel, performance of which will be examined. This will be followed by applying and simulating numerous scenarios. This will be attained by initially investigating the performance of the designed OFDM system for different modulation type and order. The next technique for examining the performance of the OFDM system would be the application of different types of encoding techniques to the best performed modulation type and order, block diagram of which is illustrated in Figure 2.7. These techniques include:

- Different modulation types (PSK, QAM, FSK)
- Different modulation orders (BPSK, 4PSK, 8PSK, 16PSK, 256PSK, 4QAM, 16QAM, 64QAM, 256QAM etc.)
- Different types of channel coding (Forward Error Correction (FEC), Convolutional Channel Encoding (CCE) and Block Channel Encoding (BCE))

The results of these different modulation types and orders and different types of encoding will be compared by the use of Bit Error Rate (BER) plots in order to examine the most suitable technique for the designed OFDM modem. A detailed background to this comparison will be provided in Chapter 3.

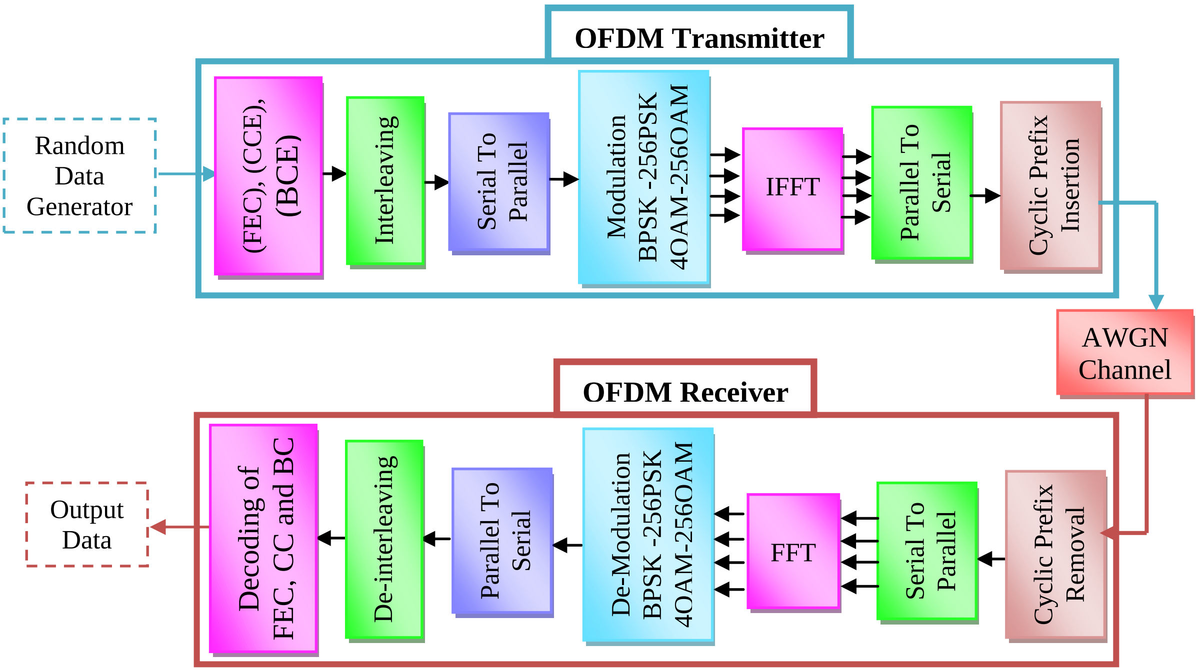


Figure 2.7. Block diagram of a more comprehensive OFDM transceiver with different modulation order, modulation type and different types of channel encoding

Following the successful investigation of the above techniques, powerline channel will be modelled. This will be achieved by modelling one type of powerline noise; the powerline coloured background noise have been selected for this research. As previously explained, the Nakagami PDF will be used to represent this type of noise amplitude distribution. In doing so, Equation (2.2) will be used in order to model the powerline channel for the present research. This will be followed by analysis of the effect of such background noise on the performance of the designed OFDM system. The analysis of the powerline modelled channel will be compared against the AWGN modelled channel, employing the best performed encoding type, modulation type and modulation order.

Once all the above aims have been achieved and therefore successful transmission of bits have been attained, the transmission of an image with the use of best encoding technique and best modulation type and order for image transmission, will be considered. This is done by initially reading a coloured (RGB) image, which has stored a three-dimensional (***m***-by-***n***-by-***3***) array of floating-point values in the range [0, 1]. This will then be converted to a gray scale image by (***m***-by-***n***-by-***1***), followed by resizing the image (e.g. to 240 x 240). The result of resized image will be reshaped with the aim of dividing it to some number of rows/columns (array of numbers) which could separately be transmitted across the system, where the selected encoding system and modulation types will be applied to it. A flow chart for the steps in the transmission of image is depicted in Figure 2.8.

2.3. Summary

In this chapter, an overview of the research carried out to date and theoretical framework for design and analysis of OFDM system for powerline based communication were studied and presented. This chapter also defined research related key terms, definitions and terminologies such as communication system, OFDM, channel, noise and powerline. More specifically it provided a literature review identifying the already completed studies and models on the design of an OFDM modem or related studies in different environments.

The research conducted to date and publications on OFDM and powerline communication were studied both chronologically and based on their subject area which can be divided into three categories as follow:

I. Researches on the use of OFDM in wireless communication carried out to improve efficiency of the systems
II. Research on the methods of modulation and improvement on the weakness of OFDM systems
III. Researches on employing the OFDM techniques in powerline communication

This chapter also provided the key tools, methods and strategies selected for achieving the aims. In doing so, the above classification of research and publications related to the OFDM and powerline communication systems provided assistance in selecting the best methods for the current project.

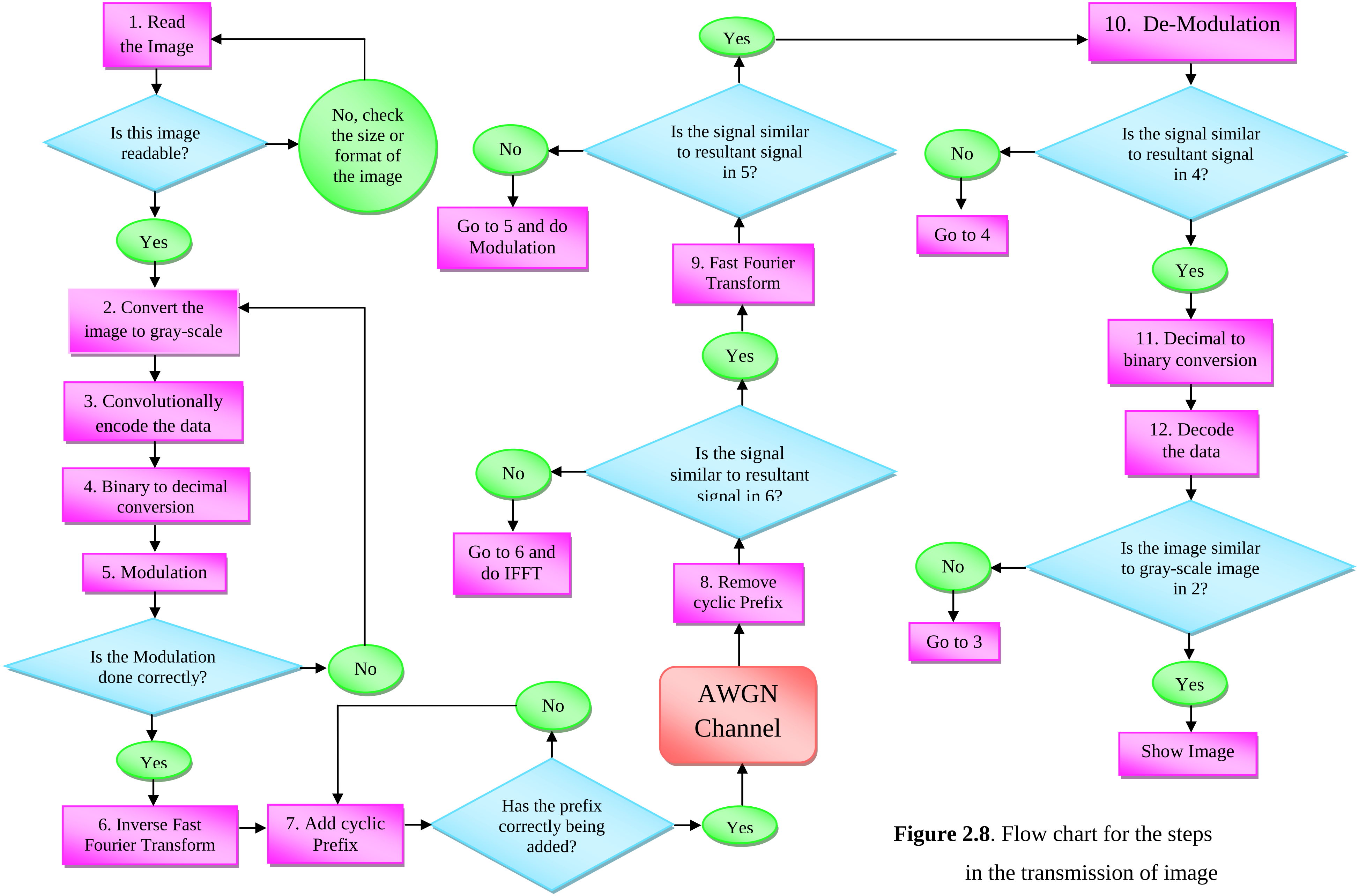


Figure 2.8. Flow chart for the steps in the transmission of image

Chapter 3

OFDM Transmitter and Simulation Results

First chapter presented a brief introduction to digital communication systems particularly OFDM communication system. An introduction to powerline communication systems, outline of aims and objectives of this project and motivation and contributions of the thesis were also covered in Chapter 1. A background overview of the research carried out to date containing the theoretical framework for design and analysis of OFDM system for powerline-based communication were discussed in Chapter 2. It also presented key tools, methods and strategies selected for achieving the stated aims. The theories, techniques and methods discussed in Chapter 2 will act as stepping stone towards obtaining the results presented in this chapter. More specifically, this chapter presents the OFDM transmitter both theoretically and graphically using the theoretical background and simulation results for each of the transmission blocks.

3.1. Theoretical Background to Digital Modulation techniques

This section aims to provide principal and theoretical background to digital modulation, and different digital bandpass modulation techniques.

3.1.1. Digital Modulation

The process, in which digital symbols get transformed into signals or waveforms that are compatible with the channel characteristics, is known as the digital modulation [2].

Two of the most common types of digital modulation are baseband modulation and bandpass modulation. In the baseband modulation, waveforms mostly take the form of shaped pulses whereas in the bandpass modulation the shaped pulses modulate a sinusoid called a carrier wave, or simply a carrier, out of which bandpass modulation are well known and often used for their important benefits in signal transmission [2].

There exist other modulation schemes one of which is known as spread spectrum modulation. In this type of modulation schemes, the systems' bandwidths are required to be greatly larger than the bandwidth required by the message (i.e. the minimum bandwidth). Such class of modulation schemes are responsible for [2]:

- Separating the signals if more than one signal uses a single channel
- Minimising the effects of interferences
- Placing a signal in a frequency band where it is required by the design

The digital bandpass modulation techniques will be considered in this project.

3.1.2. Digital Bandpass Modulation Techniques

Bandpass modulation is one of the most common types of digital modulation, in which the information signal gets converted to a sinusoidal waveform. Bandpass modulation can either be analogue or digital modulation, in which the sinusoid duration (T) is denoted as a digital symbol.

All sinusoidal signals have three main features of amplitude, phase, and frequency, making them distinguishable from one another. The process at which any change in amplitude, phase or frequency of the carrier or combination of the three features, is in line with the data to be transmitted, is defined as bandpass modulation.

A carrier signal can have a general Equation 3.1:

$$s(t) = A(t) cos\theta(t) \tag{3.1}$$

The $\theta(t)$ is a time-varying angle and can be written as Equation 3.2:

$$\theta(t) = \omega_0 t + \varphi(t) \tag{3.2}$$

By substituting Equation 3.1 into Equation 3.2 it will produce:

$$s(t) = A(t) \cos\,[\omega_0 t + \varphi(t)] \tag{3.3}$$

Where:

- $A(t)$: The time-varying amplitude
- ω_0 : The radian frequency of the carrier

- $\varphi(t)$: The phase

It is also worth mentioning that the terms ω (frequency in radians per second) and f (hertz) both represent the frequency, where they are linked by:

$$\omega = 2\pi f$$

The principal bandpass modulation and demodulation can be classified under two groups of coherent and non-coherent modulation/demodulation. Coherent modulation/demodulation is a process in which the receiver detects the signal by utilising the knowledge of the carrier's phase. The Frequency Shift Keying (FSK), Amplitude Shift Keying (ASK), Phase Shift Keying (PSK), Continuous Phase Modulation (CPM) and the hybrid combinations can be listed as the coherent modulation/demodulation types [2].

On the other hand, the non-coherent modulation/demodulation is a process where such phase reference information is not exploited by the receiver [2]. Clearly out of the two, the non-coherent system is most advantageous as it has lower complexity. The Frequency Shift Keying (FSK), Amplitude Shift Keying (ASK), Differential Phase Shift Keying (DPSK), Continuous Phase Modulation (CPM) and the hybrid combinations can be listed as the non-coherent modulation/demodulation types. Although it was previously indicated that phase information is not utilised in the non-coherent process, but the "pseudo-PSK" known as the DPSK, is an important form of non-coherent PSK as it utilises the prior symbol's phase information in order to detect the current symbol [2]. Some of the above indicated principal bandpass modulation and demodulation types will be described in the following section and are summarised in Table 3.1.

3.1.2.1. Phase Shift Keying

Phase shift keying (PSK) is one of the main digital bandpass modulation techniques and was developed during the early periods of outer-space program. This modulation technique is now extensively used in many systems and applications such as military, commercial communication systems etc.

The generic mathematical expression for PSK is [2]:

$$S_i(t) = \sqrt{\frac{2E}{T}} \cos\ [\omega_i\, t + \varphi_i(t)] \qquad 0 \le t \le T \qquad i = 1, \dots . M \qquad (3.4)$$

Where:

- E: The symbol energy
- T: The symbol time duration ($0 \le t \le T$)

The $\varphi_i(t)$ is the phase term and can be expressed as:

$$\varphi_i(t) = \frac{2\pi i}{M} \quad i = 1, \dots . M$$

One of the most common examples of PSK modulation technique is the Binary PSK (BPSK) where M is 2. In a typical BPSK modulation techniques, as illustrated in Table 3.1 (a), the phase of the $S_i(t)$ waveform is shifted to one of the two states, zero (S_1) or 180° (S_2), following a change at the symbol transitions.

The BPSK vector representation depicted in Table 3.1 (a) corresponds to a two 180° opposing vectors. Such signals that are illustrated in such way are described as the antipodal signal sets [2].

3.1.2.2. Frequency Shift Keying

Frequency Shift Keying (FSK) is another main type of digital bandpass modulation technique, and its general mathematical and analytical expression is as follow [2]:

$$S_i(t) = \sqrt{\frac{2E}{T}}\cos(\omega_i t + \varphi) \qquad 0 \le t \le T \qquad i = 1, \dots . M \tag{3.5}$$

Where:

- ω_i : The frequency term and has M discrete values
- φ : The phase term and it is an arbitrary constant
- E: The symbol energy
- T: The symbol time duration ($0 \le t \le T$)

In a typical FSK modulation, the change in the binary state of the carrier signal causes a change in the frequency of the signal. As it is illustrated in Table 3.1 (b), the frequency of the waveforms gently shifts from a lower frequency to a higher one, and from that to a higher one. The modulation techniques with such behaviour are classified as Continuous-Phase FSK (CPFSK). It is important to note that in a general M-FSK modulation technique, such changes usually take place rather sudden, as the phase is not required to be continuous. In the example presented in Table 3.1 (b), M equals 3, which corresponds to the number of waveform types. In fact, M value are selected as a non-zero power of 2 (i.e. 2, 4, 8, 16 etc) [2].

As presented in Table 3.1 (b), the vector signal can be symbolised in terms of its Cartesian co-ordinates. In other words, the mutually perpendicular axes are arranged in a way, representing the sinusoidal signals with different frequencies.

3.1.2.3. Amplitude Shift Keying

Amplitude Shift Keying (ASK) is another main type of digital bandpass modulation technique, and its general mathematical and analytical expression is as follow [2]:

$$S_i(t) = \sqrt{\frac{2E_i(t)}{T}}\cos(\omega_0\, t + \varphi) \tag{3.6}$$

$$i = 1,2,..M$$

$$0 \le t \le T$$

Where:

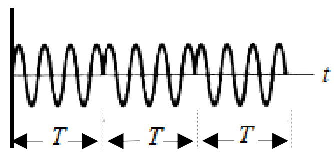
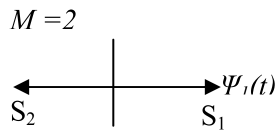
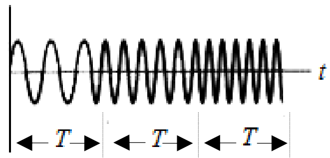
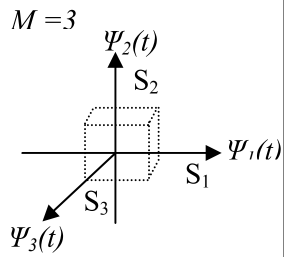
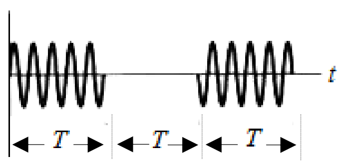
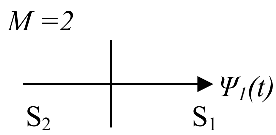
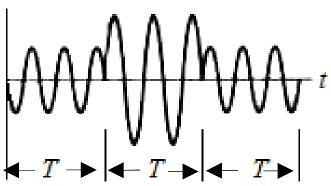
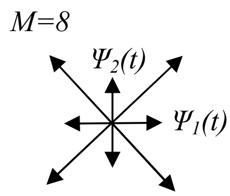
- $\sqrt{\frac{2E_i(t)}{T}}$: The amplitude term which will have *M* discrete values
- φ : The phase term and it is an arbitrary constant
- T: The symbol time duration ($0 \le t \le T$)

As it is presented in Table 3.1 (c), M value equals to 2, which corresponds to the type of the two waveforms. The waveform illustrated in Table 3.1 (c) for the ASK modulation type depict the two amplitude states of zero and $\sqrt{\frac{2E}{T}}$. It can also be observed that the vector representation of the ASK modulation type is the same as the one for the PSK modulation, containing S_1 and S_2 which correspond to the zero amplitude and a maximum amplitude respectively.

At the beginning of the twentieth century, initial and special type of ASK was developed. This special modulation type was usually referred to as Binary ASK signalling or On-Off Keying (OOK) and was commonly used in radio telegraphy.

Since the ASK is not used as broadly as before in digital communication systems, and therefore it will not be used as a modulation type for the simulation of OFDM system.

Table 3.1. Digital Modulation (a) PSK, (b) FSK, (c) ASK, (d) ASK/PSK (APK)

Modulation Technique	**Analytic and mathematical Equation**	**Waveform**	**Vector**
(a) PSK	$S_i(t) = \sqrt{\frac{2E}{T}}\cos(\omega_0 t + 2\pi i/M)$ $i = 1,2,..M$ $0 \le t \le T$ (3.4)		
(b) FSK	$S_i(t) = \sqrt{\frac{2E_i(t)}{T}}\cos(\omega_i t + \varphi)$ $i = 1,2,..M$ $0 \le t \le T$ (3.5)		
(c) ASK	$S_i(t) = \sqrt{\frac{2E_i(t)}{T}}\cos[\omega_0 t + \varphi]$ $i = 1,2,..M$ $0 \le t \le T$ (3.6)		
(d) Amplitude-Phase Keying (APK or QAM)	$S_i(t) = \sqrt{\frac{2E_i(t)}{T}}\cos[\omega_0 t + \varphi_i(t)]$ $i = 1,2,..M$ $0 \le t \le T$ (3.7)		

3.1.2.4. Quadrature Amplitude Modulation (QAM)

In addition to the 3 basic types of modulation techniques, there are other modulation techniques that are created by combining these three basic techniques. One of the most important and popular types of these combinational techniques are Quadrature Amplitude Modulation (QAM). ASK is combined with PSK to create this hybrid system known as QAM, where both the amplitude and phase are changed at the same time. QAM modulation techniques are often employed in many radio communications, data delivering related or broadcast applications [27]. A mathematical, analytical and vector presentation, as well as the waveform representation of such modulation technique is included in Table 3.1.

A method for implementing QAM modulation is through use of rectangular constellations, which can be divided into independent Pulse Amplitude Modulated (PAM) components, namely for both the In-phase and the Quadrature (I-Q) part. An example of rectangular constellations for Quadrature Phase Shift Keying (QPSK), 16QAM and 64QAM is illustrated in Figure 3.1, showing that the constellations are not normalised. So as to normalise the constellations to an average power of one, they will need to be multiplied by a normalisation factor, list of which can be found in Table 3.2. This table also contains the BPSK (2PSK) modulation, which only uses two of the four QPSK (4PSK) constellation points [27].

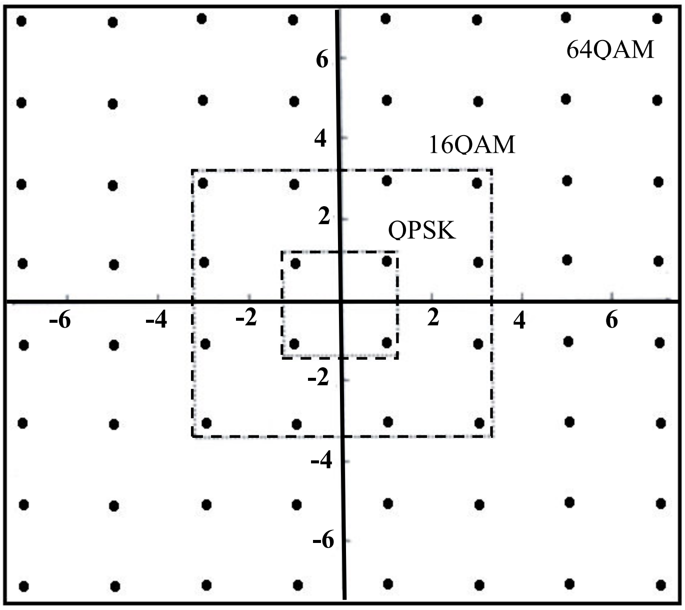


Figure 3.1. QPSK, 16-QAM and 64-QAM constellations [27]

Table 3.2. Different Modulation type, corresponding symbol rate and maximum E_b/N_o loss relative to BPSK [27]

Modulation	Symbol Rate (x bit rate)	Maximum E_b/N_o loss relative to BPSK (dB)
BPSK	1	0
QPKS	$1/2$	0
16-QAM	$1/4$	3.98
64-QAM	$1/6$	8.45

In other words, it presents the required values, in order to achieve a certain BER for an un-coded QAM link (i.e. Maximum E_b/N_o loss relative to BPSK in dB), for which these E_b/N_o loss values are confirmed to be accurate for BER values below 10^{-2} (Figure 3.2).

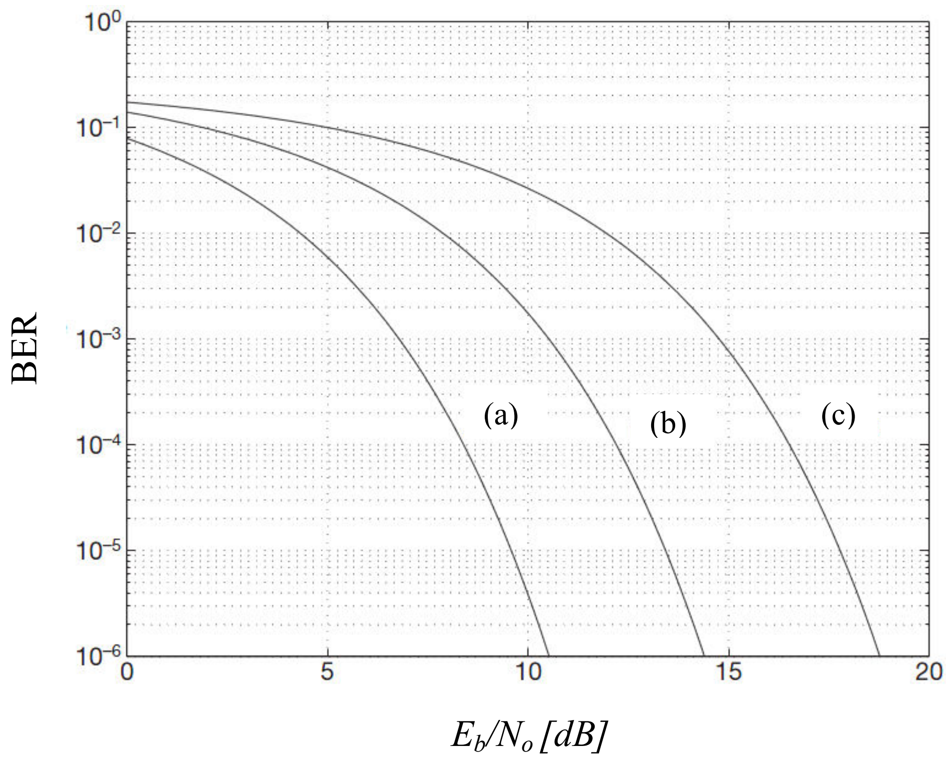


Figure 3.2. BER versus E_b/N_o for (a) BPSK / QPSK, (b) 16-QAM, (c) 64-QAM [27]

As it can be observed from Figure 3.2, the E_b/N_o for QPSK is 11 dB, 15 dB for 16QAM and 19.5 for 64-QAM. Therefore there is difference of 4.5 dB between 64QAM and 16-QAM, and 4 dB differences between 16-QAM and BPSK/QPSK. It is also worth mentioning that the constellation size for higher modulation order (i.e. 64-QAM) creates a E_b/N_o penalty of having an increased number of bits per symbol, in this example, convergence from 1 dB to 3 dB [27].

3.2. Simulation Results for Digital Modulation techniques

As explained in previous chapters, modulation is the process of facilitating the transfer of information over a medium. This includes the three main types of modulations and one of the most important and popular hybrid systems, namely Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM).

These four techniques vary in either one or two parameters of sinusoidal signal to represent the information to be sent. A sinusoidal signal has three different parameters of Amplitude, Frequency and Phase. The signals for different modulation techniques are discussed and depicted in the following figures.

3.2.1 Amplitude Shift Keying (ASK)

Having one particular amplitude for the input signal (Figure 3.3), when the carrier (Figure 3.4) is transmitting bit ‘1’, the amplitude has to change, keeping the frequency constant, when bit 0 is required to be transmitted.

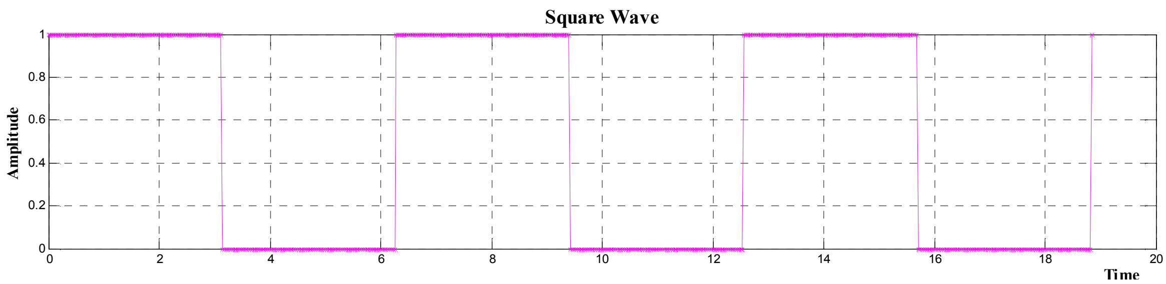


Figure 3.3. The input square signal – Information $s(t)$

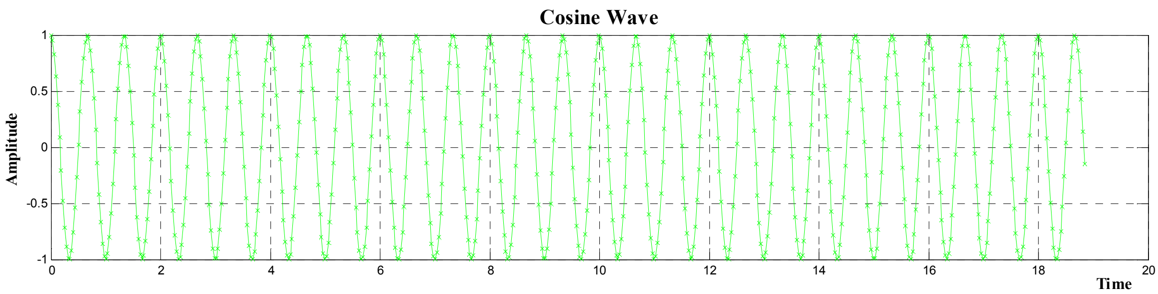


Figure 3.4. The carrier Cosine signal – $\cos(2\pi f t)$

In ASK signal, as depicted in Figure 3.5, the amplitude of the carrier is changed in response to change in state bits of the input signal (square signal). This special form of ASK is known as “On – Off Keying” (OOK), where one of the amplitude is zero.

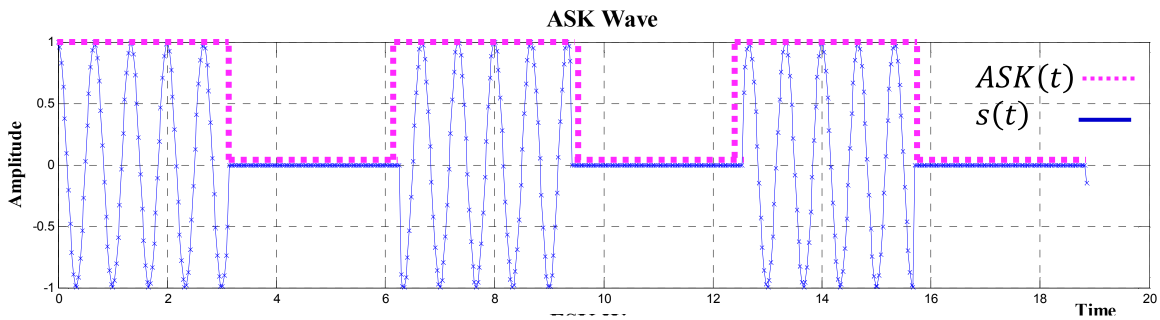


Figure 3.5. The binary ASK signal – $ASK(t) = s(t).\cos(2\pi f t)$

3.2.2. Frequency Shift Keying (FSK)

In FSK, a change in state bits of the input signal corresponds to a change in frequency; one particular frequency for the first signal and another frequency for the second signal. As it is illustrated in Figure 3.6, a change in state of the bit from '0' and '1' to '1' and '0', will result in a change in frequency of the output signal.

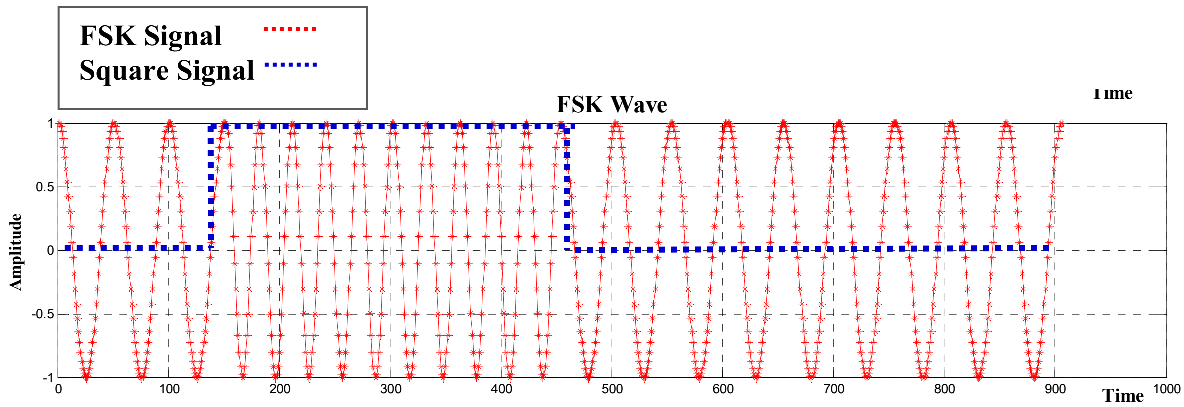


Figure 3.6. The binary FSK signal

3.2.3. Phase Shift Keying (PSK)

In PSK, a change in the state of the bits in the input signal (Figure 3.7.) corresponds to a change in the phase of the sinusoidal carrier (Figure 3.8) and hence phase change in the output signal (Figure 3.9). Phase in this context is referred to the starting angle at which the sinusoid starts. To transmit bit '0', the phase of the sinusoid is shifted by 180°.

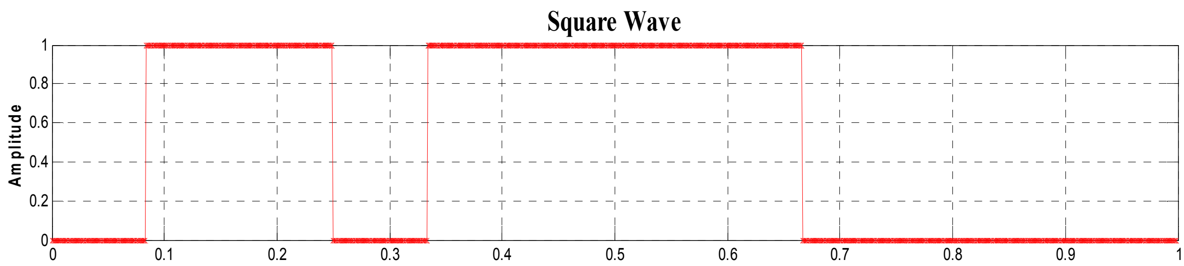


Figure 3.7. The input square signal – Information

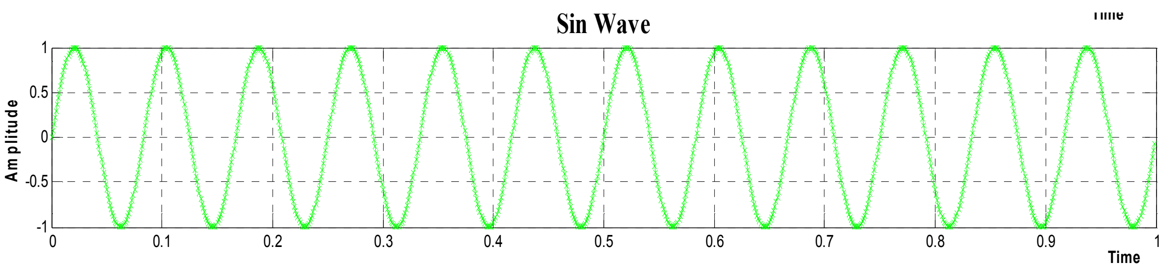


Figure 3.8. The carrier Sine signal

In PSK signal, as depicted in Figure 3.9, the phase of the carrier is changed in response to change in the state of the input signal (square signal). In other words, the phase shift represents the change in the state of the information:

$$\text{PSK:} \quad \begin{cases} \sin(2\pi f t) & \text{for bit 1} \\ \sin(2\pi f t + \pi) & \text{for bit 0} \end{cases}$$

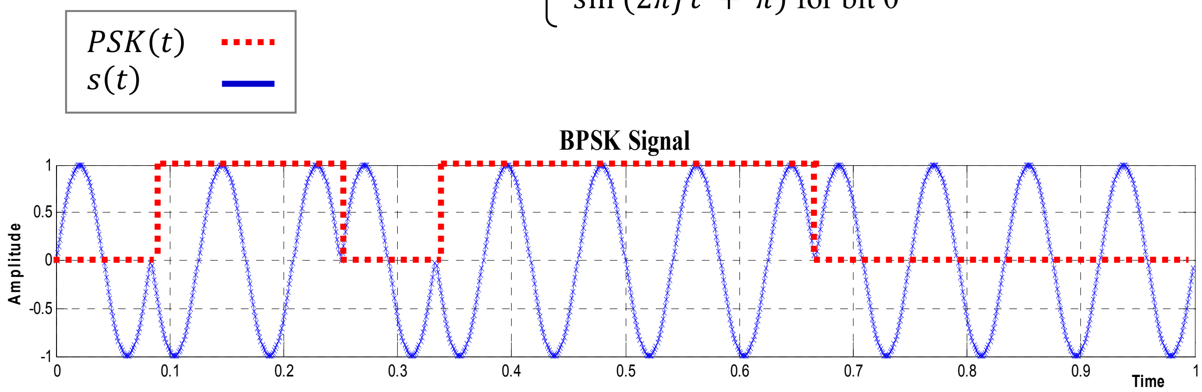


Figure 3.9. The binary PSK signal

3.2.4. Quadrature Amplitude Modulation (QAM)

In addition to the 3 basic types of modulation techniques, there are other modulation techniques that are created by combining these three basic techniques. One of the most important and popular types of these combinational techniques are Quadrature Amplitude Modulation (QAM). ASK is combined with PSK to create hybrid system known as QAM, where both the amplitude and phase are changed at the same time.

Like the above explained modulation techniques, in QAM, the phase and amplitude of the carrier signal (Figure 3.10) similarly changes in response to a change in state of the input signal. This change in the state of the input subsequently changes the amplitude and phase of the output signal, as shown in Figure 3.11.

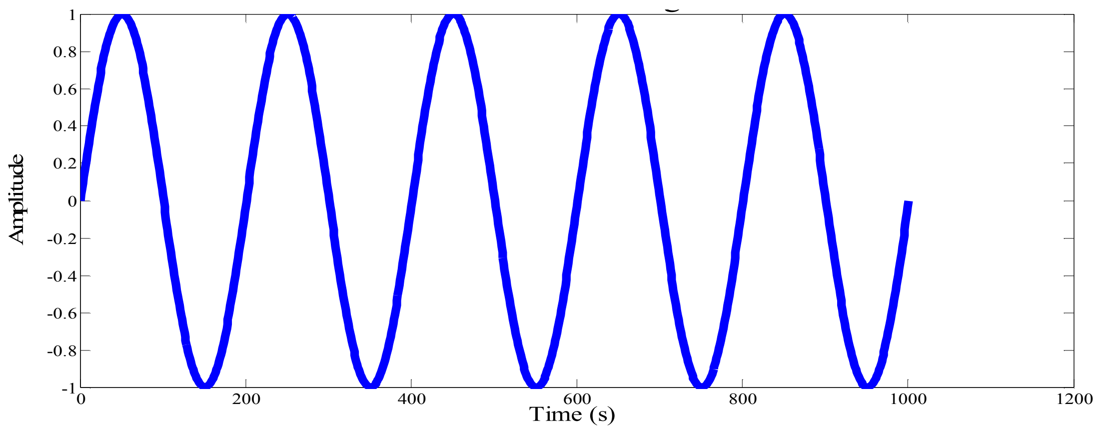


Figure 3.10. The carrier sine signal

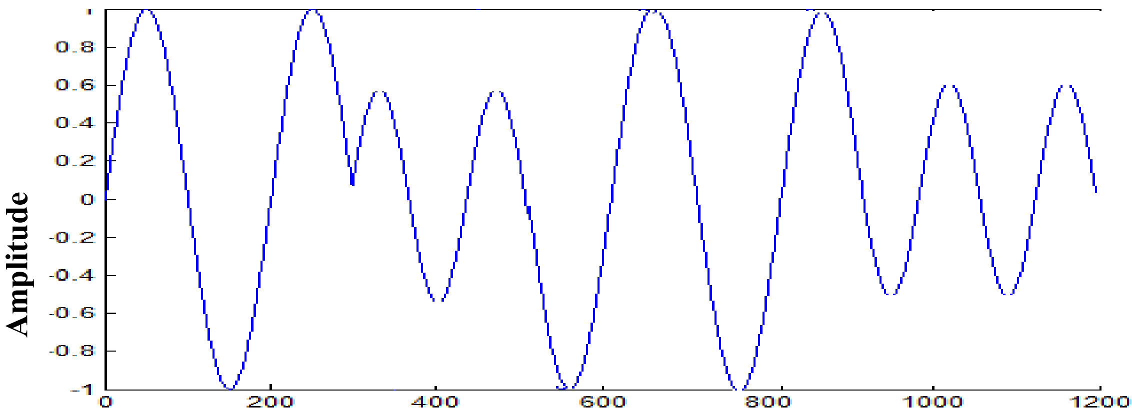


Figure 3.11. QAM – Both amplitude and phase have changed in response to a change in state of the input signal

Out of the above discussed modulation techniques, M-PSK and M-QAM are the most widely used techniques, and therefore this research concentrates on using these two modulation schemes.

As explained in the previous chapter, when either of these two modulation schemes is applied to an OFDM communication system, the minimum frequency separation that guarantees orthogonal sub-carriers is *1/T*, where *T* is the symbol duration.

3.3. Theoretical Background to OFDM Transmitter

This section will cover some of the principal and theoretical background to OFDM and the main blocks of the OFDM transmitter including basic principle of OFDM, implementation of IFFT, and cyclic prefix designed in this research.

3.3.1. The OFDM Principle

OFDM is classified as a special type of multi-carrier transmission technique, where the transmission of individual data stream occurs over number of subcarriers which have lower rate. This fundamental idea was initially proposed and patented by Chang in the middle of 1960s [136], for which it was found that the bandwidth (W) is divided into number (N_c) of smaller sub-bands, generally referred to as subcarriers.

The width of these subcarriers is:

$$\Delta f = {}^{W}/_{N_c} \tag{3.8}$$

Figure 3.12 depicts the subdivision of the bandwidth into number of sub-bands (N_c) or subcarriers, indicated as the blue arrows [136].

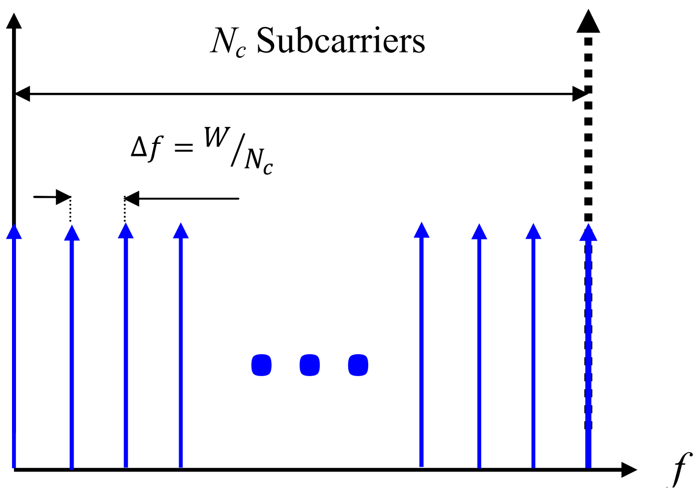


Figure 3.12. The subdivision of the bandwidth [136]

More specifically, a multicarrier system functions by partitioning the data stream into blocks of N_c data symbols, as illustrated in Figure 3.12, where the data symbols are communicated in a parallel format by modulating the N_c carriers.

Such multicarrier schemes have symbol duration of:

$$T_s = N_c / R \tag{3.9}$$

Where:

- R: The baud rate
- T_s: The symbol duration
- N_c: Subcarriers

An OFDM signal has a general form containing sum of subcarriers that are modulated. An OFDM symbol, modulated by using PSK or QAM starting at $t = t_s$ can be written as Equation (3.10) [27].

$$s(t) = \mathrm{Re}\left\{\sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s/2} \exp\left(j2\pi\left(f_c - \frac{i+0.5}{T}\right)(t-t_s)\right)\right\}, t_s \le t \le t_s + T \tag{3.10}$$

$$s(t) = 0, \qquad t < t_s, \qquad t > t_s + T$$

Where:

- $s(t)$ = OFDM symbol
- d_i = Complex modulation scheme (i.e. QAM or PSK) symbols
- N_s = The number of subcarriers
- T = The symbol duration
- f_c = The carrier frequency

The equivalent complex baseband notation of Equation (3.10) is provided in Equation (3.11). In this representation, the real and imaginary parts correspond to the in-phase and quadrature parts of the OFDM signal, which have to be multiplied by a cosine and sine of the desired carrier frequency to produce the final OFDM signal. Figure 3.13 shows the operation of the OFDM modulator in a block diagram.

$$s(t) = \sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s/2} \exp\left(j2\pi\frac{i}{T}(t-t_s)\right), t_s \le t \le t_s + T \tag{3.11}$$

$$s(t) = 0, \qquad t < t_s, \qquad t > t_s + T$$

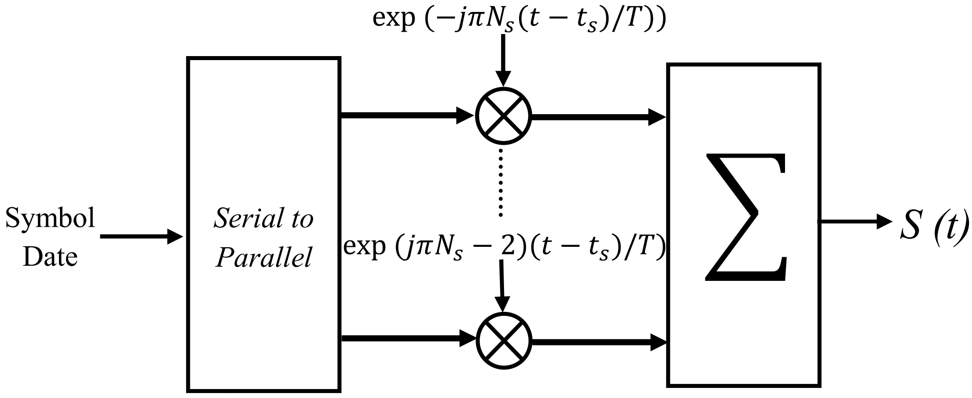


Figure 3.13. OFDM Modulator [136]

As an example, Figure 3.14 shows four subcarriers from one OFDM signal. In this example, all subcarriers have the same phase and amplitude (use of QAM modulation scheme), but in practice the amplitudes and phases may be modulated differently for each subcarrier. The mathematical relationship between these subcarriers can be accounted as the orthogonality property between them since:

- Each subcarrier has exactly an integer number of cycles in the interval *T*
- The number of cycles between adjacent subcarriers differs by exactly one

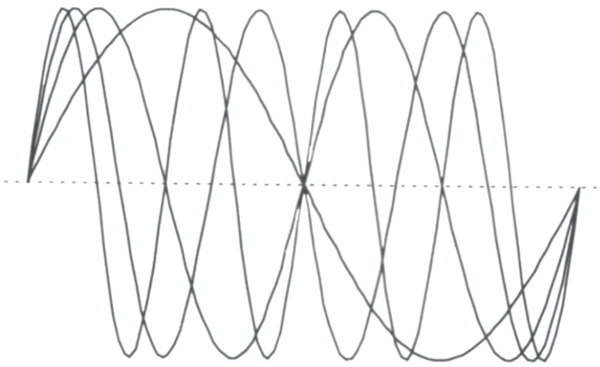


Figure 3.14. Example of four subcarriers within one OFDM symbol [27]

More specifically, if the *j*th subcarrier from Equation (3.11) is demodulated by down-converting the signal with a frequency of *j/T* and then integrating the signal over *T* seconds, the result would be Equation (3.12).

$$\int_{t_s}^{t_s+T} \exp\left(-j2\pi\frac{j}{T}(t-t_s)\right) \sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s/2} \exp\left(\mathrm{j}2\pi\frac{\mathrm{i}}{\mathrm{T}}(\mathrm{t}-\mathrm{t_s})\right)\mathrm{dt}$$

$$= \sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s/2} \int_{t_s}^{t_s+T} \exp\left(j2\pi\frac{i-j}{T}(t-t_s)\right)dt = d_{j+N_{s/2}}T \qquad (3.12)$$

By looking at the intermediate result, it can be seen that a complex carrier is integrated over T seconds. For the demodulated subcarrier j, this integration gives the desired output $d_{j+N/2}$ (multiplied by a constant factor T), which is the QAM value for that particular subcarrier. It is important to note that the integration is zero for all other subcarriers, as the frequency difference $(i\text{-}j)/T$ produces an integer number of cycles within the integration interval T, such that the integration result is always zero [27].

In order to promise a high spectral efficiency, the signals for each sub-channel must present an overlapping transmit spectra. In other words, the sub-channel waveforms must appear as orthogonally overlapping, as this would ease the separation of such overlapping sub-channel at the receiver end [136].

The orthogonality of the different OFDM subcarriers can also be demonstrated in another way. According to Equation (3.10), each OFDM symbol contains subcarriers that are non-zero over a T-second interval. Hence, the spectrum of a single symbol is a convolution of a group of Dirac pulses located at the subcarrier frequencies with the spectrum of a square pulse that is one for a T-second period and zero otherwise [27].

The amplitude spectrum of the square pulse is equal to $sinc(\pi f T)$, having zeros for all frequencies (f) that are an integer multiple of $1/T$. This effect is illustrated in Figure 3.15, which shows the overlapping *sinc* spectra of individual subcarriers. It can also be observed that, at the maximum of each subcarrier spectrum, all other subcarrier spectra are zero. This is due to the fact that an OFDM receiver calculates the spectrum values at those points that correspond to the maxima of individual subcarriers. It can therefore demodulate each subcarrier free from any interference with the other subcarriers.

In addition, Figure 3.15 shows that the OFDM spectrum fulfils Nyquist's criterion for an ISI free pulse shape; which is presented in the frequency domain and not in the time domain, for which the Nyquist criterion is usually applied.

The Nyquist ISI criterion can be described as the conditions which, when satisfied by the communication channel, provides a method for constructing the band-limited functions to overcome the effects of ISI. In addition, when successive symbols are transmitted over a channel by a linear modulation (i.e. ASK, PSK, QAM etc), the impulse response (equivalently the frequency response) of the channel makes the transmitted symbol to be spread in the time domain, causing the appearance of interference between the consecutive symbols. Such interference increases the effect of the previously transmitted symbols on the currently received symbols, thus reducing tolerance to noise. Consequently, the Nyquist theorem relates this time domain condition to an equivalent frequency domain condition [3].

Therefore, in addition to reducing the effect of ISI, an Inter-Carrier Interference (ICI) is also avoided by having the maximum of one subcarrier spectrum corresponding to zero crossing of all the others [27]. A frequency domain representation of OFDM is depicted in Figure 3.15, where each curve is a spectrum corresponding to a subcarrier.

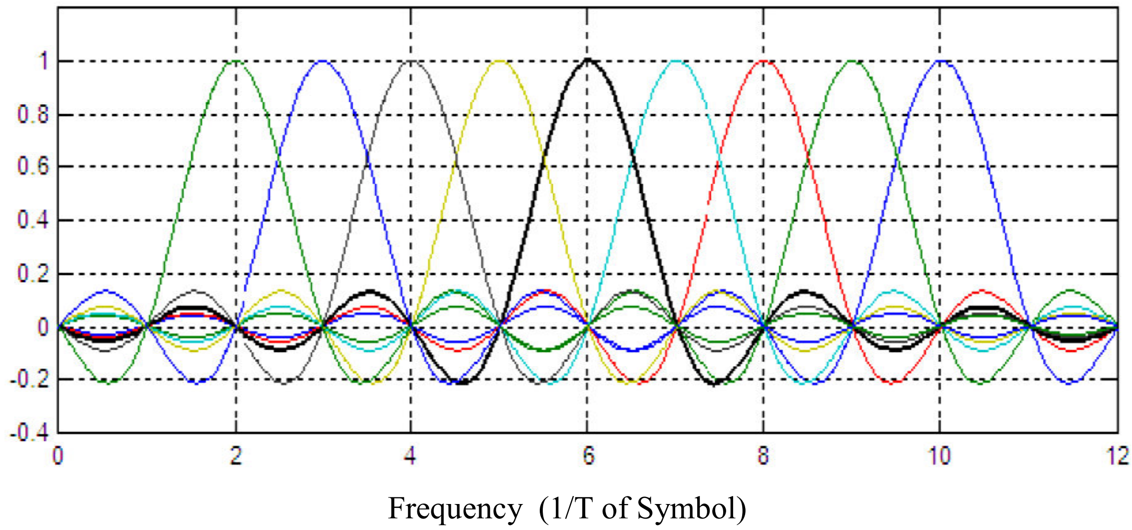


Figure 3.15. Spectra of individual subcarriers

More specifically, a general Frequency Division Multiplex (FDM) system would have the carriers distanced in a way which would allow the signals to be received by using conventional filters and demodulators. Guard bands are therefore positioned between each of the different carriers within the receiver and also in the frequency domain; which would reduce the efficiency of the spectrum [27]. A guard interval with duration of 20 μs is used as the cyclic prefix length. This length has been selected to be longer than the expected delay spread in order to protect the ISI which is caused as a result of the multipath delay spread. The concept of cyclic prefix will be covered in more details in the present chapter. The multicarrier modulation techniques that comply with these conditions are referred to as the Orthogonal Frequency Division Multiplex (OFDM) systems.

3.3.2. Implementation of IFFT/FFT

So far in this chapter, the principles of OFDM, digital modulation and different digital bandpass modulation techniques have been discussed. This section will present one of the main building blocks in the OFDM system; the modulation and demodulation.

The modulation and demodulation of the OFDM is done in the discrete-time domain, using the two well-recognised transforms, the inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT).

By considering only one time interval (e.g. for $l = 0$), the signal to be transmitted can be written as Equation (3.13), which means that for each time interval with length T, OFDM is just a Fourier synthesis for that period [37].

$$s(t) = \frac{1}{\sqrt{T}} \sum_{k=-K/2}^{K/2} S_k \exp\left(j2\pi \frac{k}{T} t\right) \Pi\left(\frac{t}{T} - \frac{1}{2}\right) \tag{3.13}$$

Assuming an ideal synchronisation between the receiver and transmitter, the FFT will be performed in the receiver side, in order to recover the data symbols (S_k), as presented in Equation (3.14) [37]:

$$S_k = \langle g_k, s \rangle = \frac{1}{\sqrt{T}} \int_0^T \exp\left(-j2\pi \frac{k}{T} t\right) s(t)\, dt. \tag{3.14}$$

A Fourier analysis is commonly implemented through Fast Fourier transform (FFT) and Fourier synthesis is implemented by the inverse fast Fourier transform (IFFT), leading to an implementation setup as shown in Figure 3.16.

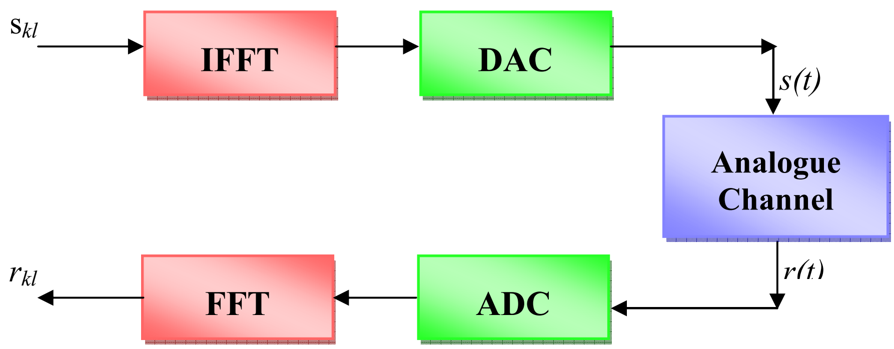


Figure 3.16. OFDM implementation by FFT [36]

As it is shown in Figure 3.16, the symbols (s_{kl}) that have been digitally modulated get divided into blocks with length K or $K+1$; where K is the number of modulated carries. These modulated blocks will then get transformed by the IFFT, and later converted to analogue and then transmitted. It is important to note that the FFT length, or commonly referred to as N_{FFT}, must be selected to be significantly larger than K, as this will ensure that [36]:

(i) The edge effects caused at the half sampling frequency are neglected

(ii) The spectrum is not affected by the response and shape of the reconstruction filter in the Digital to Analogue Converter (DAC)

Therefore, careful selection of FFT length and suppression of alias spectra should be carried out [36]. Furthermore, the spectral coefficients ($N_{FFT} - K$) which are placed outside the transmission band will be set to zero. This leaves the rest of the spectral coefficients which are placed inside the transmission band to be digitally converted at the receiver end. In the receiver part, an FFT operation is performed on each of the N_{FFT} sample block. Following the FFT operation, the K coefficients will be removed from the N_{FFT} spectral coefficients [36].

3.3.3. Cyclic Prefix

As previously explained in Chapter 1, inter symbol interference (ISI) occurs when a signal is passed through a time-dispersive channel. Such interferences have large effect on OFDM systems, as they also result in a loss of orthogonality between the subcarriers, causing a further interference known as inter carrier interference (ICI) [27].

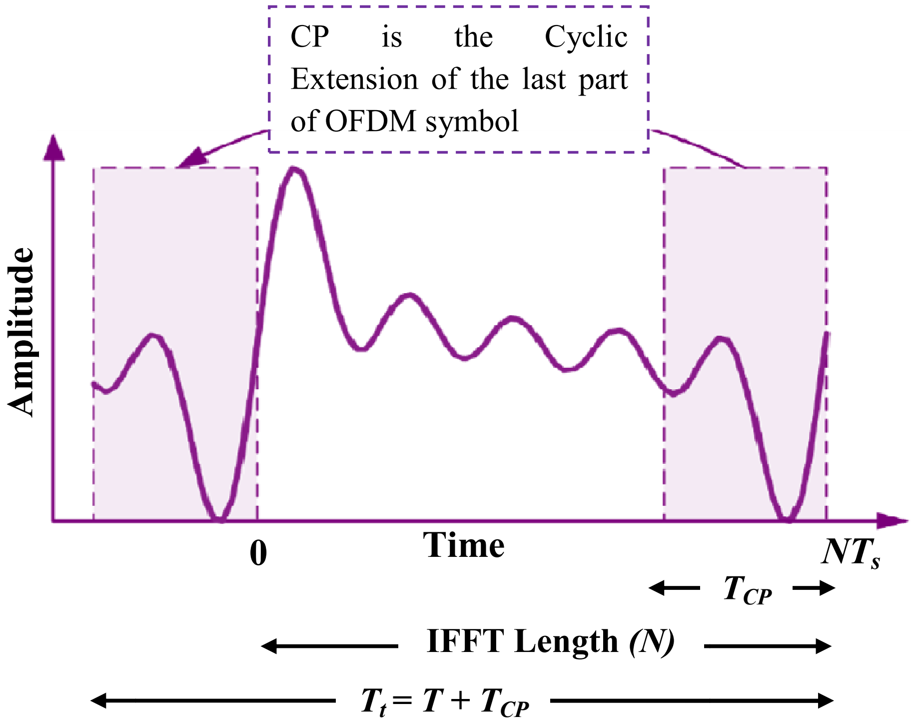


Figure 3.17. Addition of cyclic Prefix [27]

In order to overcome such interferences, concept of cyclic prefix (CP) was introduced in 1980 by Peled and Ruiz [136]. As it is depicted in Figure 3.17, a cyclic prefix can be described as a percentage copy of the last part of OFDM signal, which is appended to the transmitted signal. This added percentage copy of the signal gets removed before the demodulation in the receiver section.

The cyclic prefix should be chosen to be longer than the expected delay spread, and this would increase the benefits of the cyclic prefix as [136]:

(i) It will eliminate the ISI by acting as a guard space between the successive symbols.

(ii) It will carry out the conversion of the channel impulse response with the linear convolution into a cyclic convolution. Since in the time domain, the cyclic convolution gets translated into a scalar multiplication in the frequency domain, causing the subcarriers to remain orthogonal, and therefore eliminating any ICI [136].

As explained above, in order to mitigate and to some extend eliminate the ISI and ICI almost completely, the length of the cyclic prefix has to be extended to make it longer than the experienced impulse response. However, an increase in the length of the cyclic prefix will result in an increase in the transmitted energy, which will consequently result in a loss of Signal to Noise Ratio (SNR). Equation (3.15) presents the mathematical relationship between the insertion of the cyclic prefix and loss of SNR [136].

$$SNR_{loss} = -10log_{10}\left(1 - \frac{T_{cp}}{T}\right) \tag{3.15}$$

Where:

- T_{CP} : The length of the cyclic prefix
- T_t : Length of the transmitted symbol

The length of the transmitted symbol can be written as:

$$T_t = T + T_{CP} \tag{3.16}$$

It is important to note that the length of the cyclic prefix should be carefully selected and the following points should be considered when selecting [136]:

- The responses produced by the present filters within the system would add to the overall impulse response, which will also be compensated for by the guard interval.
- A fraction of guard interval should be retained for synchronisation. This is due to the fact that not only a perfect time acquisition can never be promised, but also the consequence of clock offset between the transmitter and receiver may still considerably increase the deviation.

3.4. Use of Basic Types Of Digital Modulation Techniques in OFDM

This part will explain and illustrate the use of the above explained basic digital modulation techniques in an OFDM. In doing so, a high-level technical computing language called MATLAB® was used in order to design and implement the outlined OFDM communication system. The codes for these algorithms have been written using the guidelines provided in [1] and [2]. The codes for design and its implementation employed in this project are provided in both the appendices and the enclosed CD.

MATLAB® is very powerful software that is widely used across all engineering disciplines, supporting various graphical input and outputs. Therefore producing efficient codes and making the simulation results easily illustratable in different graphical formats. MATLAB is also known an interpreted language for numerical computation as it allows one to perform numerical calculations without the need for complicated and time consuming programming. Another important advantage of using MATLAB is that it supports several file formats and extensions (for either Image or audio files). This will greatly help and validate the judgments with respect to the achieved results.

Beside all the stated advantages, MATLAB software has other advantages, in comparison to other programming languages such as C or C++, making it a better programming platform to use for this research.

Unlike C or C++ programming, MATLAB uses standardised built-in routines, allowing it to be simulated on any MATLAB installation. In C programming, loops are often used, whereas MATLAB uses vectors which reduces the code lines and makes the codes simpler and easier to read. The last but not least advantage of using MATLAB is its use in developing algorithms from scratch, allowing the user to write the code and analyse it line by line.

3.5. Simulation Response of Fundamental OFDM Modem

This section will present the step by step results for the designed fundamental OFDM modem. As depicted in Figure 3.18, the simplified OFDM transceiver is divided into three main sections of Transmitter, Channel and Receiver, results of which are presented below. Modulation/De-modulation, IFFT/FFT, CP insertion/removal are the most important blocks in this simplified OFDM transceiver.

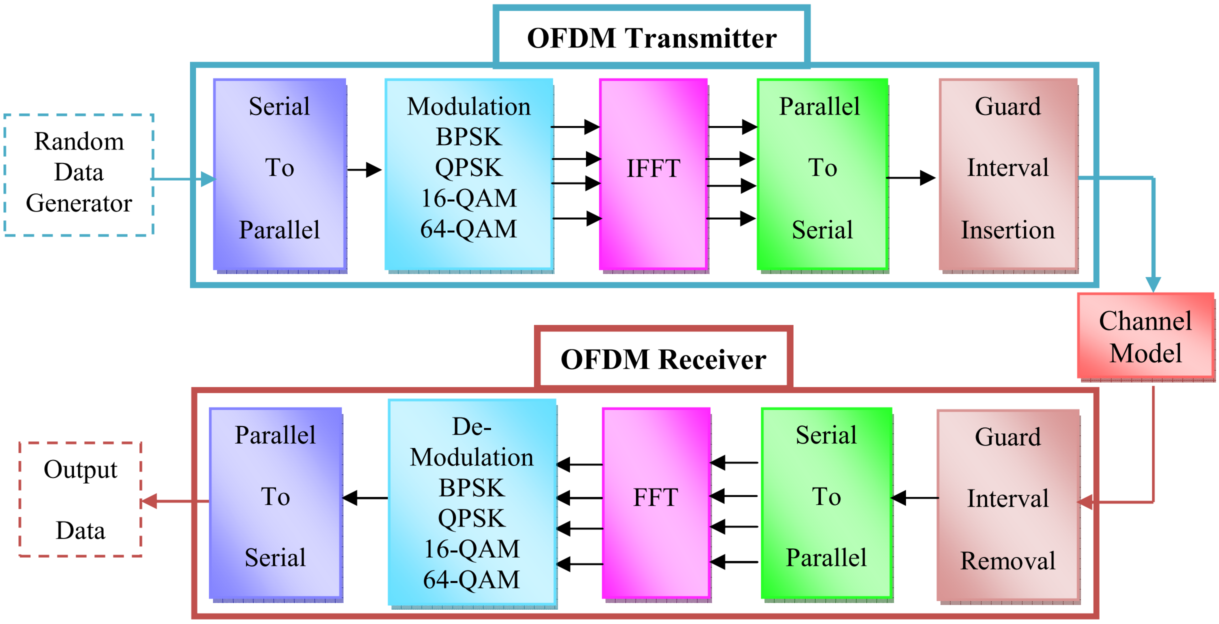


Figure 3.18. Architecture of a simplified OFDM transceiver

In order to simulate this OFDM modem, a channel bandwidth of 1 MHz, with 128 subcarriers has been selected. In addition, symbol duration of 128 µs and guard interval of 20 µs have been chosen. This makes the total block length to:

$$\textit{Total block length (148 µs) = Symbol duration (128µs) + Guard interval (20 µs)}$$

3.5.1. Simulation of Transmitter

The simulation of OFDM transmitter is discussed in this section, containing the step by step results and discussions. The architecture of this particular OFDM transmitter is depicted in Figure 3.19.

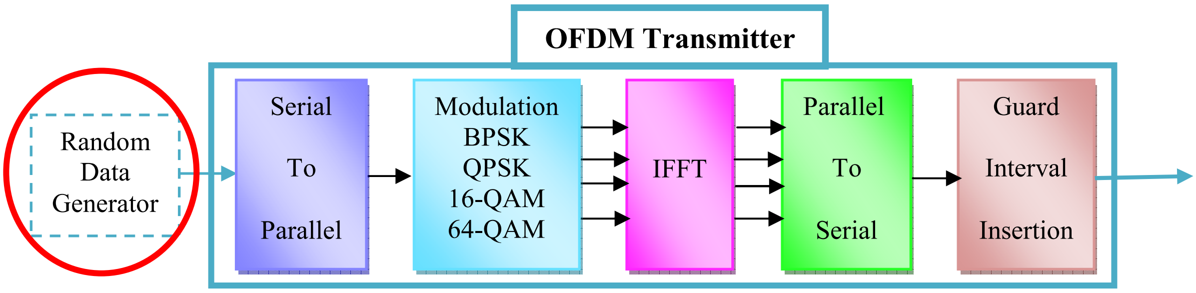


Figure 3.19. Architecture of OFDM transmitter

As depicted and highlighted in Figure 3.19, the initial stage prior to the actual OFDM transmission is to transmit the generated message, where this message could be either randomly generated binary values, audio sound, or digitally processed image.

Simulation of this part uses the uniformly distributed pseudorandom numbers, by using the "`rand(m,n)`" function which produces a 1 by 2500 pseudorandom values, where 2500 represent the number of bits. In order to produce random binary values, the previously produced values are required to be rounded to their nearest integer value. This is achieved by the use of "`round`" function, which produces 1 by 2500 bits (zeros and ones). Figure 3.20 depicts the random binary generated message.

It is important to note that the input message illustrated in Figure 3.20 and the following figures presenting an output for each block, is only part of the full message, and therefore only gives an indication of 12 bits out of 2500 bits.

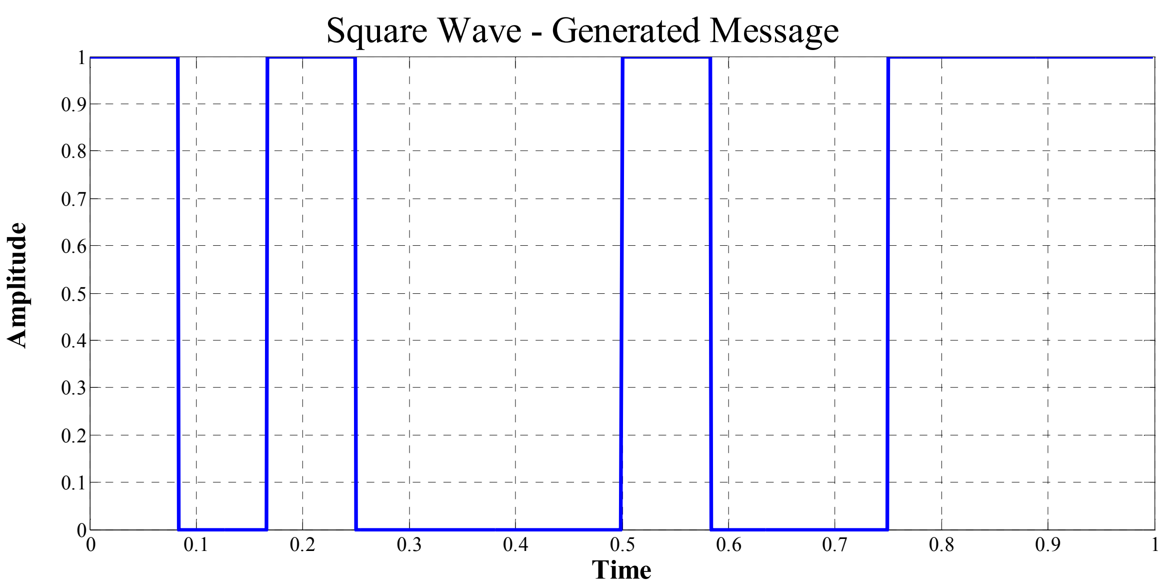


Figure 3.20. Random binary generated message

The early stage in the OFDM transmission is the conversion of the random binary generated message from serial to a parallel form, as shown in Figure 3.21.

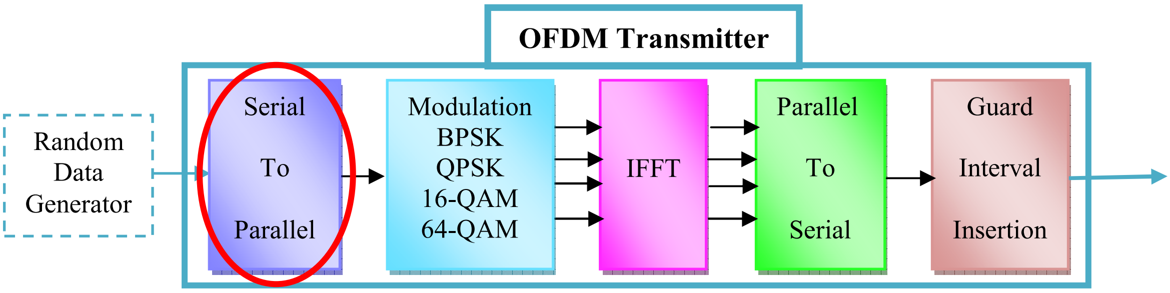


Figure 3.21. Architecture of OFDM transmitter with S/P highlighted

At this stage, the input serial data stream (Figure 3.20) is formatted into suitable size required for transmission, for example one bit for BPSK ($2^1 = 2$) or two bits for QPSK ($2^2 = 4$), which are shifted into a parallel format. Figure 3.22 illustrates the message after applying the serial to parallel conversion block.

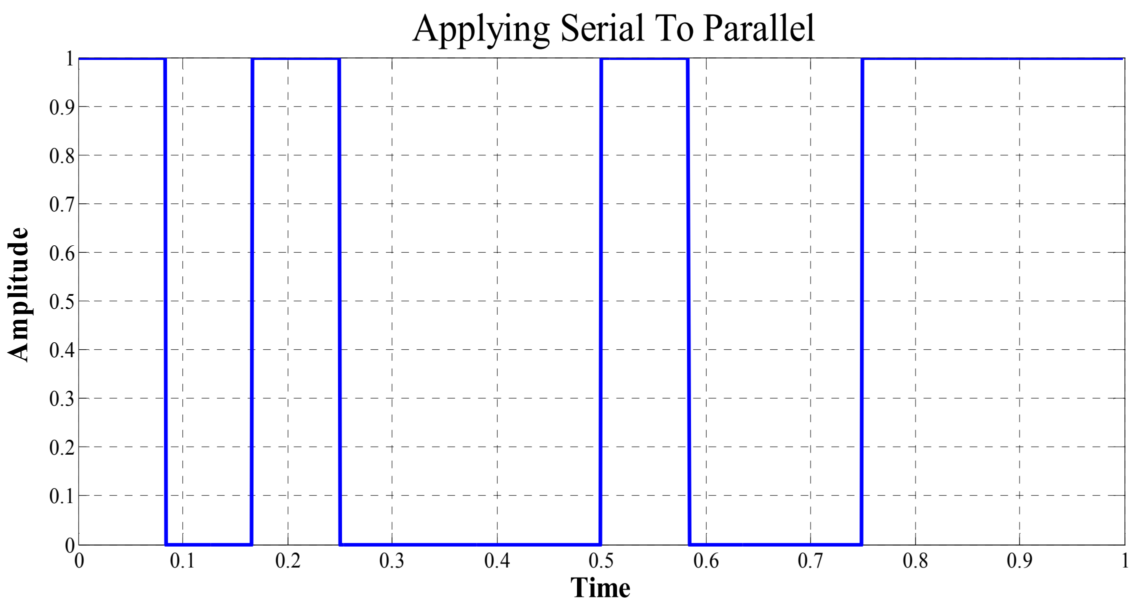


Figure 3.22. The message after applying the serial to parallel conversion

Following the serial to parallel conversion of data, they are then transmitted in parallel format by assigning each suitably selected size to one carrier in the transmission.

As it is illustrated in Figure 3.23, the second block and one of the most important blocks in this particular OFDM transmission is the Modulation block, where the data to be transmitted on each carrier is encoded with previous symbols and later mapped into a Phase Shift Keying (PSK) format.

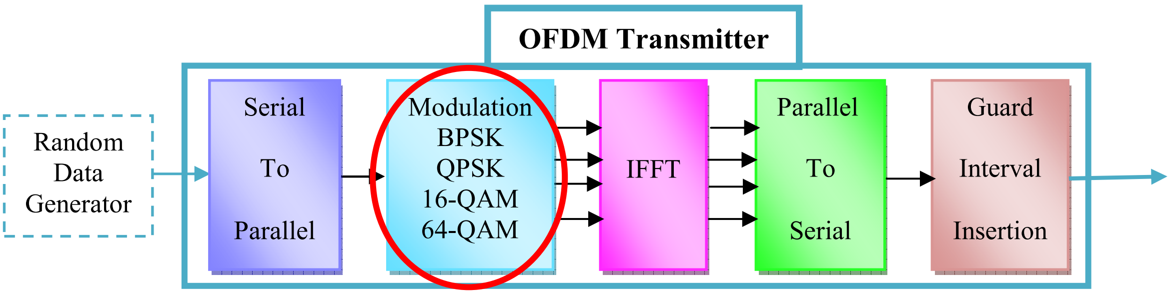


Figure 3.23. Architecture of OFDM transmitter with modulation highlighted

As explained above, Phase Shift Keying is known as one of the most commonly used modulation formats due to having the following advantages:

- Simplicity
- Production of a constant amplitude signal
- Reducing problems with amplitude fluctuations due to fading

The data on each symbol is mapped to a phase angle based on the modulation method. For example, for BPSK modulation the phase angles used are 0° and 180°, and for QPSK the phase angles used are 0°, 90°, 180°, and 270 degrees.

Applying the BPSK modulation to the parallel format data produces the modulated message depicted in Figure 3.24. By analysing Figures 3.20 and 3.24, it can clearly be seen that a change in the state bits of the input data (Figures 3.19) either from '1' to '0' or from '0' to '1', produces a change in phase with the modulated signal.

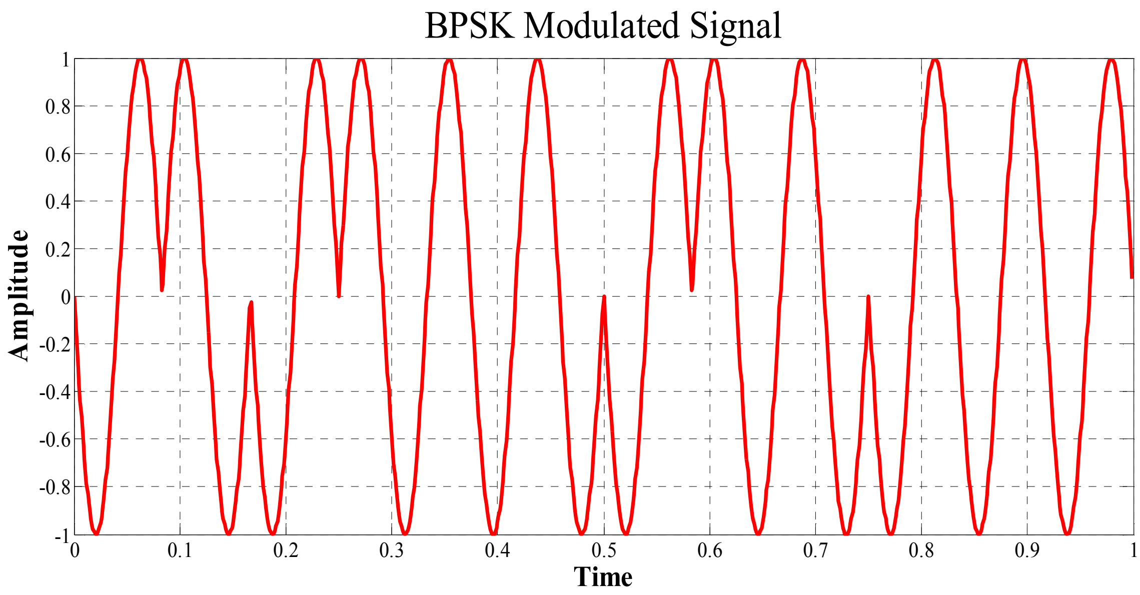


Figure 3.24. Message modulated by BPSK modulation technique

Figure 3.25 shows that the next step, after the required spectrum is worked out through modulation, is to apply the Inverse Fast Fourier Transform (IFFT) in order to find the corresponding time waveform.

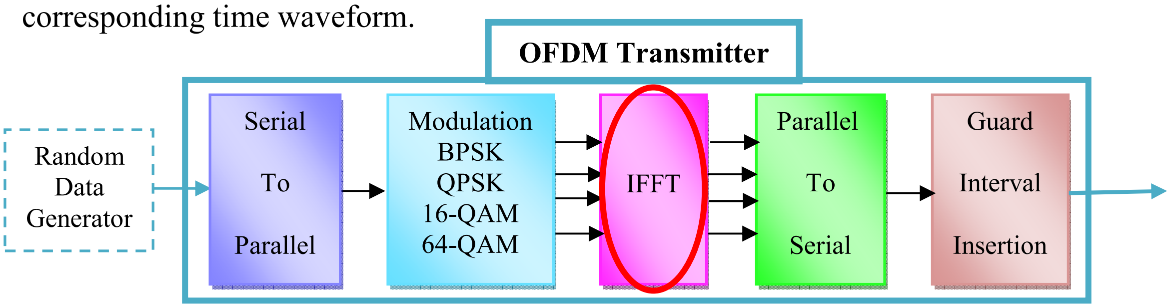


Figure 3.25. Architecture of OFDM transmitter with IFFT highlighted

In addition, IFFT can be used to implement the OFDM transmitter by the use of:

$$x_k = \sum_{n=0}^{N-1} d_n \,.\, e^{j\frac{2\pi}{N}nk} \qquad k = 0,1,2,\ldots.N-1 \qquad (3.17)$$

Where:

- x_k The output of the parallel to serial conversion in the OFDM transmitter
- d_n Pre-defined data symbol after modulation
- $e^{j\,2\pi nk}$ / N, k=0,1,…,N-1 Represents the corresponding orthogonal frequencies of the N sub-carriers

This is done by using the "`ifft(X)`" function which returns the inverse discrete Fourier transform (DFT) of vector X, computed with a fast Fourier transform (FFT) algorithm. Figure 3.26 depicts the IFFT applied to modulated message.

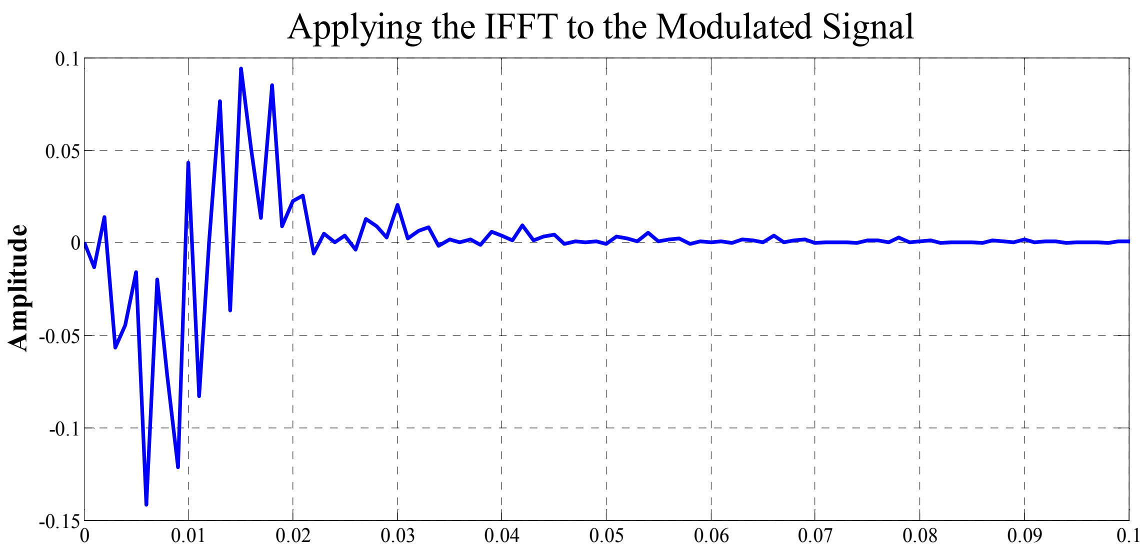


Figure 3.26. IFFT applied to the modulated message

After applying the IFFT technique to the modulated signal and applying the parallel to serial conversion, architecture of which is depicted in Figure 3.27, the cyclic prefix is then added to the start of each symbol.

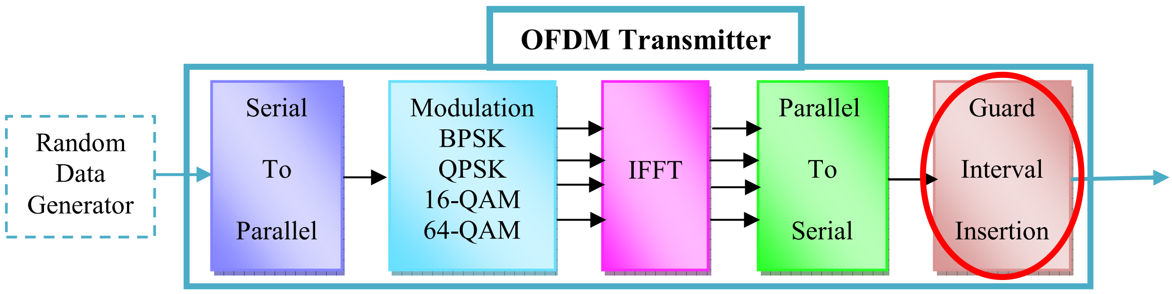


Figure 3.27. Architecture of OFDM transmitter with CP insertion highlighted

The cyclic prefix is added by copying the appropriate part of the OFDM symbol (Figure 3.28) and pre-pending it to the transmitted symbol. As it is illustrated in Figure 3.28, cyclic prefix (the copied OFDM symbol) is added to the start of the transmitting OFDM symbol.

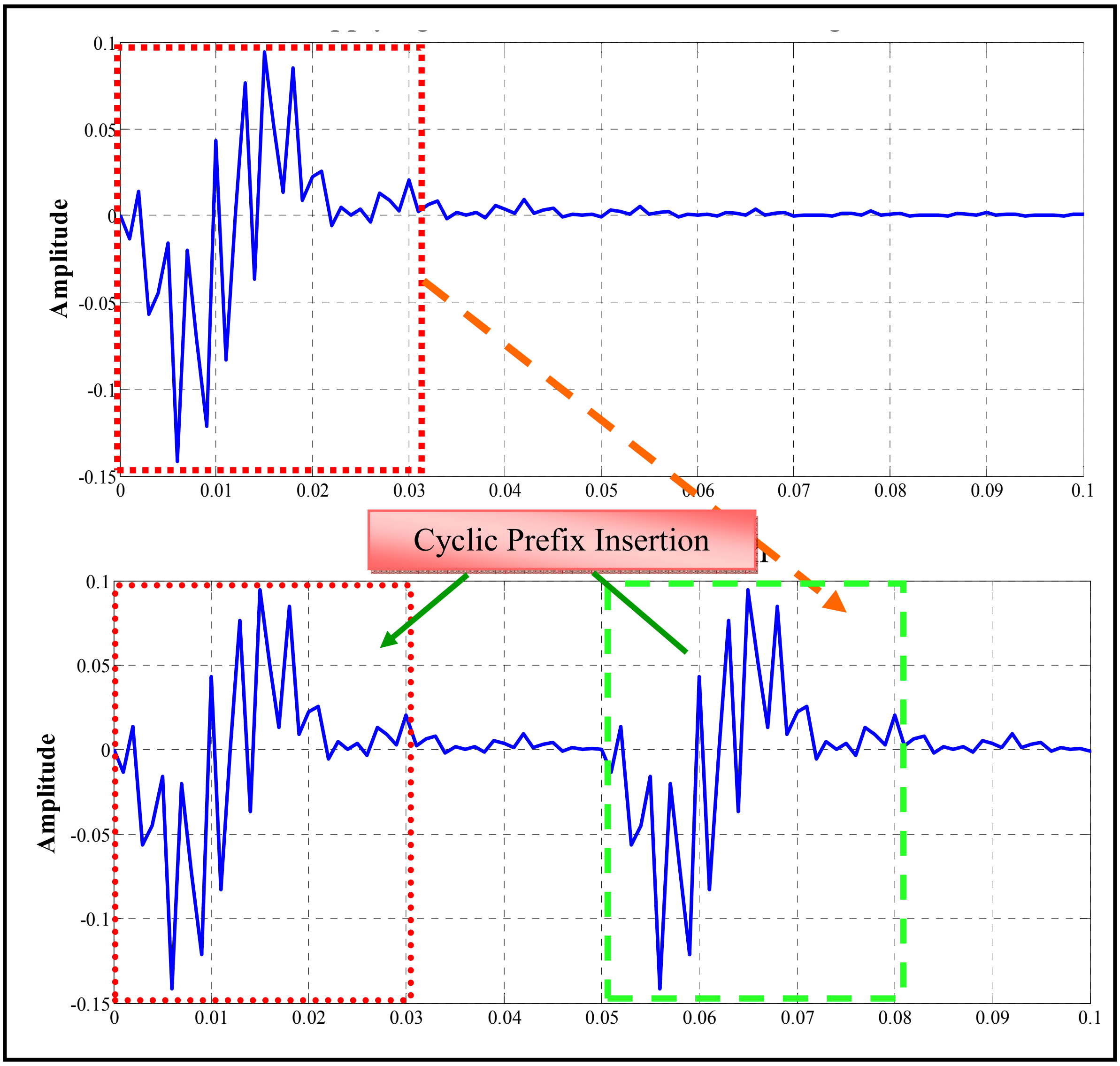


Figure 3.28. Cyclic prefix has been placed at the start of the OFDM symbol

Following the addition of cyclic prefix, the symbols are then converted back to a serial time waveform. This waveform can then be recognised as the base-band signal for the OFDM transmission.

3.6. Summary

This chapter provided principal and theoretical background to digital modulation, and different digital bandpass modulation techniques such as PSK, FSK, ASK and QAM. This chapter also contained the simulation results for the three main types of modulations technique and one of the most important and popular hybrid systems.

Following the simulation results for the main types of modulation scheme, the principal and theoretical background to the main blocks of an OFDM transmitter, including basic principle of OFDM, implementation of IFFT, and cyclic prefix were presented.

The stated basic digital modulation techniques in an OFDM were next illustrated. In doing so, a high-level technical computing language called MATLAB® was used in order to design and implement the outlined OFDM communication system. More specifically, a step by step simulation response for each block of the transmission section of the designed fundamental OFDM modem, consisting of the most important blocks such as Modulation, IFFT and CP insertion were presented. Summary of this sequential step by step simulation of the transmission section are as follows:

1) The random binary message were generated
2) These binary message were converted from serial format into a parallel
3) The parallel binary message were modulated using the BPSK
4) The IFFT were applied in order to find the corresponding time waveform
5) The cyclic prefix was added by copying a percentage of the OFDM symbol and pre-pending it to the transmitted symbol.

The simulation response for the OFDM transmitter which has been obtained in this chapter will be continued by the following chapter in achieving the simulation results for the OFDM receiver.

Chapter 4

OFDM Receiver and Simulation Results

A brief introduction to digital communication systems was presented in Chapter 1.This was followed by Chapter 2, containing the background overview of the research carried out to date and also the key methods and strategies selected for achieving the aims. The theoretical background and simulation results for each block of the transmission section were covered in Chapter 3. This chapter will cover a brief overview of some of the theoretical background to each of the blocks in the receiver section, as most of it has been extensively explained in Chapter 3. The simulation results for each block of the receiver section will also be thoroughly presented and analysed in this chapter.

4.1. Theory of AWGN model and its influence on OFDM Receiver

This section aims to provide concise principal and theoretical background to OFDM and its main units of the OFDM receiver, designed in this research.

4.1.1. The AWGN Channel

A noise can be regarded as unnecessary electrical signals that are constantly found in electrical systems. When such unwanted electrical signals get superimposed on a clean signal, the product will be an unclear signal. This ambiguity makes it very difficult for the receiver to decide on the correct symbol, and therefore restricts the rate of information transmission [137]. Noise can have different sources, natural and man-made. Natural noise is mainly generated from electrical circuits, component noise and atmospheric disturbances. Man-made noise, on the other hand, is generated from sources like spark-plug ignition, radiating electromagnetic signals and switching transients [138]. Although engineers try to reduce and to some extend eliminate the noise and its effect by shielding, filtering and correct selection of modulation, but there remains one type of natural source, known as Johnson or thermal noise which can never be eradicated [137 - 139]. Such natural noise types are a result of thermal movement of electrons in electrical components (i.e. resistors and wires etc.). As described in Chapter 2, most of the communication systems that use channel as a medium for transmission, face distortion due to presence of noise in the channel.

A very common mathematical channel model, which has also been implemented in this research project, is the Additive White Gaussian Noise (AWGN) channel. This channel model has been extensively used in determining the most suitable modulation type, modulation order and comparison between the different encoding schemes.

The AWGN is a well-recognised channel model as it represents a physical reality, provided that the thermal noise at the receiver is the only source of interference [36]. Nonetheless, due to their simplicity, AWGN are commonly characterised to symbolise for a man-made noise or other multiuser interferences.

In AWGN channel, a white Gaussian noise is added to a real or complex input signal. Depending on the real or complex format of the input signal, the Gaussian noise added will be either real or complex, therefore producing a real or complex output signal respectively; inheriting its sample time from the input signal. This channel model uses the signal processing random source for generating the noise. In doing so, the random numbers are generated using the Ziggurat method, which is the same method used by the MATLAB `randn` function.

A Probability Distribution Function (PDF) of a Gaussian distributed random variable *n*, with mean value of μ, and the variance of σ^2 can be written as Equation 4.1 [36]:

$$p(n) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{1}{2}\left(\frac{n}{\sigma}\right)^2\right] \tag{4.1}$$

Where:

- *P(n)* : PDF of a Gaussian distributed random variable *n*
- σ^2 : The Variance of *n*

The normalised Gaussian density function can be obtained when the mean value (μ) equals 0, and $\sigma = 1$. The normalised PDF is shown in Figure 4.1.

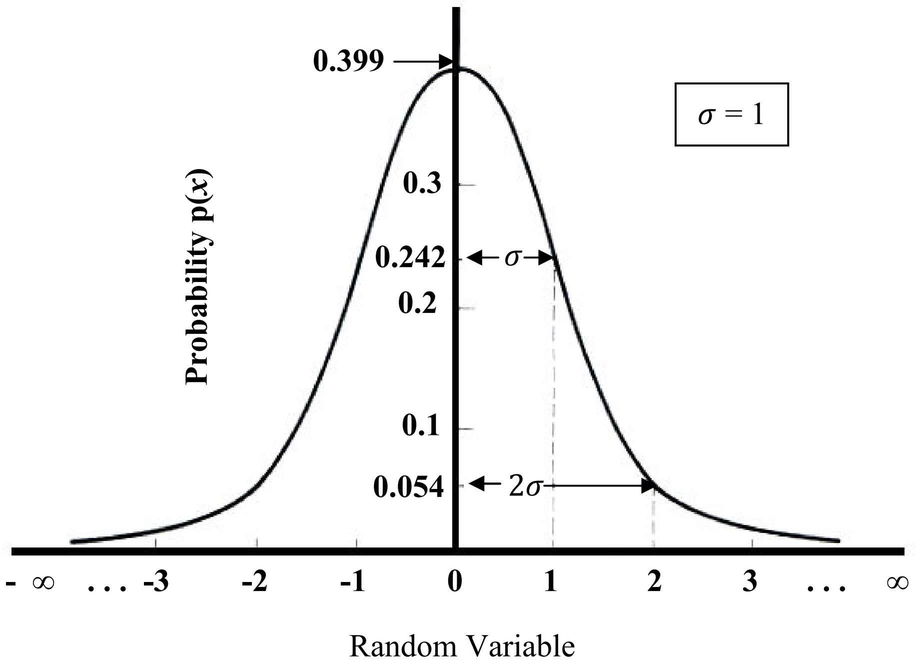


Figure 4.1. Normalised (σ = 1) Gaussian probability density function [137]

An AWGN channel may be typified as [36]:

- The noise *n (t)* is an ***additive*** random disturbance of the useful transmitted signal *S (t),* illustrated in Equation 4.2.
- This noise is categorised as ***white*** noise, as its Power Spectral Density (PSD) is constant.
- The noise has ***Gaussian*** distributed random variable with mean of zero and stationary characteristic.

The received signal in the time interval of $0 \leq t \leq T$ can be expressed as Equation 4.2. Figure 4.2 shows the typical model for the transmitted signal passed through an AWGN channel and received signal out of the channel [36].

$$r(t) = S_m(t) + n(t) \tag{4.2}$$

Where:

- *r (t)* : Received Signal
- S_m *(t)* : Transmitted Signal
- *n (t)* : Sample function of the AWGN process with power-spectral density

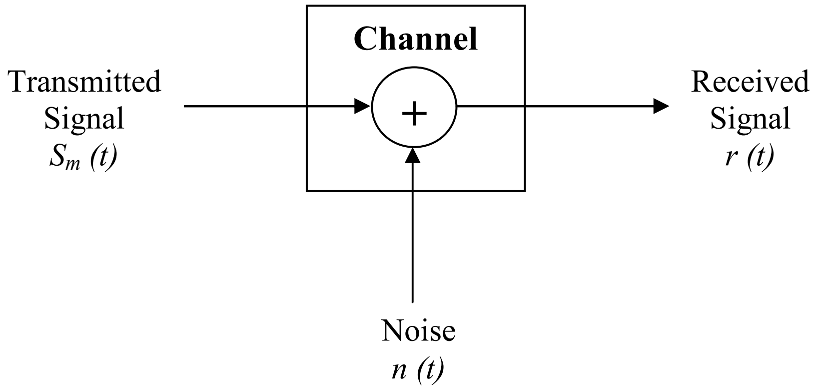


Figure 4.2. Typical model for the transmitted signal passed through an AWGN channel and received signal out of the channel [140]

The Cumulative Distribution Function (CDF) of a Gaussian or normally distributed random variable can be presented as Equation 4.3 [36]:

$$F(x) = \frac{1}{2}\left[1 + \text{erf}\left(\frac{x-\mu}{\sqrt{2\sigma^2}}\right)\right] \tag{4.3}$$

The CDF of a Gaussian distributed random variable with the mean value μ= 0 and variance of $\sigma^2 = 1$ is shown in Figure 4.3.

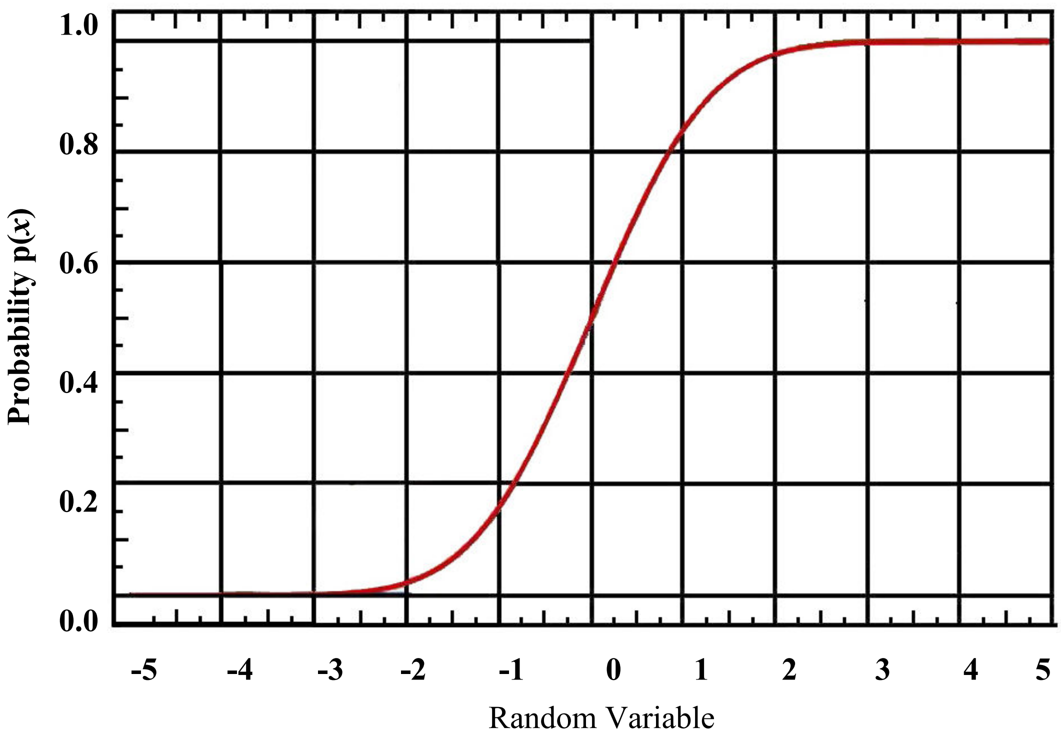


Figure 4.3. CDF of a Gaussian distributed random variable - μ = 0 and $\sigma^2 = 1$ [140]

4.1.2. Signal-to-Noise Ratio (SNR) Degradation

The SNR value is used in order to measure the performance of the channel at different points, and to compare the level of a desired signal to the level of background noise. This value can be calculated as a ratio of average signal power and average noise power, as it is likely that an instantaneous signal to noise ratios will be considerably different. A ratio higher than 1:1 indicates that there are more signal than noise. Both signal and noise power must be measured at the same and equivalent points in the system, and within the same system's bandwidth. The SNR power equation is defined in Equation (4.4) [137]:

$$SNR = \frac{Signal\ Power}{Noise\ Power} \tag{4.4}$$

Due to a very wide dynamic range of many signals, SNR values are often expressed by using the logarithmic decibel scale (i.e. dB). The SNR in dB can therefore be defined as:

$$SNR_{dB} = 10log_{10}\left(\frac{Signal\ Power}{Noise\ Power}\right) = Signal\ Power_{dB} - Noise\ Power_{\ dB} \tag{4.5}$$

It is worth noting that if the signal and the noise are measured across the same impedance, then the SNR can be obtained by calculating the square of the amplitude ratio as:

$$SNR = \frac{Signal\ Power}{Noise\ Power} = \frac{P_{\ Signal}}{P_{Noise}} = \left(\frac{A_{\ Signal}}{A_{Noise}}\right)^2 \tag{4.6}$$

- ***A*** = The Root Mean Square (RMS) amplitude

The SNR defined in Equation (4.6) can equivalently be written in the decibel format as:

$$SNR_{dB} = 10log_{10}\left(\frac{A_{\ Signal}}{A_{Noise}}\right)^2 = 20\ log_{10}\left(\frac{A_{\ Signal}}{A_{Noise}}\right) \tag{4.7}$$

The signal can have different types; for instance it can either be as a modulated carrier, baseband waveform or an information signal. A decrease in the power of the desired signal or an increase in the power of the noise signal can cause degradation to the SNR value [137].

4.1.3. Multicarrier De-modulation

The task of multicarrier de-modulation at the receiver, is based on the orthogonality between each subcarriers. As it is illustrated in the schematic view in Figure 4.4, the demodulation block contains number of N_c matched filters, which are responsible for implementation of the relation presented in Equation (4.8) [136]:

$$y_{k,m} = \int_{mT_s}^{(m+1)T_s} s(t)\, \Psi_k^*(t - mT_s)dt \tag{4.8}$$

An OFDM system with number of oscillators in the transmitter and number of matched filters in the receiver has a complex implementation for large number of subcarriers [1]. However, as it was indicated in [38], if the subcarrier numbers (N_c) is a power of two, then a cheaper approach may be used. The number of oscillators in the transmitter and number of matched filters in the receiver can therefore be replaced by an IDFT and DFT operation. In addition to being a cheaper approach, such implementation does not suffer from the inaccuracies that an analogue oscillator bank faces [136].

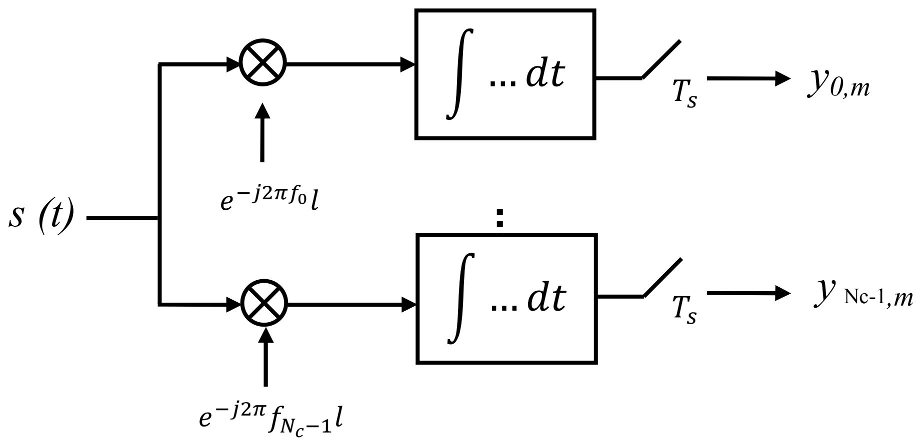


Figure 4.4. OFDM demodulation [136]

4.1.4. Serial to Parallel Conversion

At this stage, the input serial data stream is formatted into suitable size required for transmission, for example one bit for BPSK ($2^1 = 2$) or two bits for QPSK ($2^2 = 4$), which are shifted into a parallel format. Following the serial to parallel conversion of data, they are then transmitted in parallel format by assigning each suitably selected size to one carrier in the transmission [141].

4.1.5. FFT Implementation

As previously stated, the IFFT and FFT blocks are accounted as the most important blocks within the OFDM communication system, as OFDM orthogonality is provided through the use of these blocks [137].

The IFFT block in the transmitter is responsible for transformation of both amplitude and phase of each component of the spectrum into the time domain. As it was explained in the transmitter section, Chapter 3, the number of complex data is converted to the same number of data in the time domain. In the receiver, FFT block is similarly responsible for the reverse operation; the conversion of the data points from the time domain back to the frequency domain. Following the FFT operation, the demodulation of each received phase is performed. This is carried out through assessing and conversion of the phase angle of each carrier back to the data word. The achieved data words are later combined to create the original data with the same word size [141, 9].

4.1.6. Cyclic Prefix Removal

Introduction of cyclic prefix maintains the orthogonality between each of the subcarriers and also preserves the independence of the following OFDM symbols. As previously explained in Chapters 2 and 3, cyclic prefix is a percentage copy of the last part of the OFDM signal, which is affixed to the transmitted signal. Addition of this percentage copy results in circular convolution between the channel impulse response and the transmitted signal, making its frequency domain a multiplication of frequency response for both channel and transmitted signal [142]. This makes the received signal in its frequency domain to be a scaled form of the transmitted signal in its frequency domain. Therefore, formation of any distortion due to the severe channel conditions are eliminated [143].

The different blocks within the receiver perform a reverse operation to the transmitter. The cyclic prefix removal is carried out at the receiver subsystem, allowing a cyclic prefix–free signal to be passed through the different blocks of this subsystem [144, 36].

4.2. Simulation Response of Designed OFDM Modem

This section will present the step by step results for the designed fundamental OFDM modem. As depicted in Figure 4.5, the simplified OFDM transceiver is divided into three main sections namely Transmitter, Channel and Receiver, results of which are presented below. Modulation/De-modulation, IFFT/FFT, CP insertion/removal are the most important blocks in this simplified OFDM transceiver.

4.2.1. Simulation of Channel

Figure 4.5 depicts the architecture of the simplified channel, and as it is illustrated the output signal from the transmission section is used as an input to the channel. The following results present the response of AWGN channel model; background to such channel model has been provided in both Chapter 2 and section 4.1.1 of this chapter.

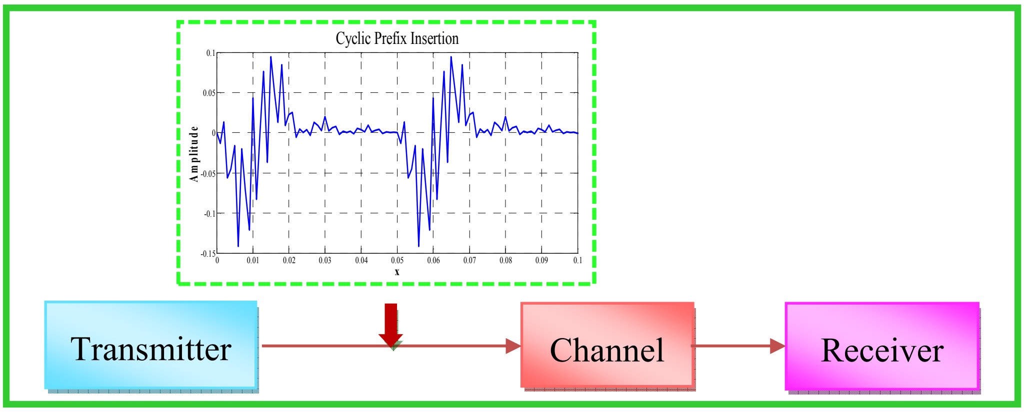


Figure 4.5. Architecture of simplified channel

In order to model the AWGN channel "`awgn(x,snr)`" function is used which adds white Gaussian noise to the signal x (i.e. the transmitted OFDM signal). The scalar SNR specifies the power ratio between the signal (transmitted OFDM signal) and the background noise (in this case the white Gaussian noise), in dB. For the following set of results SNR value of 5 has been selected. Figure 4.6 depicts the outcome of the above function.

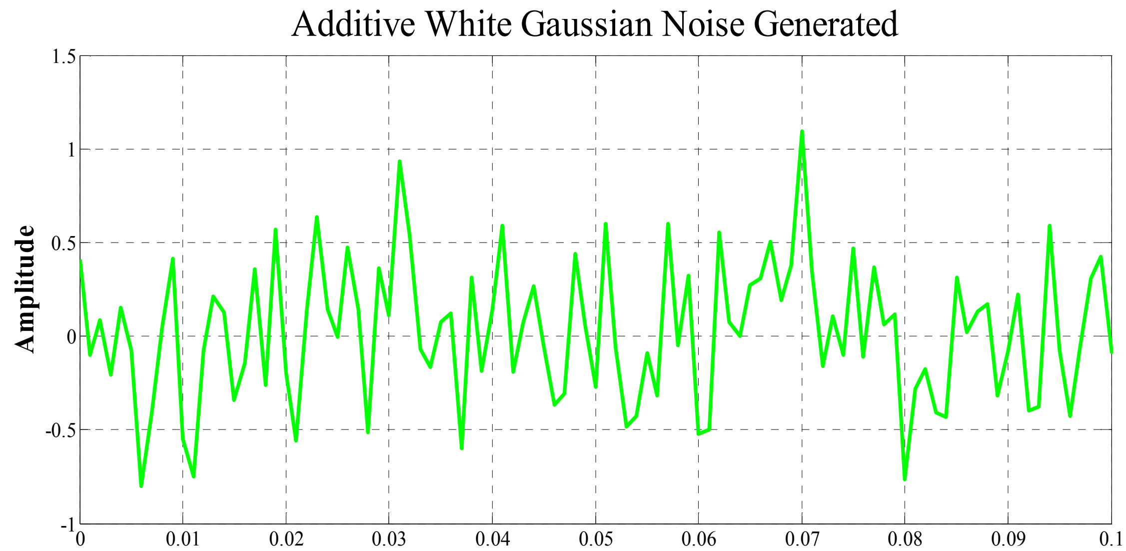


Figure 4.6. The generated Additive White Gaussian Noise with SNR = 5

Figure 4.7 illustrates OFDM signal superimposed on to the modelled noise signal. It can be observed that the OFDM signal has higher amplitude in comparison to the noise signal. These two signals will later be combined, creating a noisy signal for the channel.

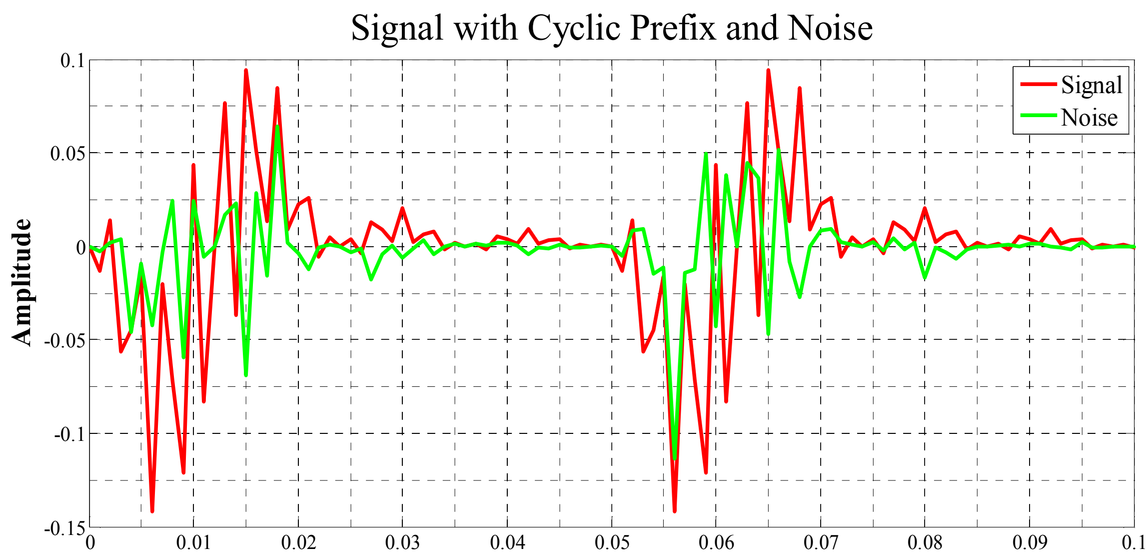


Figure 4.7. OFDM signal superimposed on to the modelled noise

Prior to applying and combining the modelled noise to the transmitted OFDM signal, the signal is scaled, as shown in Figure 4.8. The scaling of the OFDM signal may be achieved by the Equation (4.9):

$$Scaled\ Signal = \frac{std(noise)}{std(OFDM\ signal)} \times sqrt(10^{\left(\frac{SNR}{10}\right)}) \times OFDM\ signal \tag{4.9}$$

Where in MATLAB:

- std = The Standard Deviation
- $sqrt$ = Square root

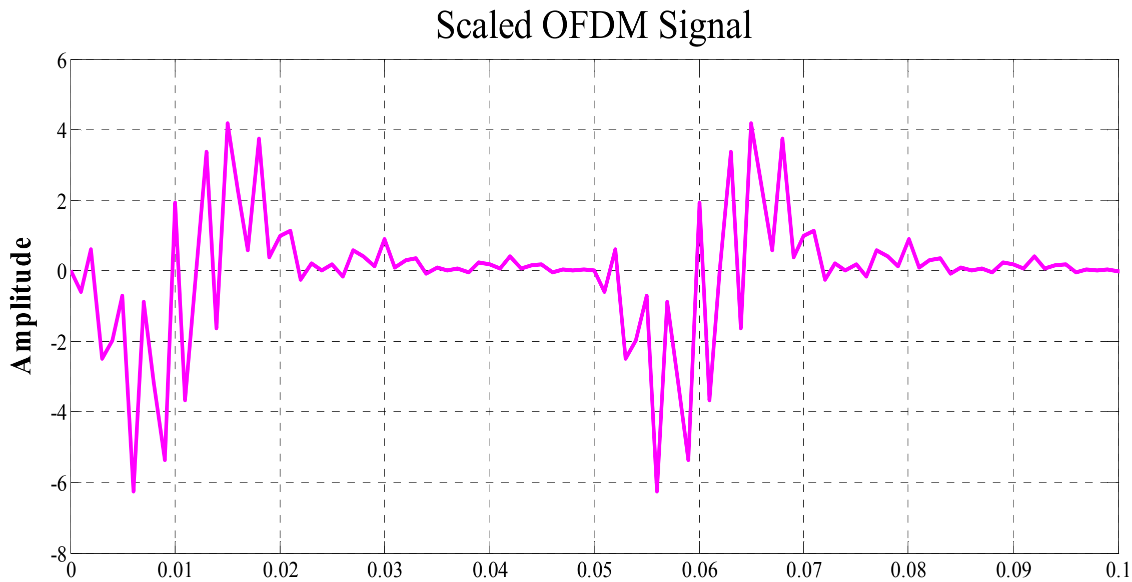


Figure 4.8. Scaled transmitted OFDM signal

Following the stage of scaling the transmitted OFDM signal, the next step is to combine the OFDM signal with the Additive White Gaussian Noise. Figure 4.9 and Figure 4.10 illustrate the non-scaled and scaled combined signals respectively.

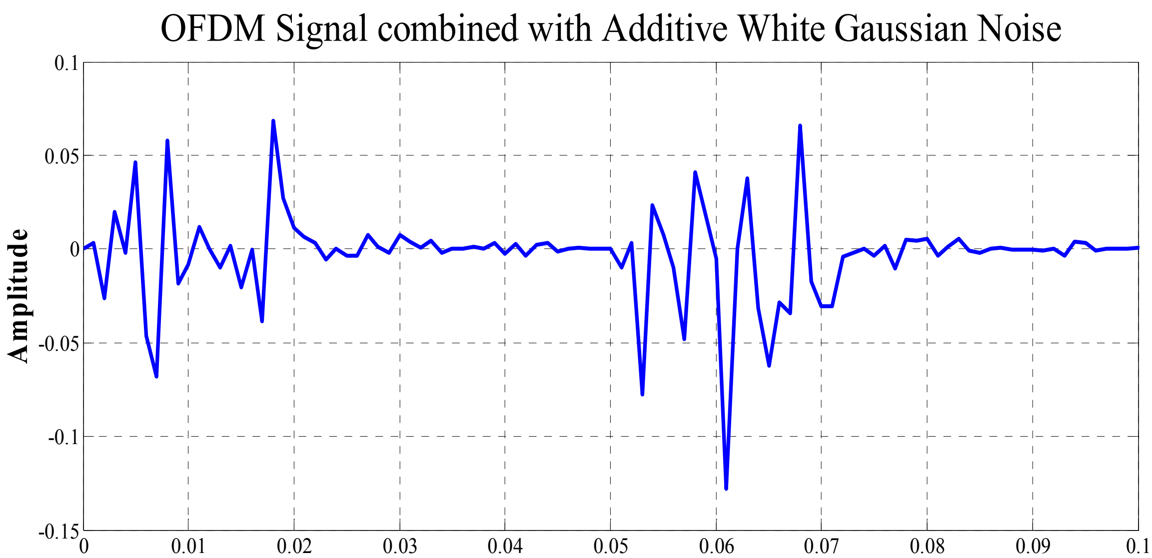


Figure 4.9. OFDM signal combined with AWGN

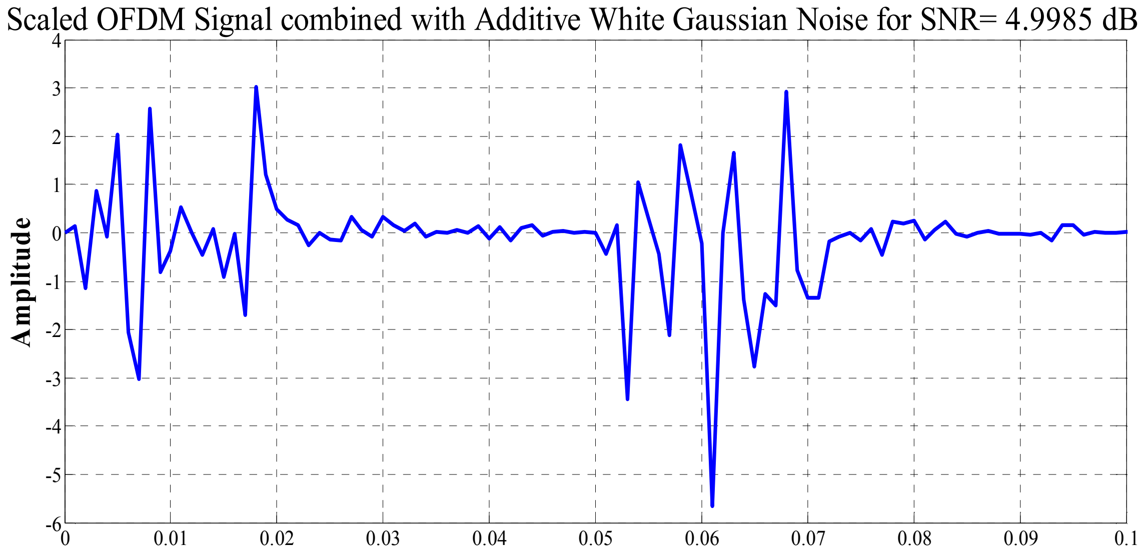


Figure 4.10. Scaled combination of OFDM signal and AWGN

The generated Additive White Gaussian Noise with SNR value of 5 dB (Figure 4.6) can also be shown as its scatter representation, illustrated in Figure 4.11. The specified locations of purple coloured circles displayed in figure below, are determined by the scaled combinational signal of OFDM and AWGN.

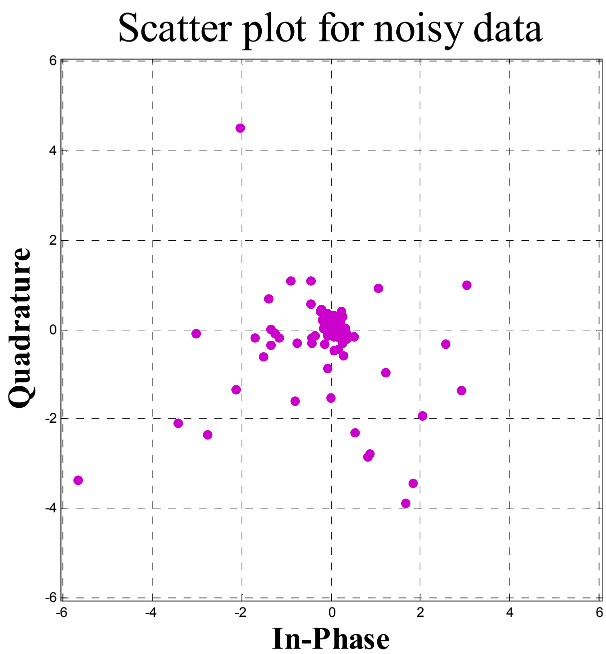


Figure 4.11. Scatter representation of the scaled combination of OFDM signal and AWGN

In order to remove the added noise from the signal entering the receiver, "`rdivide(A,B)`" array division technique has been used, where the equivalent

"`A./B`" divides each entry of 'A' by the corresponding entry of 'B'; A and B must be arrays of the same size. A scalar value for either A or B is expanded to an array of the same size as the other.

Consequently, the MATLAB code below has been used, where "Noisy-Signal" and "AWG Noise" is presented in Figures 4.10 and 4.6 respectively. The result of this noise removal is presented in Figure 4.14.

```
"NoiseRemoved=Noisy-Signal./AWG Noise;"
```

4.2.2. Simulation of Receiver

The simulation of OFDM receiver is discussed in this section, containing the step by step results and discussions. The architecture of this particular OFDM receiver is depicted in Figure 4.12.

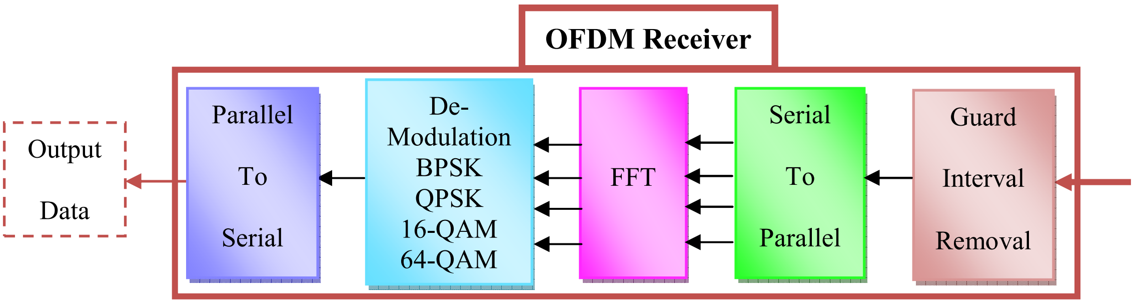


Figure 4.12. Architecture of OFDM receiver

The OFDM receiver basically does the reverse operation to its transmitter, where initially the guard interval is detected and then removed. Later, the FFT of each symbol is then taken to find the original transmitted spectrum. The phase angle of each transmission carrier is then evaluated and converted back to the original transmitted data by demodulating the received phase. The suitable data size received are then combined and re-formatted back to the original serial data stream.

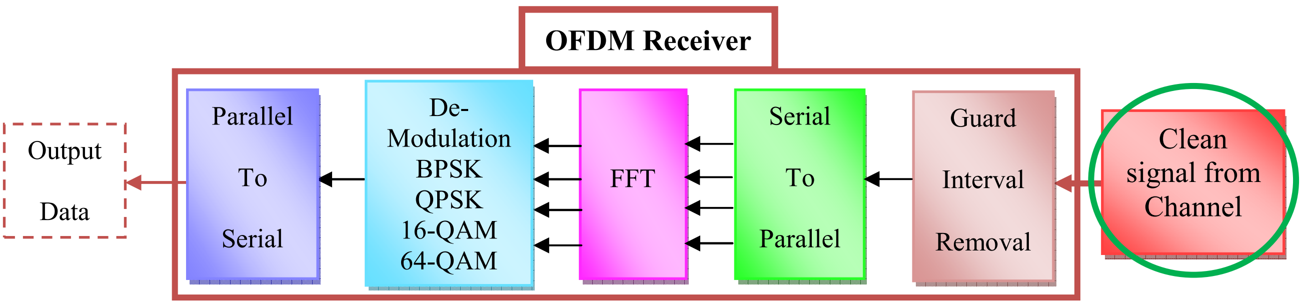


Figure 4.13. Architecture of OFDM receiver with clean signal from channel

As depicted in Figure 4.13, the initial stage for OFDM reception is to receive the output signal from the channel, where the signal is corrupted with applied noise within the channel that needs to be removed. The received input signal to the OFDM receiver, and removal of noise is shown in Figure 4.14.

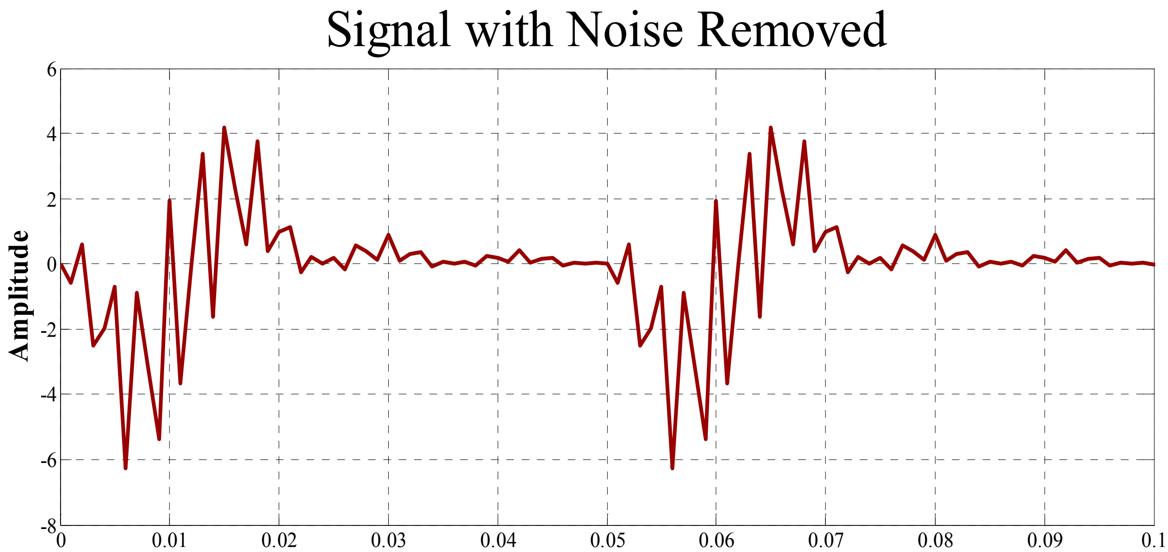


Figure 4.14. Clear input signal to the OFDM receiver

Following the reception of the signal without noise, the first step would be to detect and then remove the cyclic prefix in the received OFDM signal, shown in Figure 4.15.

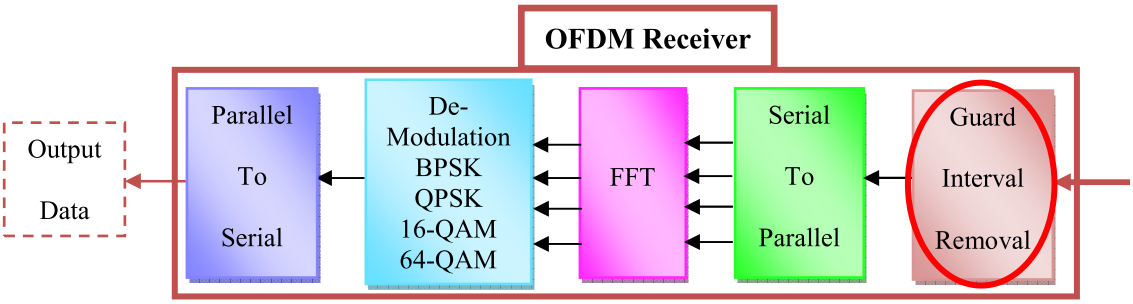


Figure 4.15. Architecture of OFDM receiver with guard interval removed

In doing so, the percentage of OFDM signal that was previously allocated to the cyclic prefix will be highlighted i.e. detected, and consequently assigned an amplitude of ‘0’ to the rest of the OFDM signal, as depicted in Figure 4.16.

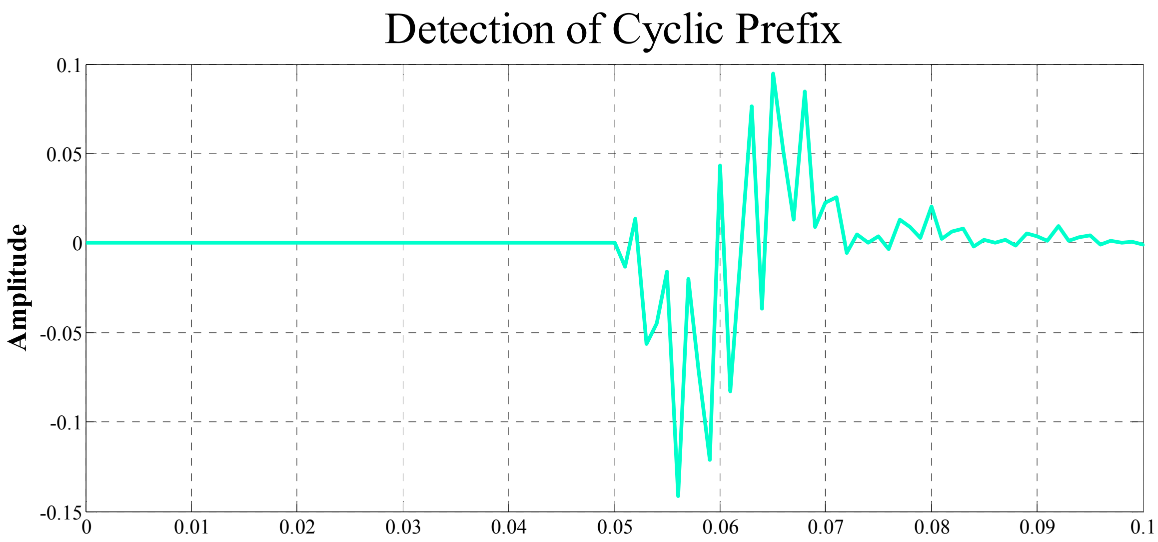


Figure 4.16. Detection of cyclic prefix

The next stage after detection of cyclic prefix would be to remove the highlighted cyclic prefix, and therefore obtaining the original signal prior to cyclic prefix insertion. Figure 4.17 shows the signal with cyclic prefix removed and as a result the original OFDM signal obtained.

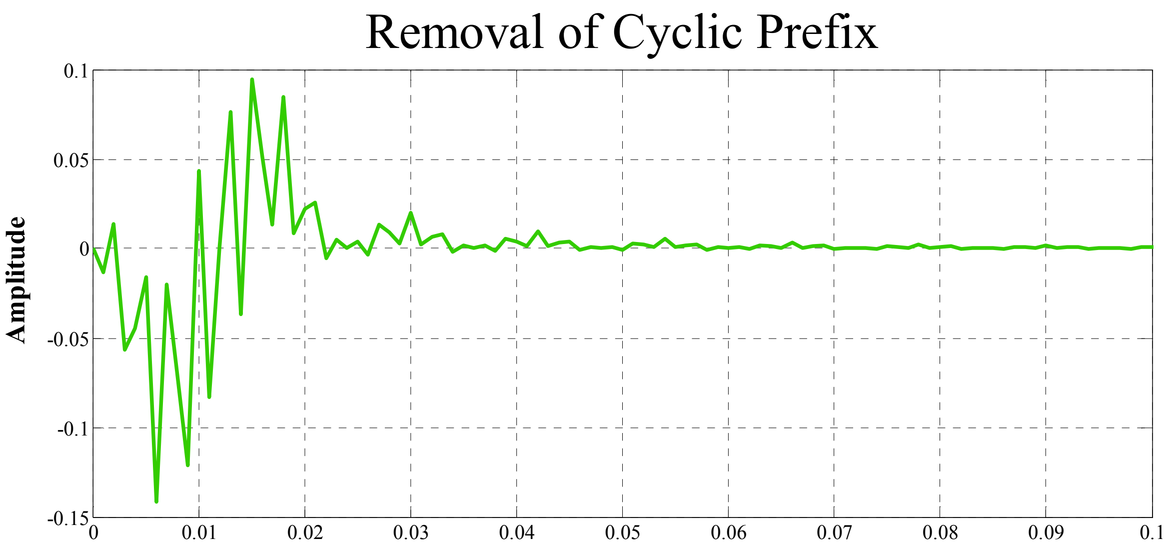


Figure 4.17. Obtaining the original signal by removing of cyclic prefix

In order to confirm the closeness and similarities between the transmitted signal (prior to cyclic prefix insertion) and the received signal (after the removal of cyclic prefix), the two signals have been superimposed onto each other for comparison, as depicted in Figure 4.18.

As it is shown in figure below, the transmitted signal is highlighted in red and the received signal is highlighted in green colour. It can be observed that these two transmitted and received signals are exact replica of each other. This confirms the correct transmission and reception of the signals and ultimately correct operation of the designed OFDM modem.

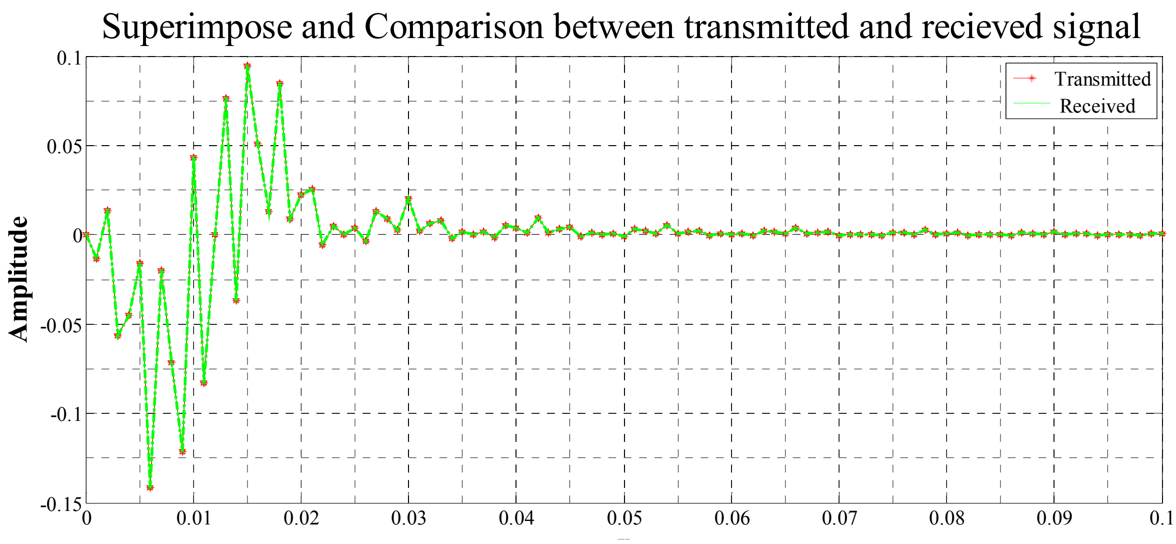


Figure 4.18. Superimpose and comparison graphs of the transmitted and received signals

Following the cyclic prefix removal and comparison between the transmitted and received signals, the next step is to initially apply the serial to parallel conversion and later apply the Fast Fourier Transform (FFT) to the signal, architecture of which is depicted in Figure 4.19.

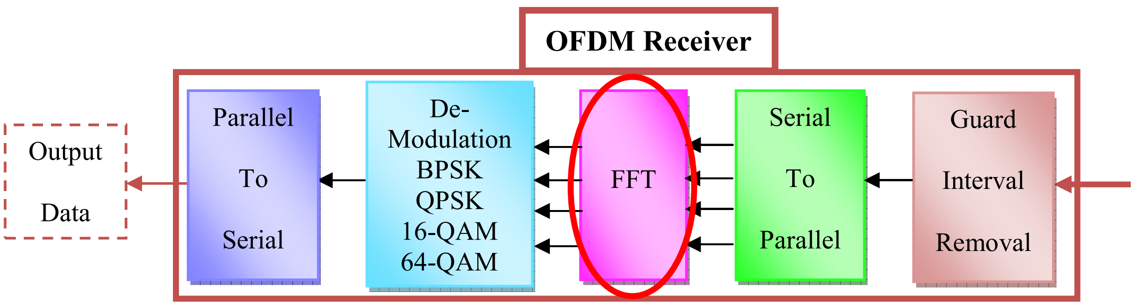


Figure 4.19. Architecture of OFDM receiver – Applying the FFT to the received signal

The result of applying this FFT demodulation technique is depicted in Figure 4.20.

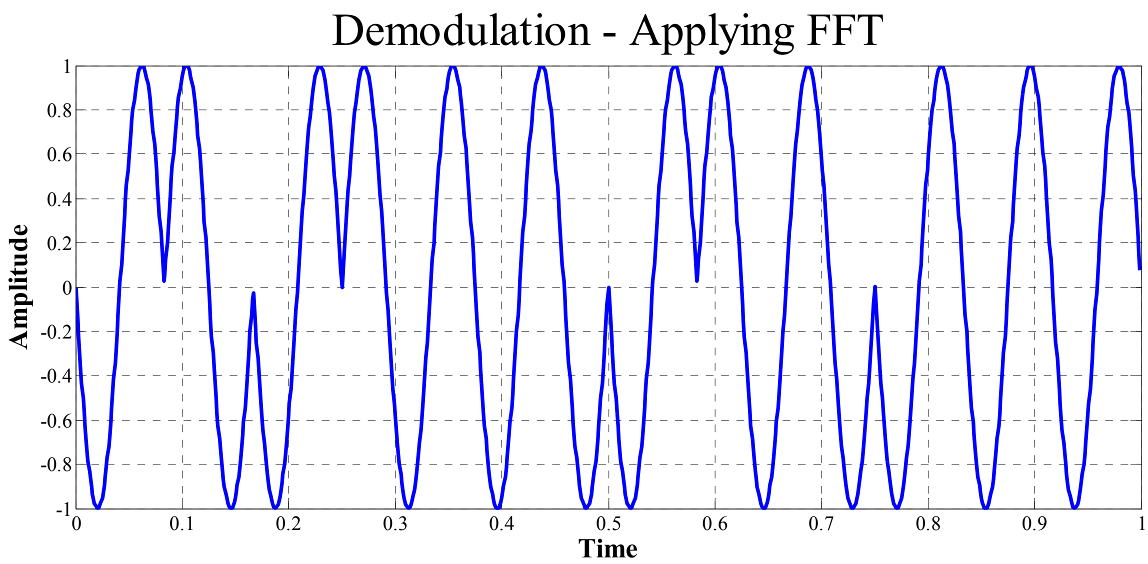


Figure 4.20. Demodulating the received signal by applying the FFT

Prior to continuing with the next de-modulation stage, various verifications on the reception of correct data are completed. One is to superimpose the transmitted square signal onto the received demodulated signal as shown in Figure 4.21.

It can be observed that with each change in state of bits, the received signal depicted in blue changes phase of 180°. This comparison clearly verifies the correct functioning of the receiver and transmitter.

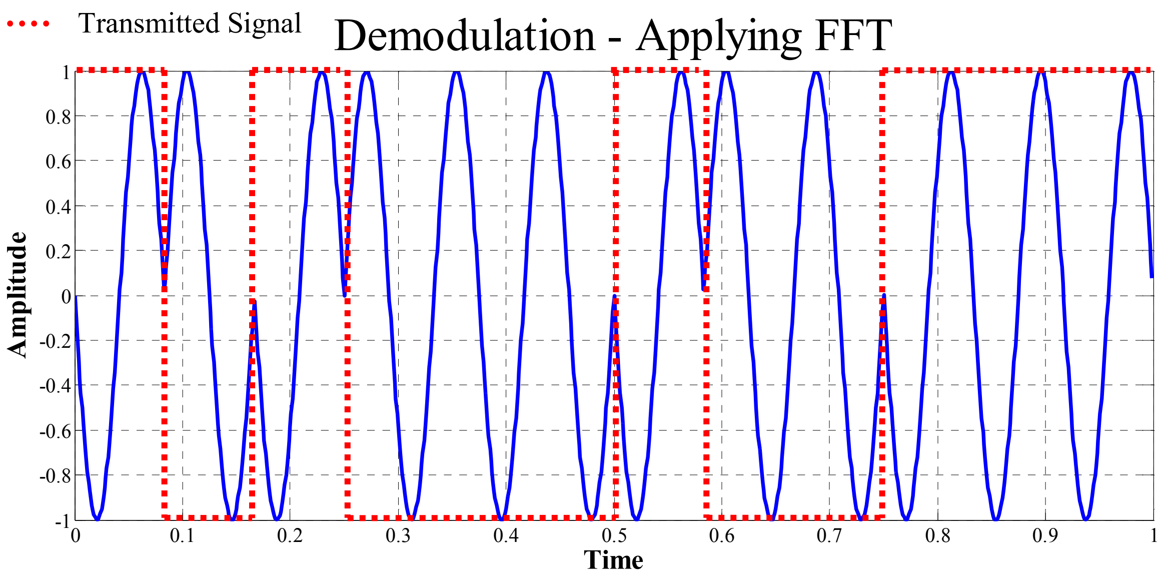


Figure 4.21. Superimposing transmitted square signal onto the received demodulated signal

The second verification is done in order to confirm the closeness and similarities between the transmitted signal (after the modulation - IFFT) and the received signal (after the demodulation – FFT), where the two signals have been superimposed onto each other for comparison, as depicted in Figure 4.22.

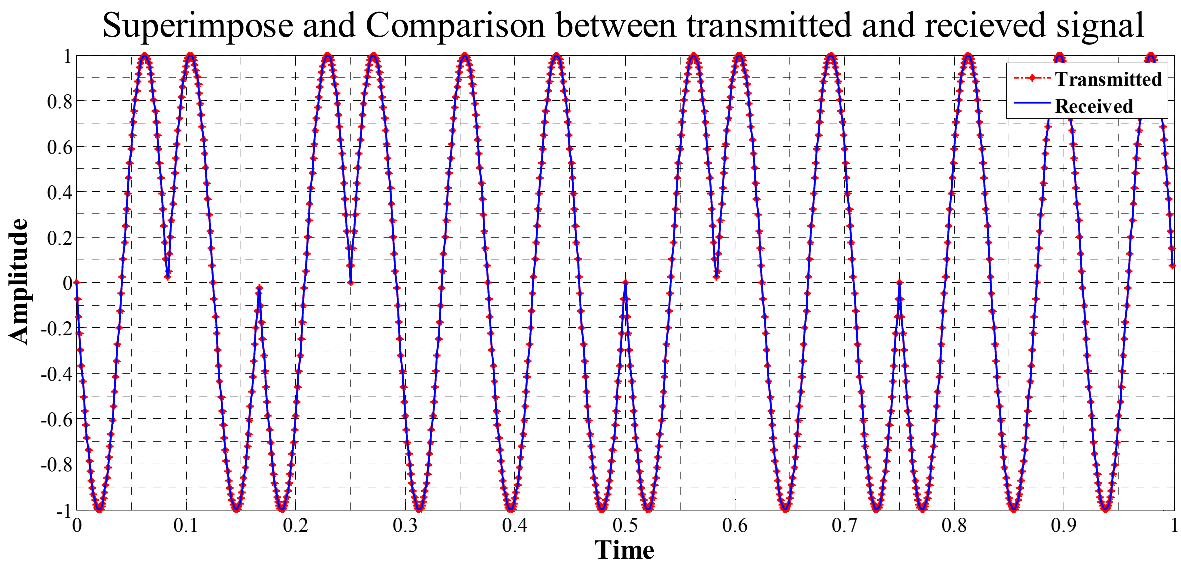


Figure 4.22. Superimpose and comparison between the modulated transmitted and demodulated received signals

As it is shown in figure above, the transmitted signal is highlighted in red line marked with red stars and the received signal is highlighted in solid blue line. It can be observed that these two modulated-transmitted and demodulated-received signals are exact replica of each other. This comparison again, clearly confirms the correct functioning of the receiver and hence correct operation of the designed OFDM modem.

The architecture of the receiver (Figure 4.23) illustrates that following the demodulation of the received signal, with use of FFT operation, and after comparison of the modulated-transmitted and demodulated-received signals, the next step would be to apply the demodulation to the received signal.

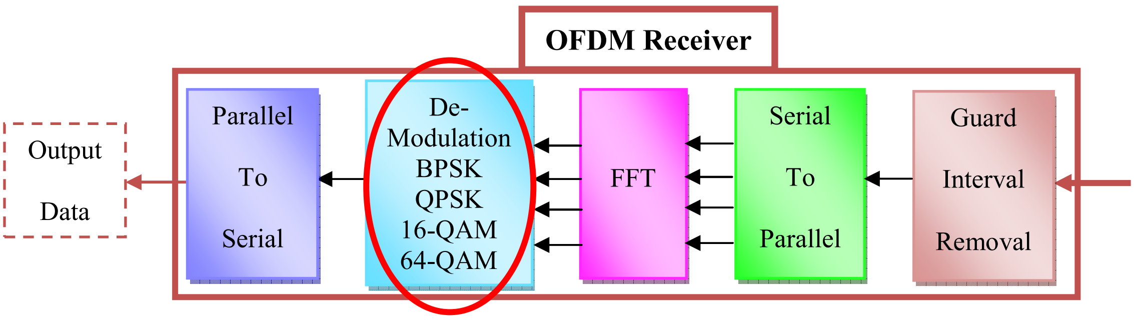


Figure 4.23. Architecture of OFDM receiver – Applying the de-modulation to the received signal

The result of applying this demodulation technique through the reverse operation of phase shift keying is depicted in Figure 4.24.

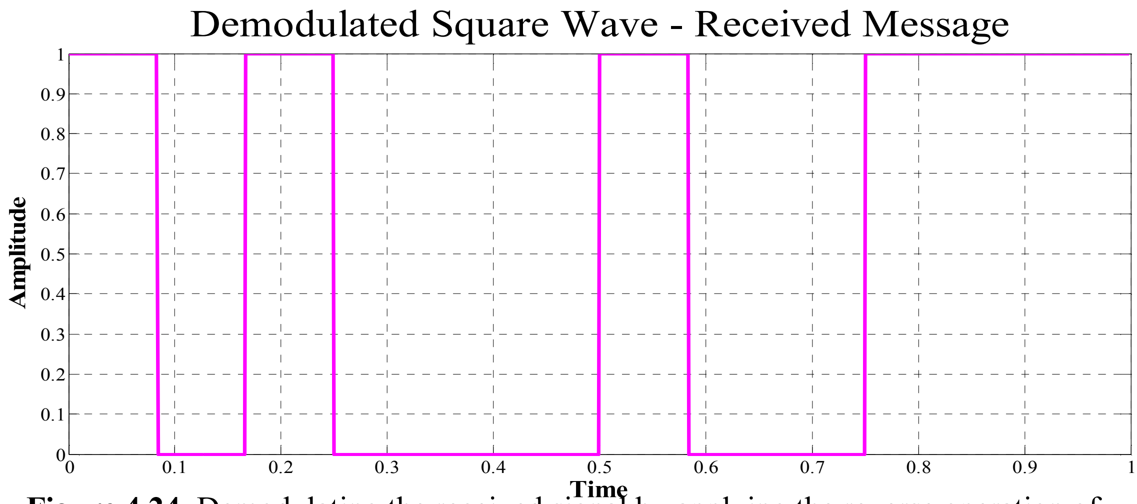


Figure 4.24. Demodulating the received signal by applying the reverse operation of PSK

Once again, in order to confirm similarities between the transmitted and received signals, the two signals have been superimposed onto each other for comparison, as depicted in Figure 4.25. As it is shown in figure below, the transmitted signal is highlighted in bright pink solid line and the received signal is highlighted in solid purple line. It can be observed that these two transmitted and received serial data stream are exact replica of each other. This greatly confirms the correct transmission and reception of the data and therefore perfect operation of the designed OFDM modem.

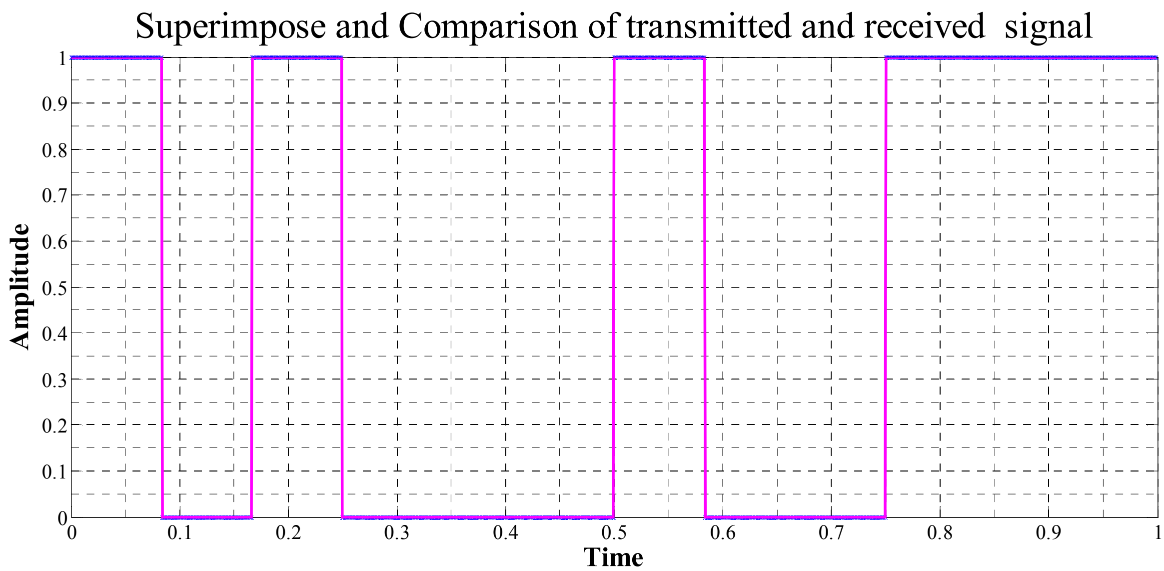


Figure 4.25. Superimpose and comparison of the transmitted and received serial data stream

As explained earlier in Chapter 3, the output message is also an indication of only 12 bits out of 2500 bits.

4.3. Summary

This chapter has covered a brief overview and some of the theoretical background to each of the blocks in the receiver section. The simulation results for each block of the receiver section were also thoroughly presented and analysed in this chapter. This chapter also provided principal and theoretical background to the AWGN channel in context of the current research; definition of SNR and indication of how it is expressed in dB, and the main building blocks of the OFDM receiver including the demodulation, serial to parallel conversion, FFT implementation and cyclic prefix removal. More specifically, a step by step simulation response for both channel and building blocks of the fundamental OFDM receiver modem were presented. Summary of this sequential step by step simulation of the reception of the message are as follows:

1) The message with CP appended to the OFDM signal is passed through the AWGN channel

2) The AWG noise is added to the signal

3) The AWGN is detected and removed

4) The CP appended to the OFDM signal is detected and removed

5) Applying the FFT to the CP-free signal, and superimposing of the transmitted and received signal in confirming the closeness and similarities between them

6) Demodulation of BPSK signal (i.e. the Output of the FFT block) and obtaining the original transmitted binary signal

By following the above steps, it was observed that the two transmitted and received signal were exact replica of each other. This greatly confirmed the correct transmission and reception of the data and therefore perfect operation of the designed OFDM modem. Therefore, this chapter has presented the simulation response for the channel and the individual units of the OFDM receiver. The theory and simulation results for a fundamental OFDM transmission including transmitter, channel and receiver were presented in both previous and the current chapter, the basic theory of which will be employed in designing a more comprehensive OFDM system which will be presented in the following chapter.

Chapter 5

OFDM System and Simulation Results

The theory and simulation results to OFDM transmitter and receiver were presented in Chapters 3 and 4. This chapter attempts to present a brief theoretical background to techniques employed in design of full OFDM system followed by the simulation response and comparative performance studies on comprehensive OFDM modem. This comparative performance study was conducted to understand and recognise the most suitable technique for the transmission of message or image within a communication system.

5.1. Theoretical Background to Techniques Employed in Design of Full OFDM System

The results presented in this chapter are based on the three comparative performance for different modulation type and order, and also application of forward error correction scheme. The theoretical background to the different modulation types were thoroughly covered in Chapters 3 and 4. The theories for forward error correction and channel encoding are therefore, covered in the present chapter. This section aims to provide a concise theoretical background to the techniques employed in designing of full OFDM communication system for this research.

5.1.1. Basic Concepts of Channel Encoding

The channel coding, in digital communication, is a term mainly referring to the Forward Error Correction code and interleaving. Such encoding scheme is employed to control errors in data transmission and protect data sent over the channel for storage or retrieval. As it is illustrated in Figure 5.1, the channel encoder is one of the main units within the transmitter and receiver subsystems.

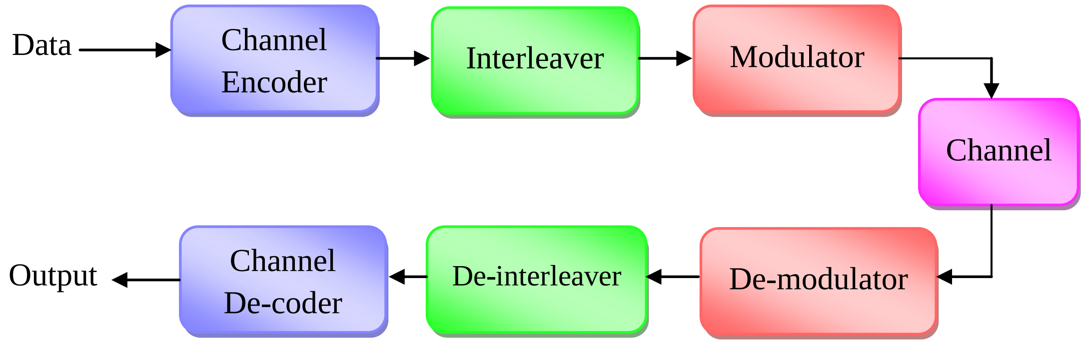


Figure 5.1. A typical communication system

In a typical communication system, the data is initially coded and then interleaved. Interleaving block is responsible for avoiding the burst errors. The interleaved data is then transmitted through a modulation over a noisy channel. These operations are reversed at the receiver, in order to retrieve the transmitted data.

The basic principles for all the correction codes are the same; as the errors introduced in the process of transmission or storage can be corrected by adding the redundancy to the information. The code word or the coded sequence is fundamentally obtained by adding the redundant symbol to the information symbol, as illustrated in Figure 5.2.

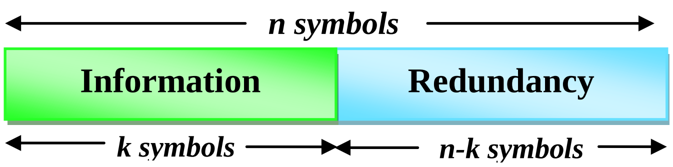


Figure 5.2. A systematic block encoding for error correction [145]

Figure 5.2 shows a systematic block encoding for error correction, where the information symbols appear in the leftmost (first) k positions of a code word. The remaining symbols ($n - k$ symbols) are a function of the information symbols. Such symbols provide redundancy, which can be used for error correction and/or detection purposes. It is also worth mentioning that, the order of information and redundancy can be switched [145].

Channel coding can be classified in two main categories of convolutional coding and block coding. Both of which have found practical applications. Convolutional coding is a more commonly used channel coding, while the block coding is usually based on the finite field arithmetic and abstract algebra.

In this research Forward Error Correction (FEC), Convolutional Channel Encoding (CCE) and Block Channel Encoding (BCE) have been used, background of which is presented below.

5.1.2. Forward Error Correction (FEC) Coding

In the FEC coding scheme, the transmitted data is encoded in a way allowing some of the error caused by the channel noise, to be detected and corrected. The purpose of such coding scheme is to improve channel's ability. This is achieved when the data being transmitted is added to some of the designed redundant information (Figure 5.2), process of which is referred to as channel coding.

5.1.3. Convolutional Channel Encoding (CCE)

Convolutional coding technique works on data with serial format (i.e. one or few bits at a time), where it is responsible for mapping each *k* bits of the input stream on the *n* bits of the output stream. Mapping of the input bits on the output bits is achieved by convolving the input bits with the binary impulse response. Such encoding technique can be implemented using a simple shift registers and modulo-2 adders; Figure 5.3 presents an encoder with code rate of ½.

The coding rate is chosen based on the standards and the desired data rate; in which the data that are encoded through a convolutional encoder must have a coding rate (*R*) of 1/2, 2/3 or 3/4 [27]. Code rate of ½ has been employed in this research and is one of the most commonly applied convolutional codes, where it consists of one input data and two output data.

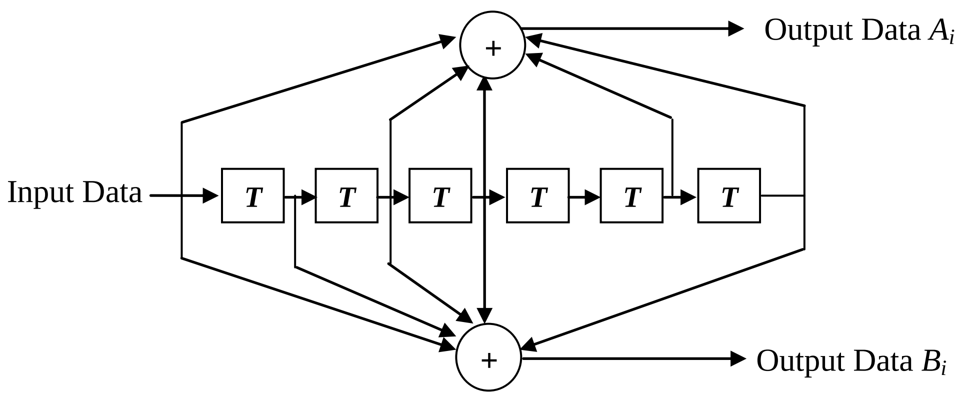


Figure 5.3. Block diagram of convolutional encoder for k = 7 [27]

As illustrated in Figure 5.3, this convolutional encoder consists of one input data and two output data (A_i and B_i), hence the coding rate of ½. It is worth mentioning that the two output data get interleaved to produce a coded data sequence as: $\{A_1B_1\ A_2B_2\ ...\}$. The output bits (A_i, B_i) depend on both the input data and the six input bits stored in the shift registers, i.e. total of 7 input bits. The number of bits that determine the output bits; in this case 7 or as a rule, the length of the shift register plus 1, are called the *constraint length*. The bit values for each corresponding taps of the shift registers are usually specified by the equivalent generator vectors or generator polynomials. The generator vectors employed in this research, and the example illustrated above, are {1011011, 1111001} or {133, 171} in octal, which directly correspond with the number of taps on the shift registers plus one input bit [27]. Therefore the generator vectors are generally selected in way that their octal format produces the same number of binary values as the one required by the constraint length. Table 5.1 presents a list of constraint length (length of shift registers plus 1) and the corresponding vector generator for the rate ½ convolutional codes.

Table 5.1. Rate ½ Convolutional Codes [146]

Constraint Length	Vector Generator (Octal)
3	(5,7)
4	(15,17)
5	(23,35)
6	(53,75)
7	(133,171)
8	(247,371)
9	(561,753)
10	(1167,1545)

Decoding of the above explained encoding technique (Convolutional encoding) is usually performed by the soft decision Viterbi decoding. Such decoding technique is known for its efficiency in achieving the most optimal maximum likelihood (ML) estimate of the encoded sequence [147]. It is important to state that an increase in the constraint length will significantly increase the complexity of Viterbi decoding, therefore a constraint length of no higher than 10 will be selected for the practical implementation. Nevertheless, the convolutional codes for large constraint length can still be decoded using suboptimal decoding techniques like sequential decoding [37, 147, 148].

5.1.4. Block Channel Encoding (BCE)

Unlike convolutional encoding, block encoding works on large message blocks, usually around hundreds of bytes. Such encoding technique operates by encoding a block of k input symbols into n coded symbols, where $n > k$, i.e. addition of redundant symbols (n-k) [27].

The message inside each block holds k information symbol over an alphabet set $\sum$. A mathematical expression for each message is given by Equation 5.1. Therefore, the total possible number of different message can be written as: $|\sum|^k$

$$m = (m_1, m_2, \ldots, m_k) \in \sum^k \tag{5.1}$$

In addition, the message (m) gets transformed onto code-word (c); mathematical expression for each code-word is given in Equation 5.2. The $\sum^n$ represents code of block length (n) [146].

$$c = (c_1, c_2, \ldots, c_n) \in \sum^n \tag{5.2}$$

Similarly, the total possible number of different code-words can be written as: $|\sum|^k$, where k is referred to as the *dimension*. Additionally, the rate of block codes (R) can be described as Equation 5.3 [146]:

$$R = \frac{k}{n} \tag{5.3}$$

As stated above, redundant symbols are added in a block coding scheme, purpose of which is an increase in the minimum Hamming distance. Minimum Hamming distance (d_{min}) is referred to as the least number of different symbols between each pair of code-words [38]. For d_{min}, the block code can correct number of errors, denoted as t ; mathematical expression for t is given in Equation 5.4 [37, 149]:

$$t \leq floor\ (\frac{d_{min} - 1}{2}) \tag{5.4}$$

Note: $floor(x)$ is a floor function which rounds the x downwards to the closest integer value.

The notations of: $(n, k, d)_{\Sigma}$ correspond to:

- *n*: Block length
- *k*: Dimension
- $\sum$: Alpha set
- *d*: Distance

There are different types of useful convolutional and block codes, together with variety of decoding algorithms. Unlike convolutional encoding, block encoding cannot be efficiently decoded with Soft-Decisions Decoding (SDD). However, this limitation of block encoding has been resolved during the recent developments of theory and design of SDD algorithms [146]. This research will therefore study and recognise the most suitable encoding technique for the transmission of message or image within a communication system.

5.1.5. Interleaving Technique

As discussed in Chapters 1 and 2, due to the frequency selective nature of high data rate communication channels, OFDM subcarriers generally have different amplitudes. Occurrence of deep fades in the frequency spectrum can reduce reliability of the affected groups of subcarriers. This, therefore, causes bit errors to occur in bursts instead of being randomly scattered [37]. Since the forward error correction codes do not generally deal with error bursts, there needs to be a technique to randomise the occurrence of bit errors. This can be achieved by applying the interleaving prior to decoding. Following interleaving, the coded bits in the transmitter, are permuted in a certain way, which ensures that the adjacent bits are separated by several bits. While in the receiver, a reverse permutation is carried out before decoding.

One of the commonly used forms of interleaving technique is the Block interleaver. In such techniques, input bits are written in a matrix column by column and read out row by row, Table 5.2 is an example for operation of this technique. As it is illustrated in this table, the bit numbers of a block interleaver operate on a block size of 48 bits. These 48 bits are written in the matrix according to the order (column by column) and the interleaved bits are delivered row by row, and therefore, the output bit numbers are 0, 8, 16, 24, 32, 40, 1, 9, ... 47.

Table 5.2. Interleaving scheme [37]

0	8	16	24	32	40
1	9	17	25	33	41
2	10	18	26	34	42
3	11	19	27	35	43
4	12	20	28	36	44
5	13	21	29	37	45
6	14	22	30	38	46
7	15	23	31	39	47

This operation can also be applied on symbols instead of the bits; for example, the matrix can be filled using 48 16-QAM symbols, having 4 bits per symbol. So, although the symbol order are changed due to interleaving, but the bit order within each symbol remains unchanged. Such symbol-based interleaving technique is particularly practical for Reed-Solomon codes, since these codes work on symbols rather than bits [37]. Since this type of code (Reed-Solomon), can only correct a limited number of symbol errors per block length, interleaving should therefore, be carried out over several block lengths, attempting to spread the symbol errors over different Reed-Solomon blocks.

If a general block interleaver is assumed to have a block size of N_B (N_B: number of bits) and d columns, the i^{th} bit on the output (or interleaved bit) will be equal to the k^{th} bit on the input. In other words, every bit that enters the input of the interleaver block, gets relocated based on the applied modulation scheme, in order to randomly spread the burst errors over the entire block, where k is given by Equation 5.5 [37]:

$$k = id - (N_B - 1)floor\left(\frac{id}{N_B}\right) \tag{5.5}$$

Conventional interleaver is also possible to use in place of a block interleaver, example of which is illustrated in Figure 5.4.

As it is shown in this figure, the input symbol (or bit) is cyclically written, by the interleaver, into one of *k* shift registers which introduces a delay of 0 to *k-1* symbol durations. The output symbols (or bits) of the shift registers are cyclically read out, to produce the interleaved symbols [37].

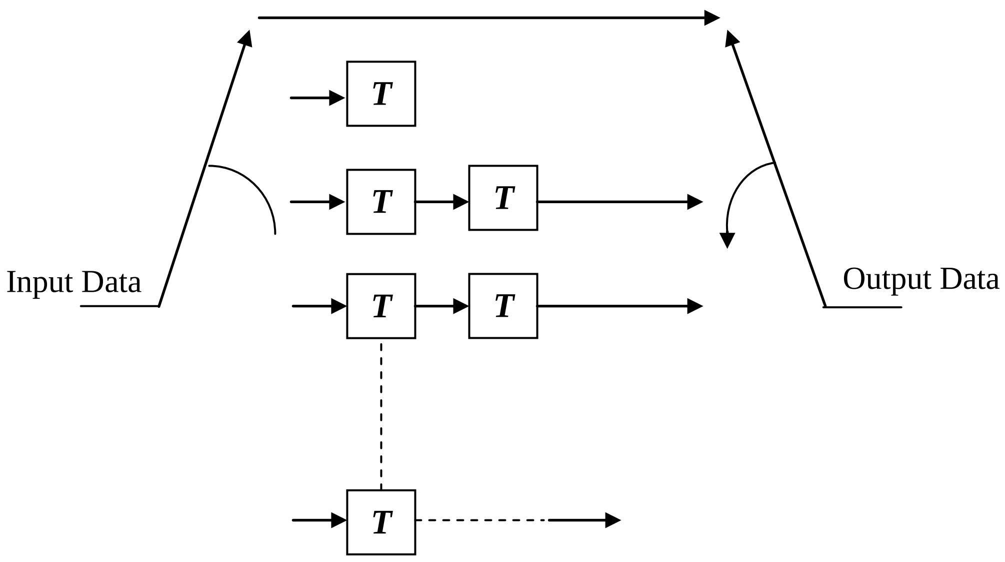


Figure 5.4. Convolutional interleaver [37]

5.2. Simulation Response and Comparative performance studies on more comprehensive OFDM

Chapters 3 and 4 illustrated the input and output signal shape for different types of digital modulation techniques and later presented the simulation response of fundamental OFDM modem. The obtained results greatly confirmed the correct transmission and reception of the data and therefore perfect operation of the designed OFDM modem. Furthermore, this section will include analysing three different techniques listed below, for achieving better communication performance, all of which will be further explained in the following parts:

i) Different modulation order

ii) Different modulation type

iii) Application of Forward Error Correction scheme

It is important to note that, in order to have a full functioning communication system, the three basic units of communication system, i.e. transmitter, channel and receiver should be available. Consequently, in order to decide on the most suitable modulation type, modulation order and Channel encoding and error correction type, a channel should be available. In this project, the AWGN channel has been selected as a linear continuous memory-less channel model.

Table 5.3 consists of simulation parameters for MATLAB simulation model and the values used in this research, in an attempt to analyse the AWGN channel by applying the three techniques and schemes stated above.

It is important to note that the modulation orders of 32, 128 and 512 (i.e. 2^5, 2^7 and 2^9) for the chosen schemes has not been plotted for simplicity of the following graphs, as for example the BER graphs for modulation order of 512 will be very similar to the BER graphs of modulation order of 256 and 1024 .

Table 5.3. Simulation parameters and the values used by the MATLAB simulation model

Parameter	Value
Nominal channel bandwidth	2.5 MHz
Cyclic prefix	1/4
Number of used sub carriers	200
Modulation Types	PSK, FSK, QAM
Modulation Orders	2, 4, 8, 16, 64,256, 1024
Channel	AWGN

By using the parameters and values of Table 5.3, OFDM modem is simulated and different comparison graphs are produced and illustrated in order to demonstrate the performance of the system and effects of combining each technique.

5.2.1. Different Modulation Order

The number of different symbols that are transmitted through digital communication are known as the modulation order. Second order digital modulation for PSK is commonly referred to as binary phase shift keying (BPSK) which is known to be the simplest form of modulation, due to transmission of only two symbols. The higher-order modulations, as the name implies are the high modulation order of 4 and above.

The performance of a communication system depends on several factors, one of which is determining the bit error rate or symbol error rate of the applied technique [6, 7]. These Bit Error Rate (BER) or Symbol Error Rate (SER) will be presented and discussed in the next few sub-sections.

The performance of communication system is usually presented through the use of BER waterfall graphs, representing the number of errors that occur in a string of bits. Figures 5.5 and 5.6 depict BER comparative performance study for M-PSK and its generalisation as m-ary QAM (M-QAM). It is also worth mentioning that E_s is the energy in one symbol and N_o is the noise power spectral density.

It is also worth noting that the SER plot for PSK and QAM modulation scheme, illustrated in Figures 5.5 and 5.6, are a simulation response for the symbols passing through an AWGN channel and therefore, the noise produced are due to the presence of the additive White Gaussian noise.

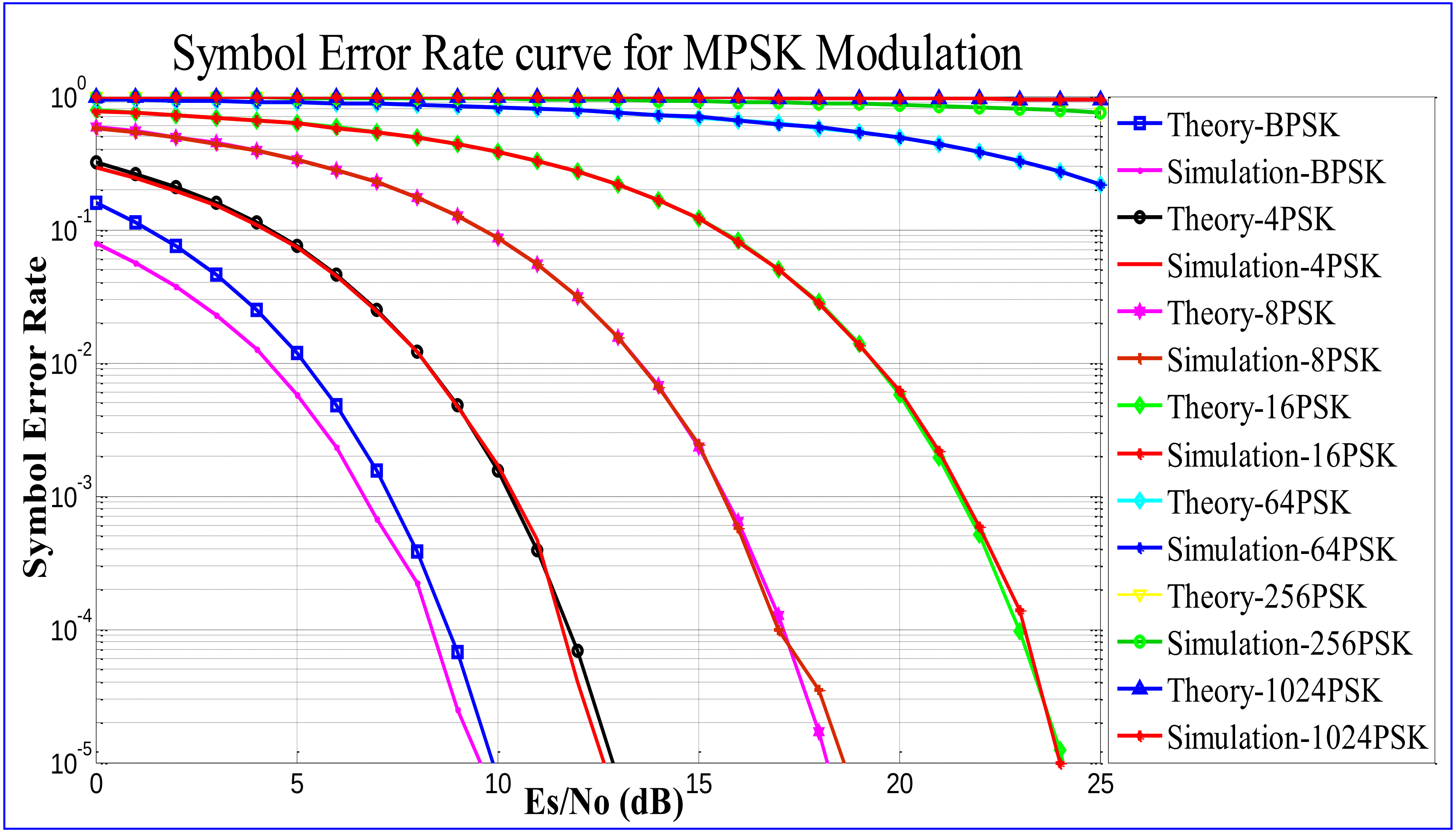


Figure 5.5. Symbol Error Rate for PSK modulation with different modulation order

Table 5.4 summarises the simulation results presented in Figure 5.5 for different modulation order.

Table 5.4. Simulation results for different modulation order (***n***PSK)

PSK Modulation Order	Bit per symbol	Symbol Rate (x bit rate)	Maximum E_s/N_o loss relative to BPSK (dB)
BPSK	1	1	0
QPSK	2	$^1/_2$	3
8PSK	3	$^1/_3$	8.7
16 PSK	4	$^1/_4$	14.5
64 PSK	6	$^1/_6$	-
256 PSK	8	$^1/_8$	-
1024 PSK	10	$^1/_{10}$	-

It is illustrated in figure 5.5 and highlighted in Table 5.4, that M-PSK outperforms when the modulation order is M = 2 (i.e. BPSK). It can also be seen that lower modulation order (e.g. BPSK and QPSK) produces lower SER values and hence better performance. This relation can be regarded as the direct proportionality between the SER value and the modulation order.

In contrast, higher order modulation schemes (e.g. 64PSK, 256PSK, etc) are able to carry high data rates, offer much faster data rates and are less resilient to noise and interference. However, lower order modulation formats (e.g. BPSK, QPSK, etc.) offer lower data rates but are more robust in presence of noise.

In addition to lower data rates and high strength of the BPSK modulation in presence of noise, they are also the simplest modulation format for implementation. Beside these advantages, their very good performance in communication systems, in comparison to the rest of the PSK modulation orders, makes them the most suitable modulation order.

Although BPSK is known to be the most suitable modulation order, but some communication systems require data rates beyond those offered by BPSK or 8-PSK, for which different modulation orders of QAM are functional. This is due to the fact that in QAM modulation, greater distance between adjacent points in the I-Q plane is achieved by distributing the points more evenly, as depicted in Table 5.5. This way is advantageous as it reduces the errors by separating the points on the constellation. A variety of forms of QAM are available, some of the more common forms include 4QAM, 16QAM, 64QAM, 128QAM and 256QAM, which are depicted in Figure 5.6.

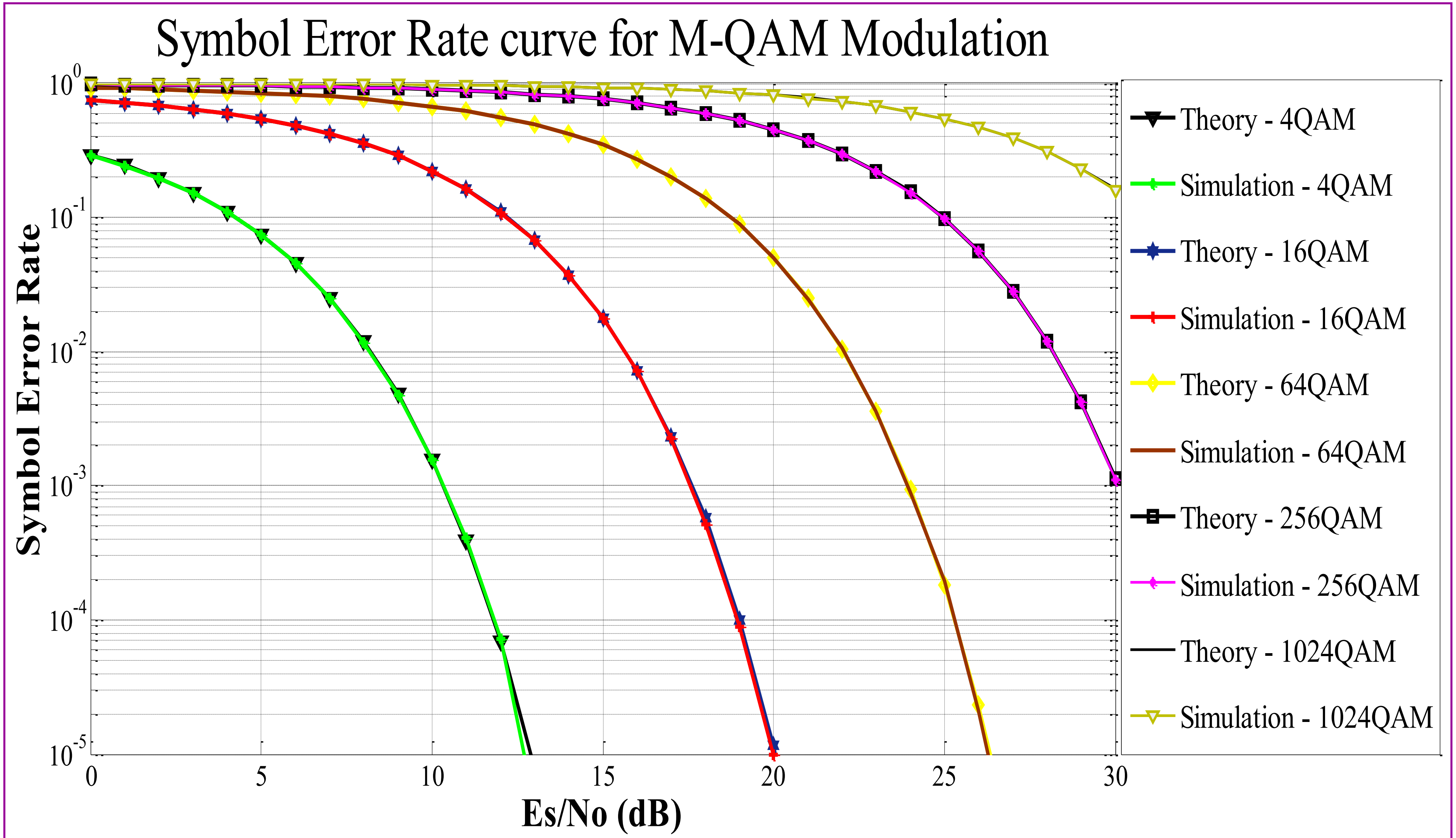
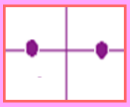
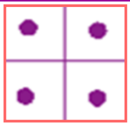
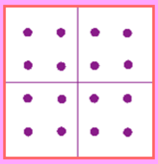
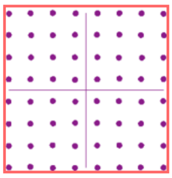
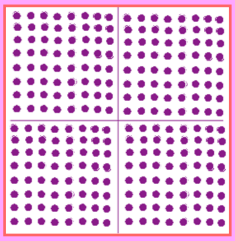
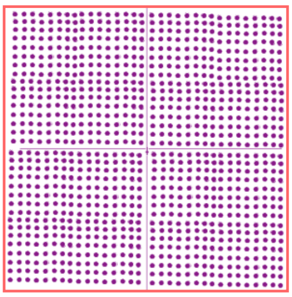


Figure 5.6. Symbol Error Rate for QAM modulation with different modulation order

Table 5.5 summarises the simulation results presented in Figure 5.6 for different QAM modulation order. The different positions for the bit states within different forms of QAM are presented in constellation diagrams shown in Table 5.5. It can be observed that the number of points on the QAM constellation diagram increases with an increase in the order of QAM modulation.

Table 5.5. Simulation results for different modulation order (***n***QAM)

QAM Modulation Order	Bit per symbol	Symbol Rate (x bit rate)	Maximum E_s/N_o loss relative to BPSK (dB)	M- QAM Constellation diagrams
BPSK	1	1	0	
4-QAM	2	$^1/_2$	3	
16- QAM	4	$^1/_4$	10.5	
64- QAM	6	$^1/_6$	16.3	
256- QAM	8	$^1/_8$	-	
1024- QAM	10	$^1/_{10}$	-	

Although using higher modulation order QAM in communication system allows more bits per symbol to be transmitted, and considering that the energy of the constellation is essentially required to remain the same; then the closer together the points on the constellation are, the weaker and more susceptible to noise the transmission would be. This would, in comparison to the lower order QAM, produce higher bit error rate keeping the balance between attaining the higher data rates and preserving an acceptable bit error rate for any communication system.

As it is presented in Figure 5.6 and highlighted in Table 5.5, the M-QAM outperforms when the modulation order is lower (i.e. 4QAM). It can also be seen that lower modulation order such as 4QAM produces the lower SER values, similar results to 4PSK, and hence better performance. This relation can again be regarded as the direct proportionality between the SER value and the modulation order.

However, the main advantage of using QAM is that it is a higher order form of modulation. As a result of having a higher order format; it is able to carry more bits of information per symbol, offers much faster data rates and is less resilient to noise and interferences. However, lower order modulation formats (e.g. BPSK, 4QAM and 16QAM etc.) offer lower data rates but are more robust in presence of noise.

In addition to lower data rates and high strength of 4QAM modulation in presence of noise, they are also simple modulation format for implementation. Beside these advantages, their good performance in communication systems, in comparison to the rest of the QAM modulation orders, makes them the suitable modulation order.

Following the analysis and comparison of different modulation orders for PSK and QAM, Table 5.6 is produced in order to present the most suitable modulation type/order according to the highest number of advantages. It is worth mentioning that every tick in the Table 5.6, for each modulation type/order stands for that particular advantage, therefore the higher the number of ticks, the better the performance of that particular modulation type or order.

Table 5.6. Category of overall performance for all the simulated modulation types and orders

Modulation Types and Orders	Higher Data Rate (Depends on application)	Lower Data Rate (Depends on application)	Simple to Implement	Robust in presence of noise	Highly Reliable
BPSK		✓	✓	✓	✓
4PSK		✓		✓	
8PSK		✓		✓	
16PSK	✓				
64PSK	✓				
256PSK	✓				
1024PSK	✓				
4FSK		✓	✓		
8FSK		✓			
16FSK	✓				
4QAM		✓	✓	✓	✓
8QAM		✓			
16QAM	✓				
64QAM	✓				
256QAM	✓				
1024QAM	✓				

It is worth mentioning that, these factors do not necessarily become selection criteria for application in other communication systems, as in some systems a fast or slow data rate is required whereas in others, the simple implementation is accounted as priority.

After creating the above table, a column graph depicted in Figure 5.7 is produced. This graph is designed by having the different modulation types and orders versus the number of advantages (ticks) shown in Table 5.6. As it is illustrated figure below, BPSK and 4QAM have the highest number of advantages; hence they are the most suitable and highly reliable modulation types for this types of communication system.

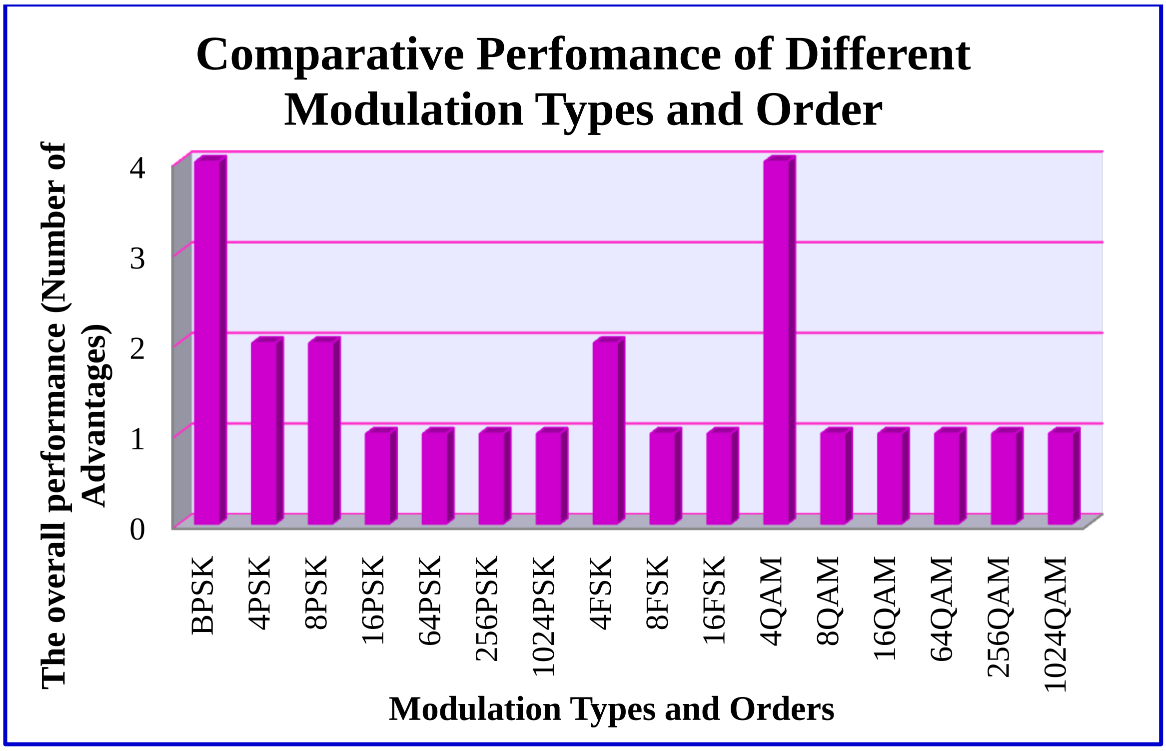


Figure 5.7. Different modulation types and orders versus the number of advantages (ticks)

5.2.2. Different Modulation Types

The performance and characteristics of a system is significantly dependent on the choice of digital modulation scheme. There is no basic rule for choosing a suitable scheme. However, one scheme is better than other depending on the following factors:

- The channel
- Required levels of performance
- The required data rate
- Latency
- Available bandwidth

This part will consider the key performance of the main M-ary modulation schemes (M-PSK, M-FSK and M-QAM) and compares them to each other. This comparison will be carried out according to performances of these modulation schemes using BER graphs in the presence of Additive White Gaussian Noise (AWGN). This means that the performance will be comparatively analysed by varying the modulation order for PSK, FSK and QAM. Comparative performance study using the BER graphs for 2PSK, 4PSK, 8PSK and 2FSK, 4FSK, 8FSK has been completed and illustrated in Figure 5.8.

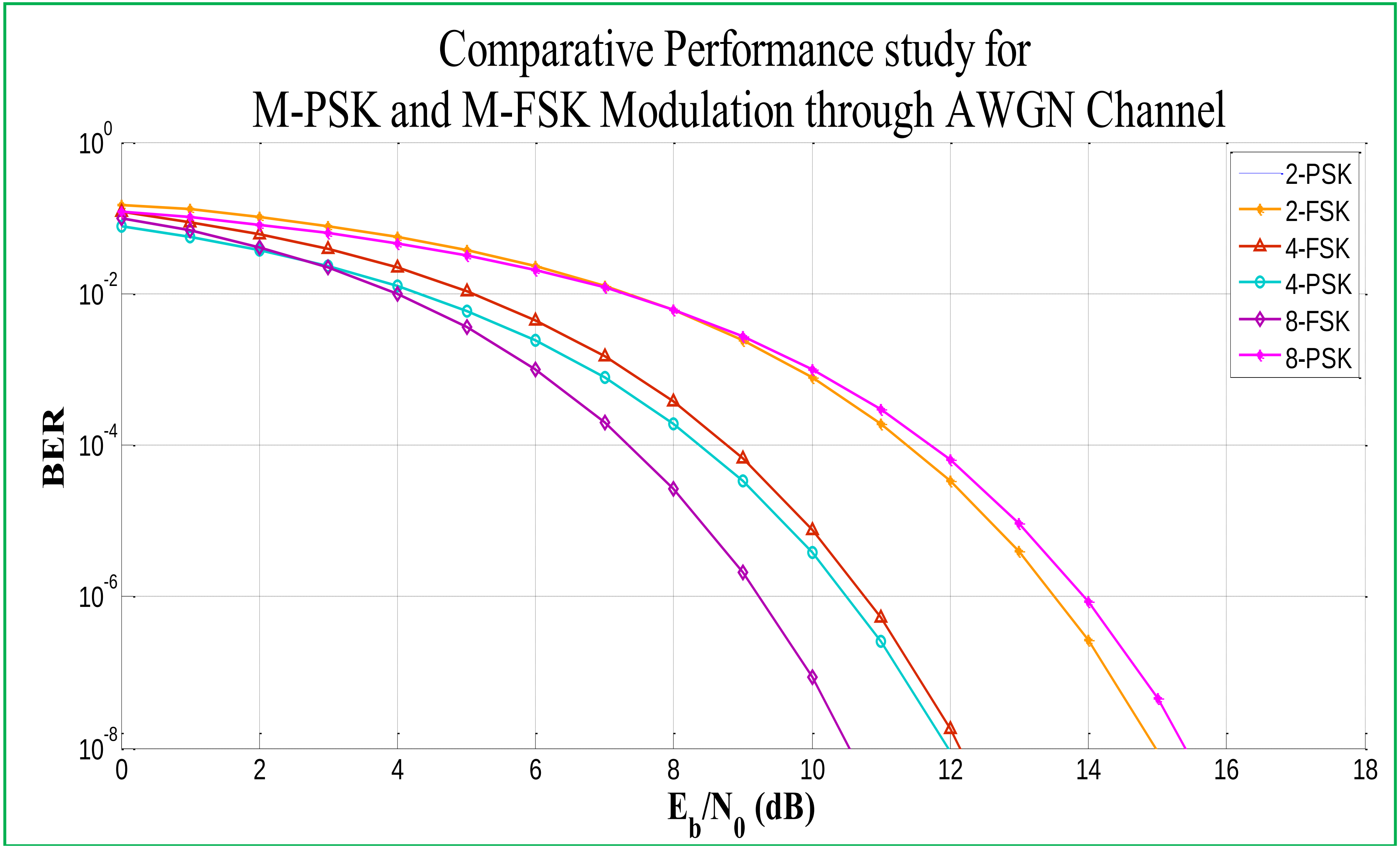


Figure 5.8. Comparative performance study for M-PSK and M-FSK modulation through AWGN channel

As it can be observed from Figure 5.8, some of the data, e.g. BER plot for 2-PSK, cannot be seen; this is due to the fact that the simulation response for 2-PSK coincides with 8-FSK.

Table 5.7. Simulation results for different modulation type and order (***n***PSK and ***n***FSK)

Different modulation types and order	**Bit per symbol**	**Symbol Rate (x bit rate)**	**Maximum E_b/N_o loss (dB)**
2-PSK	1	1	10.5
2-FSK	1	1	15
4-PSK	2	$^1/_2$	12
4-FSK	2	$^1/_2$	12.2
8-PSK	3	$^1/_3$	15.5
8-FSK	3	$^1/_3$	10.5

Based on the graphs illustrated in Figure 5.8 and results presented in Table 5.7, it can be observed that results for M-PSK are showing better performance for lower modulation order. As predicted, lower order modulation formats (e.g. 2PSK and 4PSK) offer lower data rates but are more robust in the presence of noise.

It is also noticeable, that the BER value for higher modulation order (M = 8) is smaller in FSK, but its performance is worse due to the incapability of reproducing the expected signal at the receiver end.

Comparative performance study using the BER graphs for 4PSK, 8PSK, 16PSK and 4QAM, 8QAM, 16QAM has been completed and illustrated figure below.

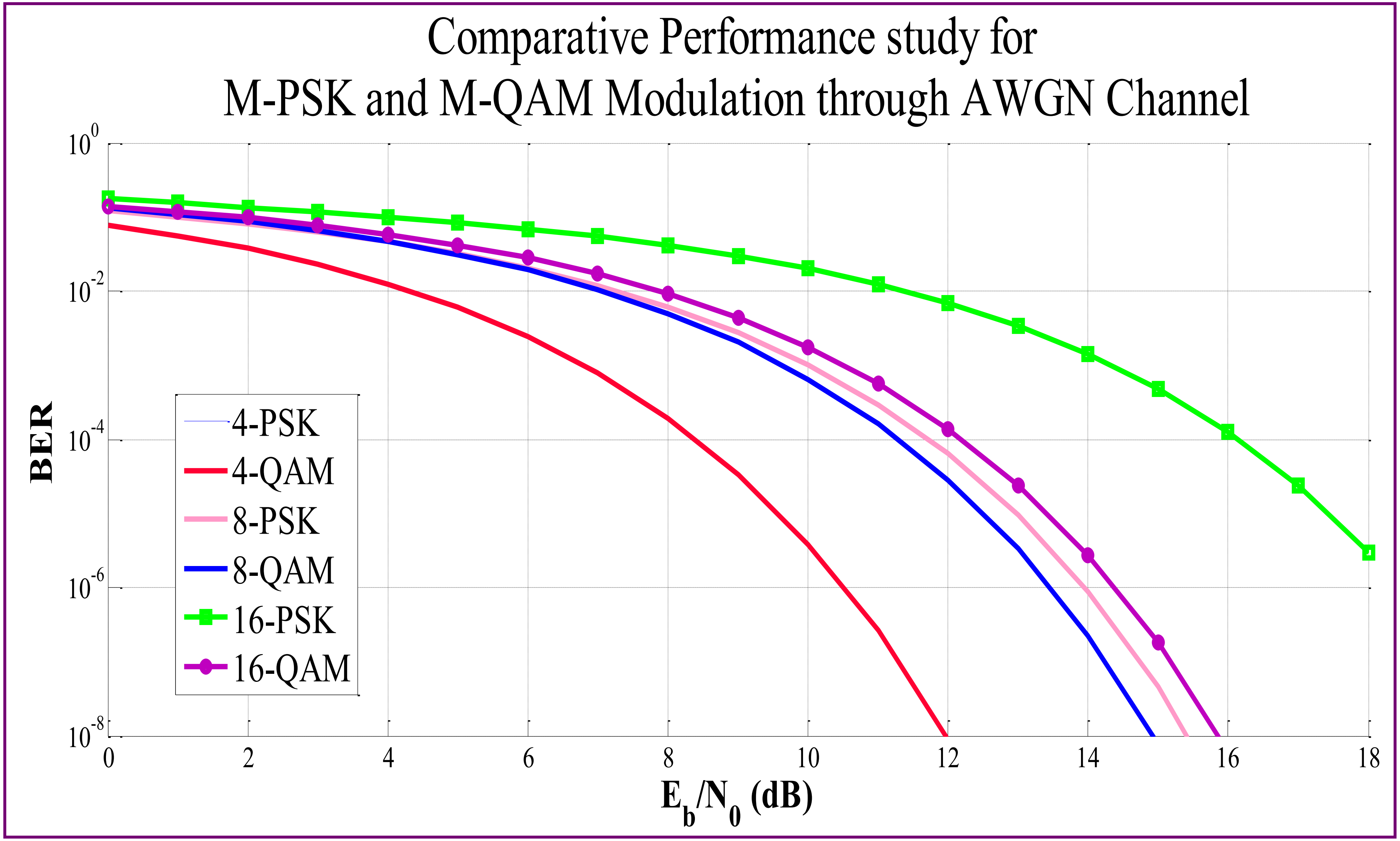


Figure 5.9. Comparative performance study for M-PSK and M-QAM modulation through AWGN channel

As it can be observed from Figure 5.9, some of the data, e.g. BER plot for 4-PSK, cannot be seen; this is due to the fact that the BER plot for 4-PSK coincides with the one for 4-QAM.

Table 5.8. Simulation results for different modulation type and order (***n***PSK and ***n***QAM)

Different modulation types and order	Bit per symbol	Symbol Rate (x bit rate)	Maximum E_b/N_o loss (dB)
4-PSK	2	$^1/_2$	12
4-QAM	2	$^1/_2$	12
8-PSK	3	$^1/_3$	15.5
8-QAM	3	$^1/_3$	15
16-PSK	4	$^1/_4$	-
16-QAM	4	$^1/_4$	15.9

Based on the graphs illustrated in Figure 5.9 and results presented in Table 5.8, it can be said that although M-PSK and M-QAM show similar E_b/N_o values, but results for PSK are showing better performance for lower modulation order (BPSK and QPSK). It is also noticeable that the results for M-QAM are showing better performance for higher modulation order in comparison to the higher modulation order for M-PSK.

In addition, maximum E_b/N_o loss for 4PSK and 4QAM are both 12 dB. Therefore, when faster data rates are required, higher order QAM is the better option. This is in comparison to the M-PSK modulation, as M-QAM modulation is able to carry more bits of information per symbol and is less resilient to noise and interferences. This ofcourse can be categorised as one of the main advantages of using M-QAM.

Moreover, the bit error rate for PSK and QAM is sharply decreased with respect to modulation order, in this case M = 4. Figure 5.9, also clearly illustrates that the performance of 4PSK and 4QAM is better than that of others.

Comparative performance study using the BER graphs for 4FSK, 8FSK, 16FSK and 4QAM, 8QAM, 16QAM has been completed and illustrated in Figure 5.10.

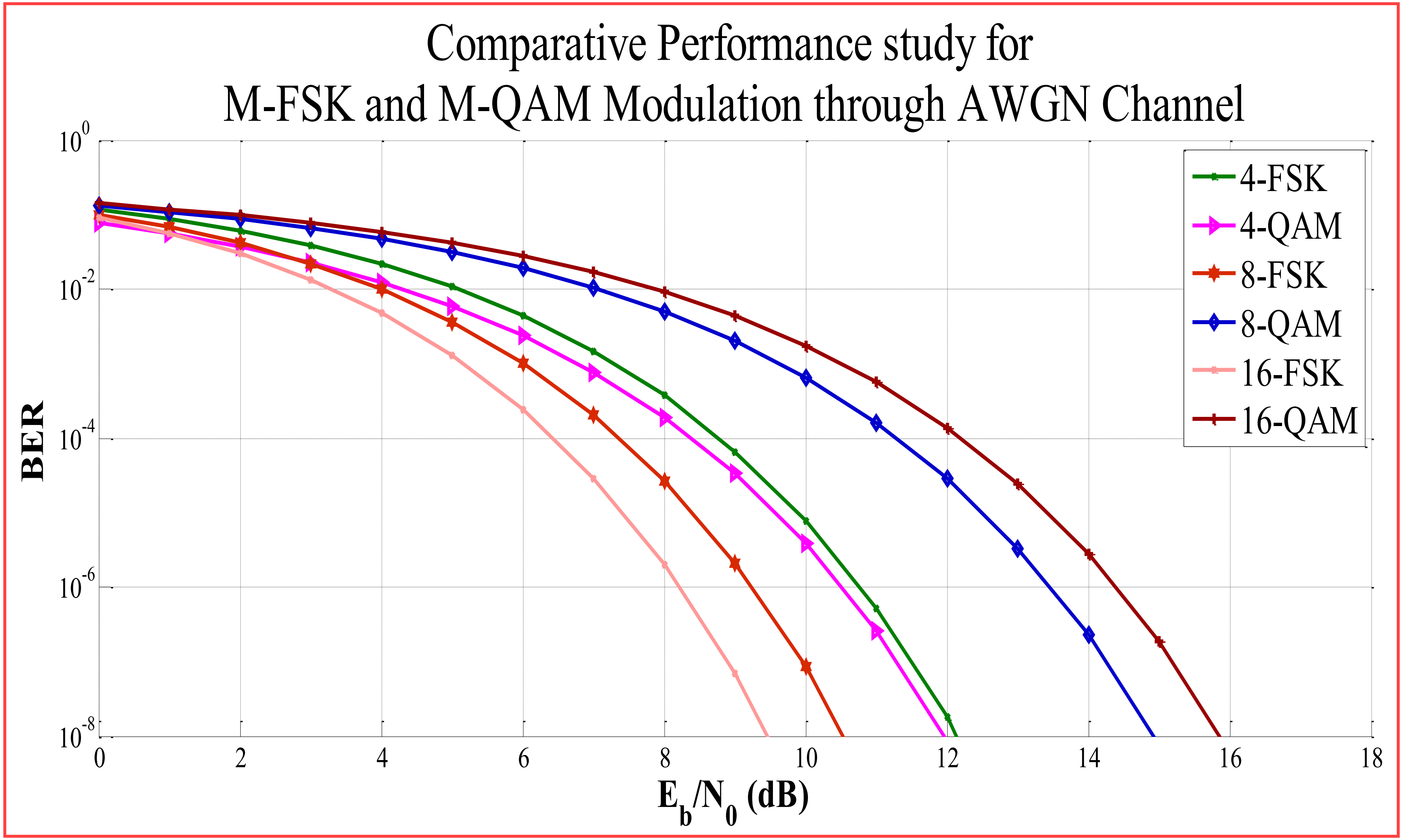


Figure 5.10. Comparative performance study for M-FSK and M-QAM modulation through AWGN channel

Table 5.9. Simulation results for different modulation type and order (***n***FSK and ***n***QAM)

Different modulation types and order	Bit per symbol	Symbol Rate (x bit rate)	Maximum E_b/N_o loss (dB)
4-FSK	2	$^1/_2$	12.1
4-QAM	2	$^1/_2$	12
8-FSK	3	$^1/_3$	10.5
8-QAM	3	$^1/_3$	15
16-FSK	4	$^1/_4$	9.5
16-QAM	4	$^1/_4$	15.8

Based on the graphs illustrated in Figure 5.10 and results presented in Table 5.9, it can be observed that results for M-QAM are showing better performance for both lower and higher modulation order in comparison to the M-FSK modulation.

Lower order modulation formats such as 4QAM offers a lower data rate but is more robust in the presence of noise. However, when faster data rates are required, higher order QAM is the better option in comparison to the M-FSK modulation. This is due to ability of M-QAM modulation to carry more bits of information per symbol and its lower resilient to noise and interferences. It is also noticeable that maximum E_b/N_o loss value for higher modulation order (M = 8 and M = 16) is smaller in FSK, but its performance is worse due to the incapability of reproducing the expected signal at the received end.

The PSK and QAM are the best selected modulation types, due to their simple implementation, strength in presence of noise and better performance in the communication system.

5.2.3. Application of Forward Error Correction

Following the design, simulation and result presentation for the basic structure of an OFDM modem using different modulation orders for PSK, FSK and QAM, the next stage is to design and build a more comprehensive OFDM modem, architecture of which is depicted in Figure 5.11, using the parameters of Table 5.3.

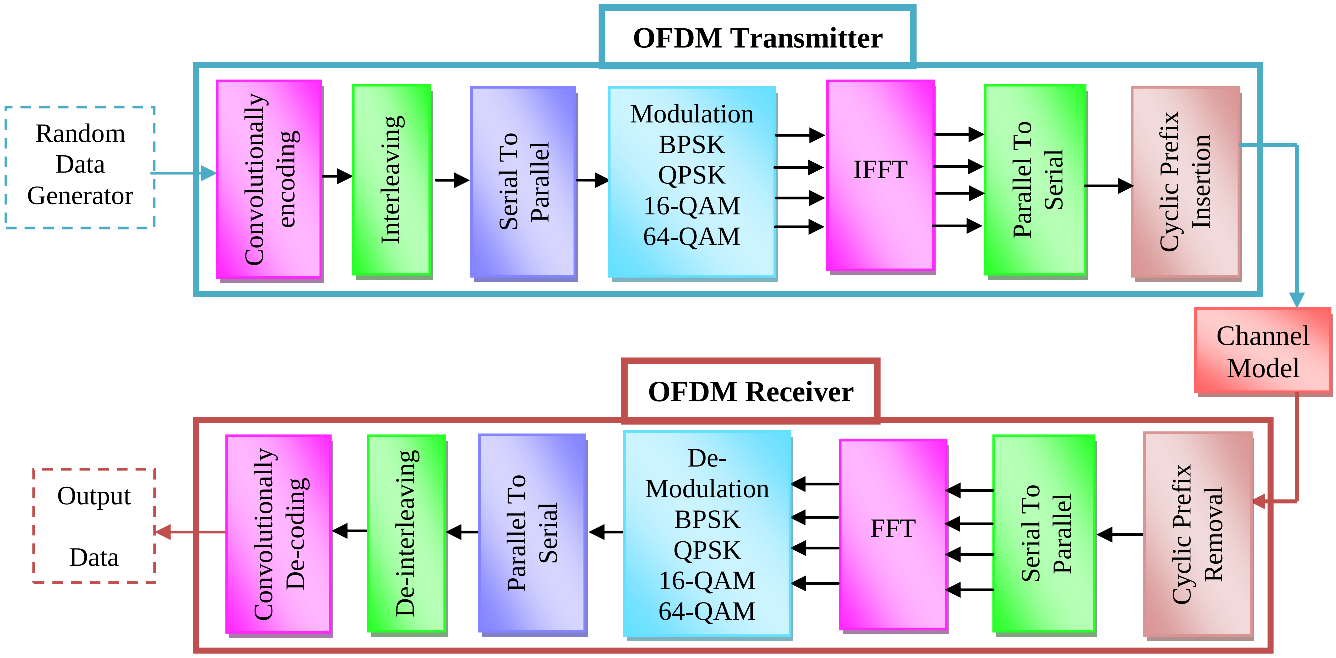


Figure 5.11. Architecture of a more comprehensive OFDM transceiver

In this section, the influence of forward error correction on the designed OFDM system through the use of convolutional encoding is simulated and studied. In addition, the BER comparison performance study for *hard-decision* and *soft-decision* Viterbi decoding is also evaluated and compared with the OFDM system without application of FEC.

Results depicted in the following figures present the performance of an encoded system with the following encoder characteristics:

- Code rate of = ½
- Constraint length = 7 Code
- Generator polynomials/vectors = [1011011, 1111001] or { 133,171}

Figure 5.12 shows that applying the FEC, results in an improvement in the BER performance.

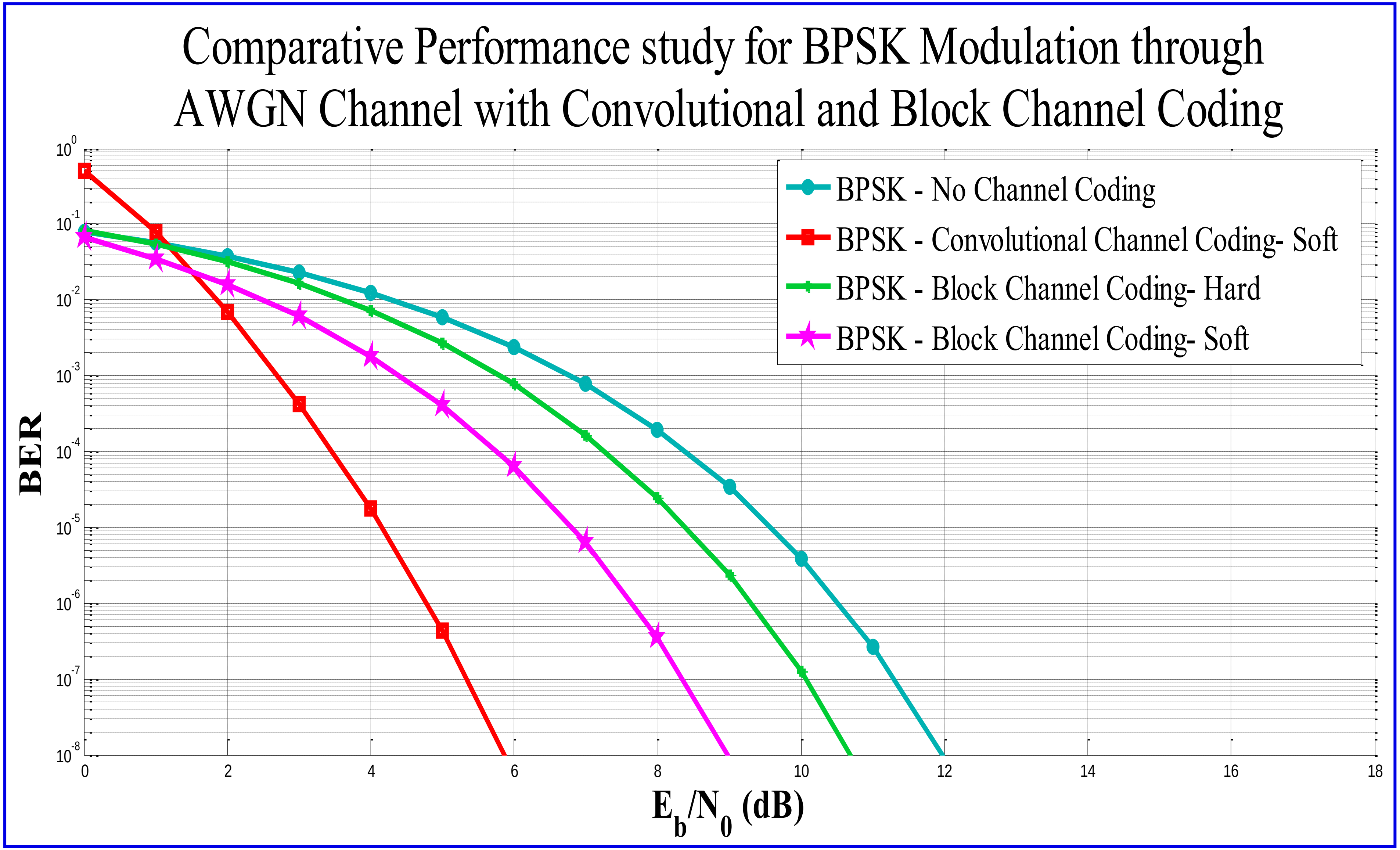


Figure 5.12. Comparative performance study for BPSK modulation through AWGN channel with Convolutional and Block channel coding

Table 5.10. Comparative performance for BPSK modulation through AWGN channel with convolutional and block channel encoding

Different scenario (BPSK)	Bit per symbol	E_b/N_o value (dB)	Improvement of E_b/N_o value in comparison to No-channel coding (dB)
No- Channel Coding	1	12	0
Convolutional Channel Coding - Soft	1	5.8	6.2
Block Channel Coding - Hard	1	10.8	1.2
Block Channel Coding - Soft	1	9	3

By analysing the graphs illustrated in Figure 5.12 and results presented in Table 5.10, it can be seen that by applying the convolutional encoding, there is improvement of 6.2 dB in comparison to a channel without convolutional encoding. After the convolutional channel coding, the next most improvement in the channel encoding is by use of block channel coding. Figure 5.12 shows the bit error ratio versus E_b/N_o for un-coded BPSK and for coded BPSK using the previously stated characteristics. As illustrated again by Figure 5.12, for a bit error ratio of 10^{-5}, the coded link (convolutionally encoded) needs about 5.5 dB less E_b/N_o compared with that of the un-coded link. For lower bit error ratios, this coding gain converges to a maximum value of about 6.2 dB. Therefore, convolutionally encoding the system has proved to make a considerable improvement. Figure 5.13 and Figure 5.14 illustrate the comparative performance study for B-PSK, 4PSK, 4QAM, 16PSK and 16QAM modulation through AWGN channel with convolutional and block channel encoding.

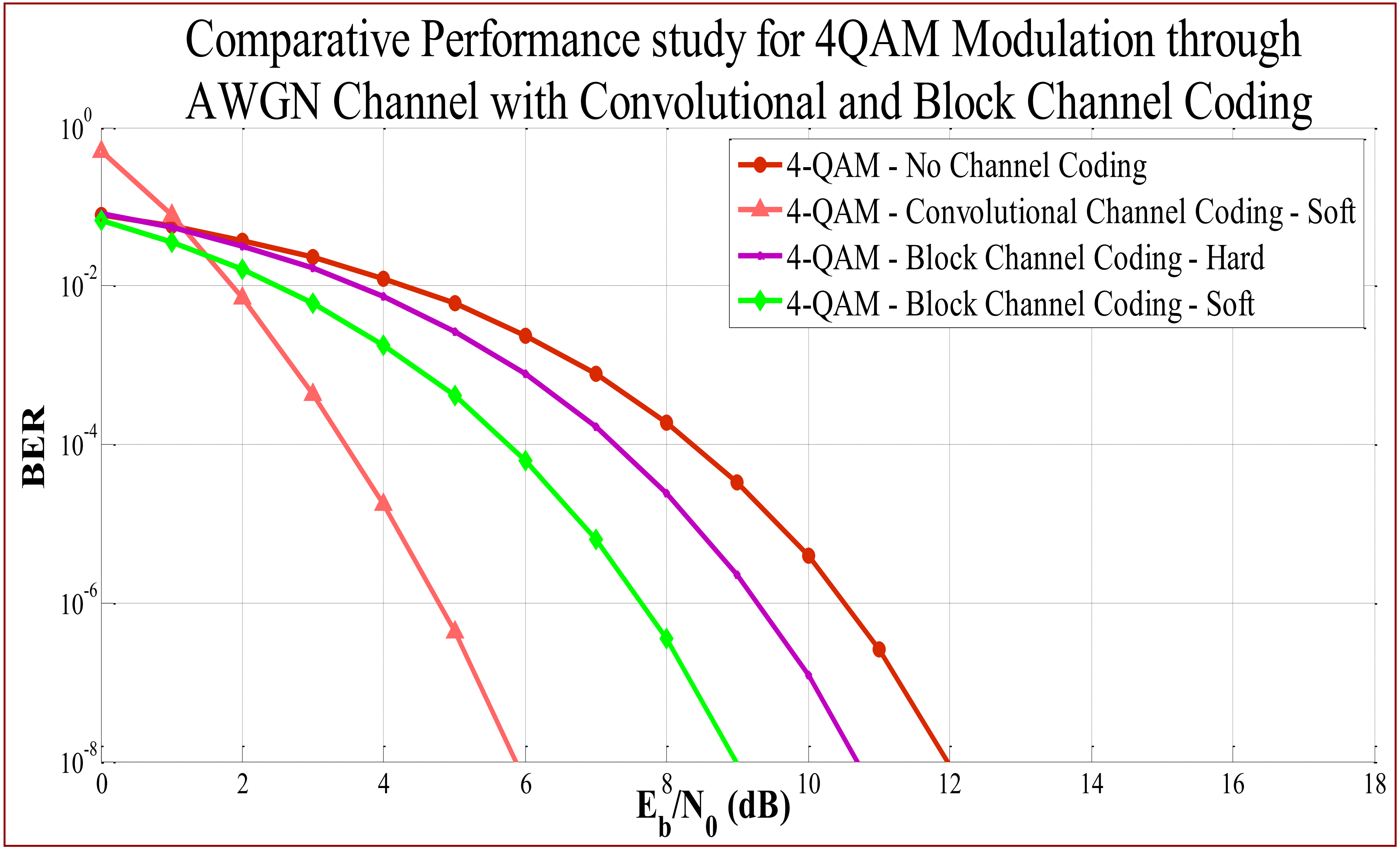


Figure 5.13. Comparative performance study for 4QAM modulation through AWGN channel with Convolutional and Block channel coding

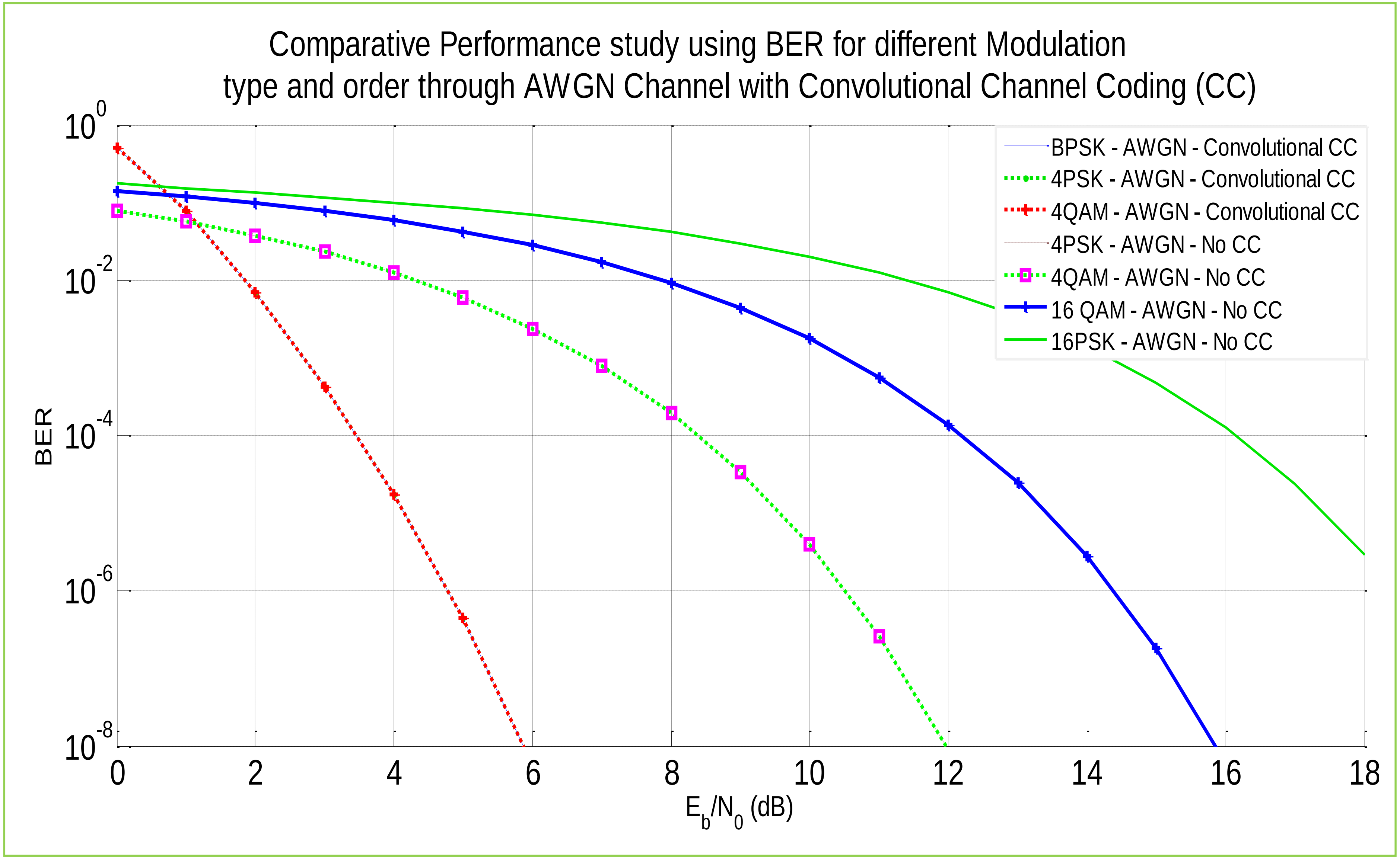


Figure 5.14. Comparative performance study using BER for PSK and QAM with/without convolutional channel coding

As it can be observed from Figure 5.14, some of the data cannot be seen; this is due to the fact some of the data coincides with other data. For instance, the BER plot of BPSK, 4-PSK and 4-QAM with Convolutional coding coincides with each other. Also, the BER plot of 4-PSK without Convolutional coding, coincides with the BER plot for 4-QAM without Convolutional coding.

Table 5.11. Comparative performance for 4QAM modulation through AWGN channel with convolutional and block channel encoding

Different scenario (4QAM)	Bit per symbol	E_b/N_o value (dB)	Improvement of E_b/N_o value in comparison to No-channel coding (dB)
No- Channel Coding	2	12	0
Convolutional Channel Coding - Soft	2	5.9	6.2
Block Channel Coding - Hard	2	10.7	1.3
Block Channel Coding - Soft	2	9	3

By analysing the graphs illustrated in Figures 5.13, 5.14 and results presented in Table 5.11, it can be stated that applying the convolutional encoding to both BPSK and 4QAM modulation, produces a very similar results. It can also be observed that there is improvement of 6.2 dB in comparison to a channel without convolutional encoding. After the convolutional channel coding, the next most improvement in the channel encoding is by use of block channel coding.

Figure 5.13 shows the bit error ratio versus E_b/N_o for un-coded 4QAM and for coded 4QAM using the above stated characteristics and parameters. Similarly for 4QAM modulation, for a bit error ratio of 10^{-5}, the coded link (convolutionally encoded) needs about 5.5 dB less E_b/N_o compared with that of the un-coded link. For lower bit error ratios, this coding gain converges to a maximum value of about 6.1 dB.

Therefore convolutionally encoding the system has proved to make a considerable improvement for both BPSK and 4QAM modulation system. In addition, Convolutional

Channel Encoding (CCE) allows the receiver to correct errors without demanding a reverse channel to request retransmission of data. After the CCE- soft technique, the next suitable technique is the Block Channel Encoding - soft (BCE) technique, with E_b/N_o of 9 dB, i.e. the second lowest E_b/N_o value. Soft-decision algorithms in FEC, unlike hard-decision, process analogue signals allowing for much higher error-correction performance (CCE-Soft and BCE-Soft). In BCE also, the added redundancy enables the receiver to reliably detect and correct errors over communication channel.

5.3. Comparative performance studies to examine the noise effect

In order to investigate the performance of the designed OFDM system, analysis is conducted to examine the effects of noise, initially using AWGN and subsequently with powerline coloured background noise. In doing so, the specific channel for these types of noise are primarily required to be modelled according to the appropriate equations and characteristics pointed out in Chapter 2. In addition, based on the comparison, analysis and discussions completed on the previous section of this chapter, BPSK is selected as the modulation technique to be used for the rest of this chapter, due it its reliability and good performance in the communication system.

Following the modelling of each channel, it may be said that each of these individual channel is subject to various types of noise, distortions and interferences which may lead to errors. Therefore, like any other communication system, some form of channel encoding mechanism is used to reliably recover the information. The channel encoding is composed of 2 steps, FEC and interleaving.

For this part of the current chapter, the convolutional encoding and soft-decision Viterbi decoding is used for the basic data transmission, as they comparatively produced a better performance in the previous section and are extensively used for real time error correction. If the encoding mechanism is not used, then the system integrity may be compromised due to the introduction of error into the data. Therefore, it is necessary to assess the performance of the system through the ideal way of using BER graphs. In order words, by using BER graphs, the rates at which errors occur in a transmission system are graphically presentable.

5.3.1. Additive White Gaussian Noise (AWGN)

This section offers an insight into the influence of AWGN on the designed OFDM communication system. In doing so, the AWGN is required to be modelled according to the characteristics pointed out in Chapter 4.

The additive white Gaussian noise is created when noise with Gaussian distribution is added to the transmitted signal as it passes through the communication channel. This type of noise may sometimes be referred to as white noise, due to the flat shape of its power spectral density. In other words, for any non-zero time offset, the noise autocorrelation in the time domain is zero.

Figures 5.15 to 5.17 illustrate the different presentation of the BPSK modulated signal through an AWGN channel. The modelled AWGN for this project has variance of 0dB. Figure 5.15 presents the scatter plot for the transmitted BPSK signal through the AWGN channel. It can be seen that the 2 bits have phase difference of 180°. Figure 5.16 depicts the scatter plot example of present AWGN in the channel.

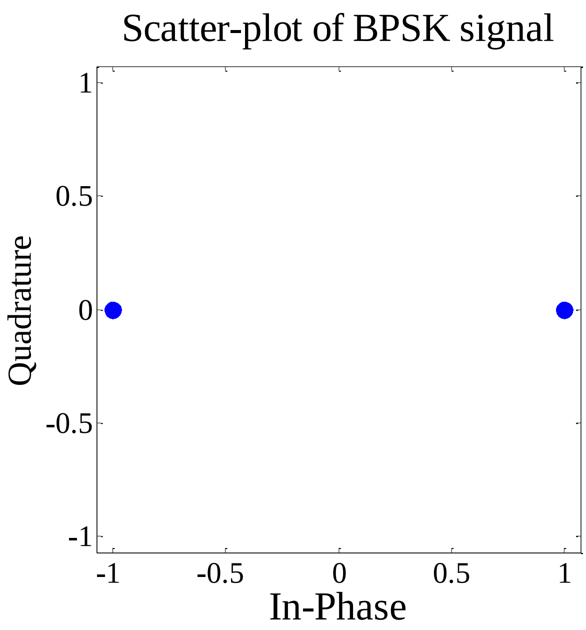


Figure 5.15. The scatter plot of a BPSK signal through an AWGN channel

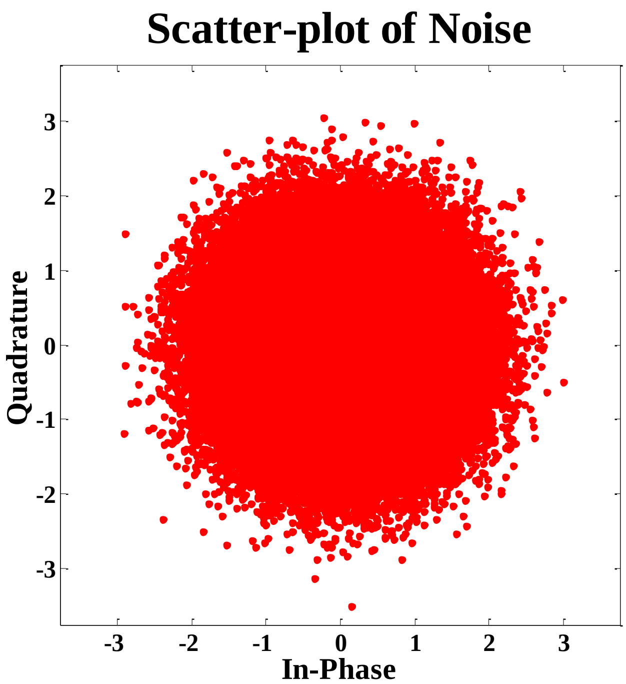


Figure 5.16. The scatter plot of the noise in the AWGN channel

Figure 5.17 depicts the scatter plot for the transmitted BPSK signal which is affected by the AWGN noise present in the channel. Again it can be observed that the 2 bits being affected by the noise have phase difference of 180°. The result of applying such kind of AWGN is comparatively illustrated in Figure 5.20.

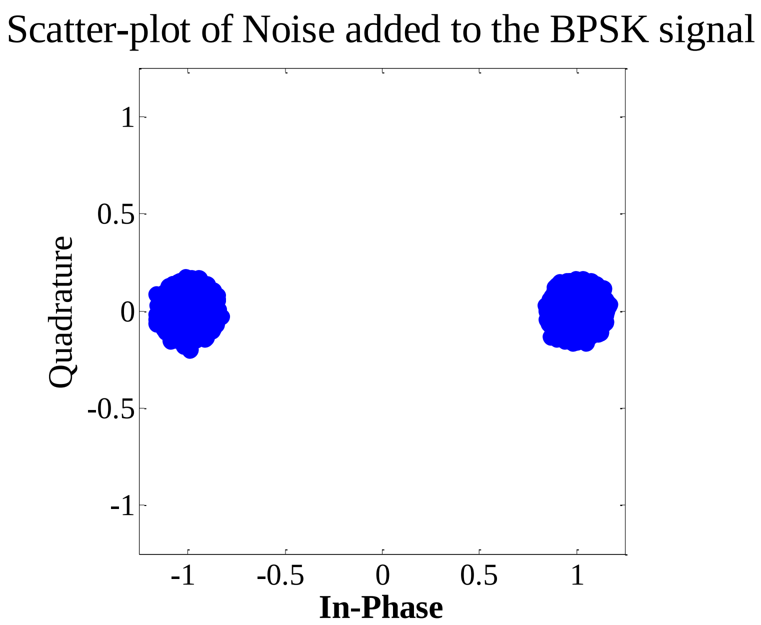


Figure 5.17. The scatter plot of a BPSK signal through an AWGN channel

5.3.2. Powerline coloured background noise

This section offers an insight into the influence of powerline coloured background noise on the designed OFDM communication system. In doing so, the powerline coloured background noise is required to be modelled according to the suitably selected characteristics pointed out in Chapter 2.

In order to model the powerline coloured background noise, initially statistical analysis method was employed to understand the random behaviour of the noise. Following an extensive study of the noise amplitude spectrum, the probability distribution of the time-domain noise amplitude was investigated and therefore the probability density function was obtained. Figures 5.18 and 5.19 present the output of different steps towards obtaining the PDF of this noise and the Nakagami PDF for different *m* values.

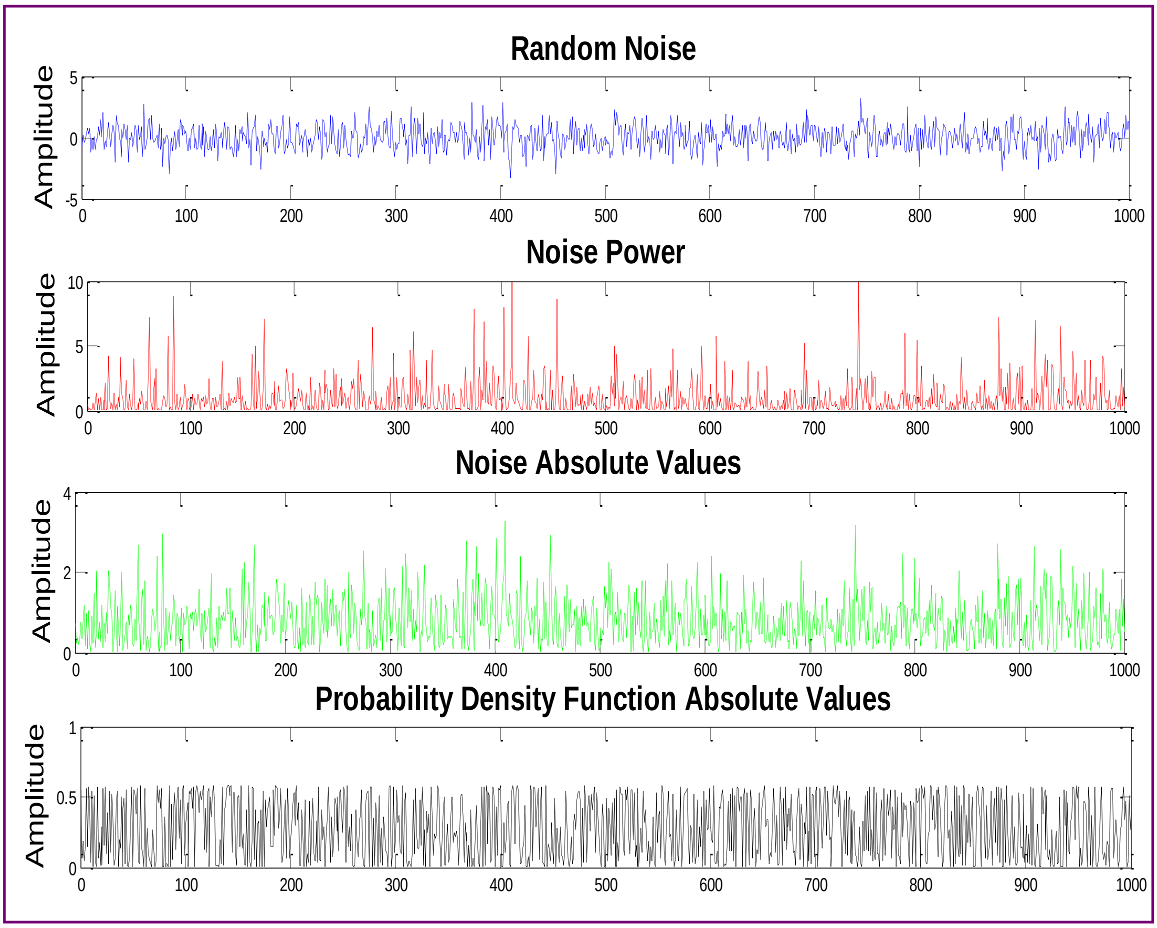


Figure 5.18. Graphs of random input noise, noise power, noise absolute value and absolute value of its PDF

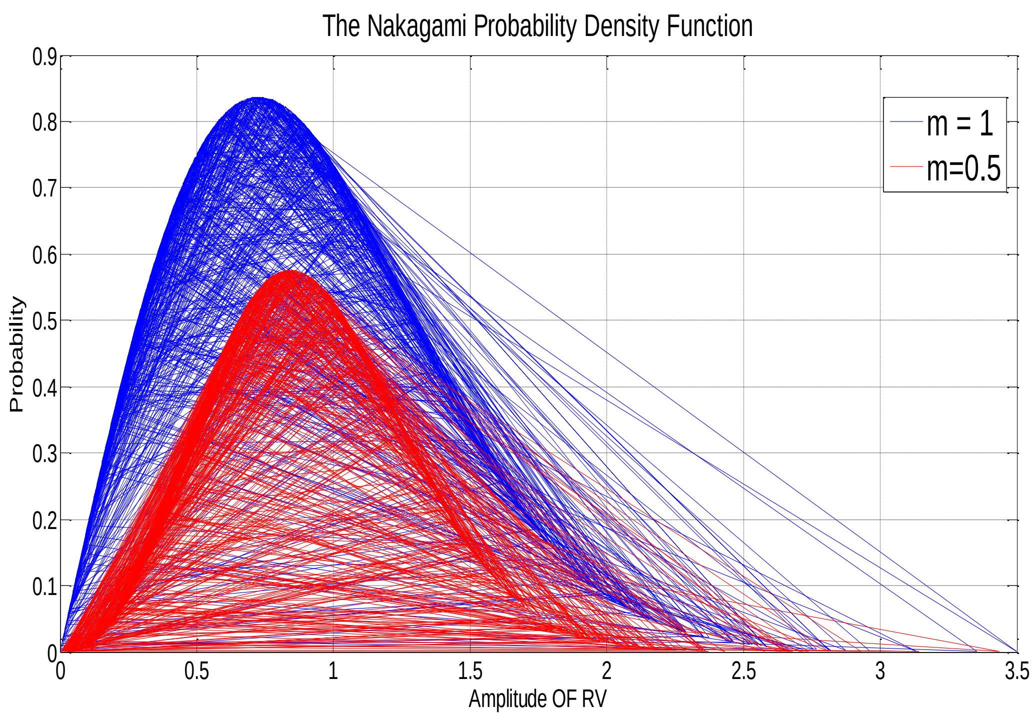


Figure 5.19. The Nakagami Probability Density Function for $m = 1$ and $m = 0.5$

Following modelling of both the AWGN and the powerline background noise, the appropriate modelling equations and parameters were input and subsequently applied to the channel, creating the required channel model. Figure 5.20 depicts the BER comparative performance study for the two above explained channel models; the AWGN channel and modelled powerline channel.

For the AWGN channel, it can be observed that when the modelled white Gaussian noise is applied to an un-coded system, it produces a waterfall graph with a very differently low performance. However, when this modelled noise is applied into a coded system, its performance is greatly improved (solid blue line).

Furthermore, it can be observed that, when the modelled powerline coloured background noise is applied to an un-coded system it does not have rational effect on the performance of the channel and hence the system. However, when this modelled powerline coloured background noise is applied to an encoded system, it creates a better performance on the system.

Figure below also shows the bit error ratio versus Signal-to-Noise Ratio (dB) for both un-coded and encoded BPSK using the previously stated noise parameters and characteristics.

It is illustrated that for the AWGN channel, the convolutionally encoded link with bit error rate of 10^{-2}, needs about 5 dB less compared with that of the un-coded link. For lower bit error rate i.e. 10^{-3}, this coding gain converges to a value of about 5.3 dB. The BER under BPSK modulation technique over AWGN, with encoder produces a Signal-to-Noise Ratio (SNR) value of 10.7 dB but in the case of un-coded system the SNR value is 15dB. This shows that the encoding system has in fact, accurately encoded the communication system in order to correctly detect the noise present in the channel, and subsequently produce an improvement on the performance of the system.

It is also demonstrated that, for the modelled powerline channel, the convolutionally encoded link with bit error rate of approximate $10^{-1.7}$, needs about 3.5 dB less compared with that of the un-coded link. For lower bit error rate i.e. approximately 10^{-2}, this coding gain converges to a value of about 6 dB. The BER under BPSK modulation technique over modelled powerline channel, with encoder produces a SNR value of 8.8 dB but in the case of un-coded system the SNR value is 15 dB. These values again show that the encoding system has accurately encoded the communication system, in order to correctly detect the noise present in the channel, and subsequently produce an improvement on the performance of the system.

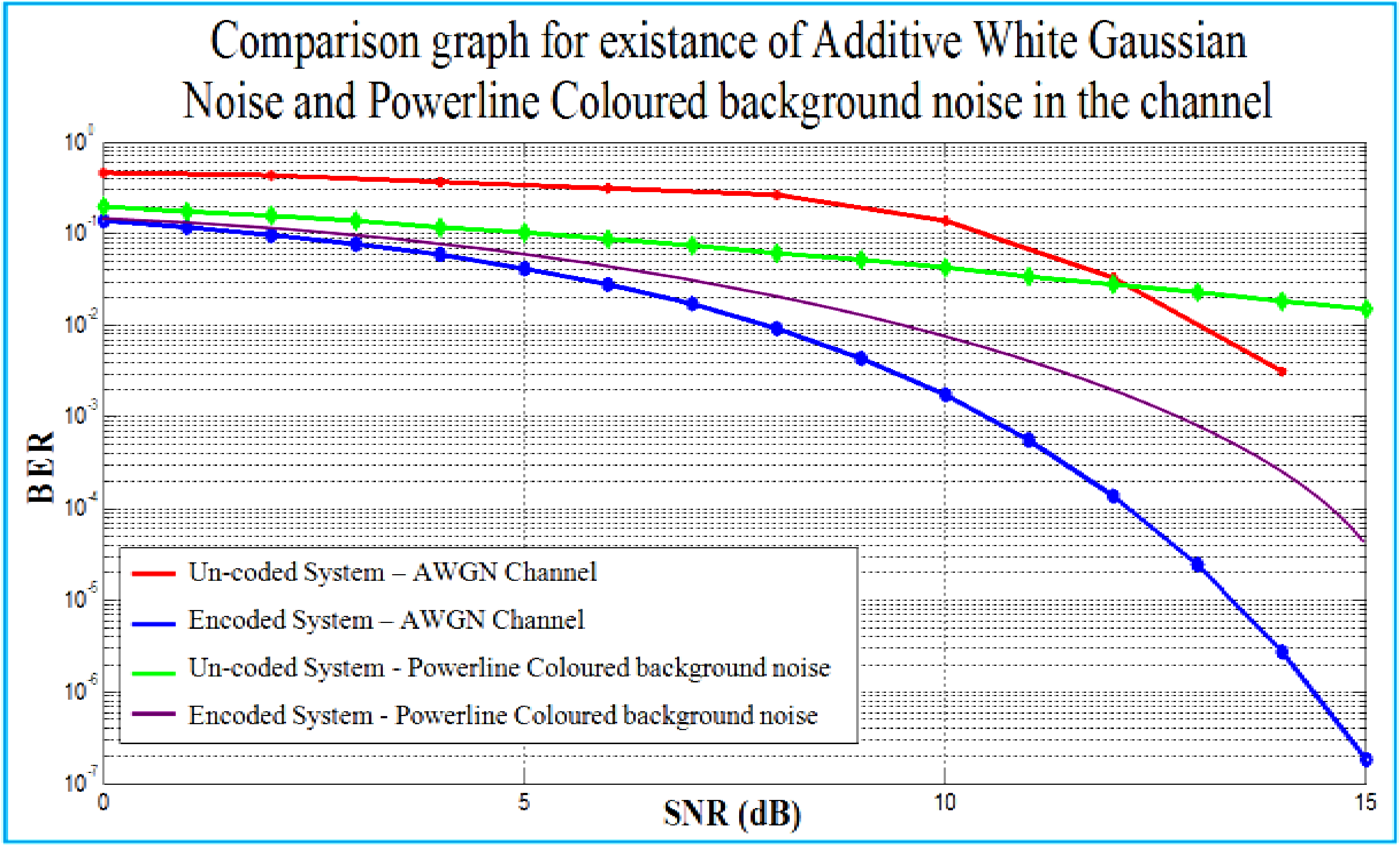


Figure 5.20. Comparative performance study for AWGN and powerline Coloured background noise in the channel

5.4. Comparison of Results

Following the simulation, synthesis, results, analysis and discussions completed in this chapter, a summary of the comparison between the different techniques employed in this research is noted in Table 5.12, identifying the best selected technique with their advantages and disadvantages.

Table 5.12. Overall comparison table, identifying the best selected technique with their advantages and disadvantages

Different techniques for achieving better performance	Different Techniques	Improved dB values E_b/N_o (dB) E_s/N_o (dB) / SNR	Better Performance	Notes ☑: advantage ☒: disadvantage
Modulation Order	**2PSK**	**9.5**	**2-PSK** It offers a lower data rates but is robust in presence of noise, therefore produces a better performance	☑ Simplest to implement ☑ Very good performance in the communication system ☑ More robust and resilient in presence of noise and interference ☒ Offers lower data rates
	4PSK	**12.5**		
	8PSK	**18.2**		
	4QAM	**12.5**	**4-QAM** Produces same result as 4-PSK and it offers a lower data rates but is robust in presence of noise, therefore produces a better performance	☑ More robust in presence of noise ☑ Better performance in the system in comparison to the higher order modulation ☒ 4-QAM carries lower data rates
	16QAM	**20**		
	64QAM	**25.8**		
Modulation Types	**4PSK**	**12**	**PSK** **QAM**	☑ More robust in presence of noise ☑ 4PSK and 4QAM are both simple to implement ☑ Better performance in the communication system
	4FSK	**12.2**		

	4QAM	**12**		☑ when faster data rates are required, 4QAM is a better option ☒ Offers lower data rates
Application of FEC to BPSK	**No-FEC[1]**	**12**	**CCE – Soft** **BCE - Soft**	☑ Improvement of 6.2 dB in comparison to No-FEC ☑ For a BER of 10^{-5}, the CCE needs about 5.5 dB less Eb/No compared with No-FEC ☑ For lower BER, this coding gain converges to a maximum value of about 6.2 dB ☑ CCE has proven to make a considerable improvement ☑ CCE allows the receiver to correct errors without demanding a reverse channel to request retransmission of data ☑ Soft-decision algorithms in FEC, unlike hard-decision, process analogue signals allowing for much higher error-correction performance (CCE-Soft and BCE-Soft) ☑ In BCE, the added redundancy enables the receiver to reliably detect and correct errors over communication channel ☒ CCE is applied in situations where retransmissions are relatively costly or impossible such as when broadcasting to multiple receivers such as multicast ☒ If retransmission is required due to applying CCE, recovery of the corrupted data is necessary
	CCE[2] - Soft	**5.9**		
	BCE[3] - Hard	**10.7**		
	BCE - Soft	**9**		
Modelling of AWGN - BPSK	**Un-coded System**	**SNR = 15**	**Modelling of AWGN under BPSK modulation with Convolutionally Encoded Channel System**	☑ Convolutionally encoded link with BER of 10^{-2}, needs about 5 dB less compared with that of the un-coded link ☑ For BER of 10^{-3} coding gain converges to a value of about 5.3 dB ☑ The BER under BPSK modulation technique over AWGN, with encoder produces a SNR value of 10.7 dB but in the case of un-coded system the SNR is 15dB ☑ Encoding has accurately detected and corrected the present noise in the channel and produced an improvement on the performance of the system
	Convolutionally Channel Encoded System	**SNR = 10.7**		

Modelling of Powerline Coloured Background - BPSK	**Un-coded System**	**SNR = 15**	**Modelling of Powerline Coloured Background channel under BPSK modulation with Convolutionally Encoded Channel System**	☑ For modelled powerline channel Convolutionally encoded link with BER of $10^{-1.7}$, needs about 3.5 dB less compared with that of the un-coded link ☑ For BER of 10^{-2} coding gain converges to a value of about 6 dB ☑ The BER under BPSK modulation technique over modelled powerline channel, with encoder produces a SNR value of 8.8 dB but in the case of un-coded system the SNR is 15dB ☑ Encoding has accurately detected and corrected the present noise in the channel and produced an improvement on the performance of the system
	Convolution ally Channel **En-coded System**	**SNR = 8.8**		

[1] Forward Error Correction (FEC), [2] Convolutional Channel Encoding (CCE), [3] Block Channel Encoding (BCE)

5.5. Picture Quality Versus Signal to Noise Ratio

In addition to the transmission of bits (zeroes and ones) and following the comparative performance studies on the OFDM modem by means of analysing them using different techniques and scenarios which has so far been the subject of this chapter; the next stage is the transmission of an image which will be considered in this section.

Furthermore, this section will illustrate the work undertaken in order to improve the degradation performance of OFDM system in the presence of high noise in the channel. Table 5.13 illustrates the transmission of an image through an OFDM system, with channel of different noise level. As it is illustrated in this table, the first image in the left hand side column is the original input image, and the image next to it is the gray scale image of the original input image. The gray scale image is the image to which the different techniques such as the convolutional encoding/decoding, modulation/ demodulation in the transmitter and receiver will be applied.

As it is illustrated in Table 5.13, like many other digital communication systems, the performance of this OFDM system is only acceptable, up to some critical channel noise level. In other words, if the noise level is raised above that critical level, the performance of the system fails very quickly. Such matters may highly affect the performance of the wireless telecommunications, where the drops in the signal may lead to diminution in reliability of the communication.

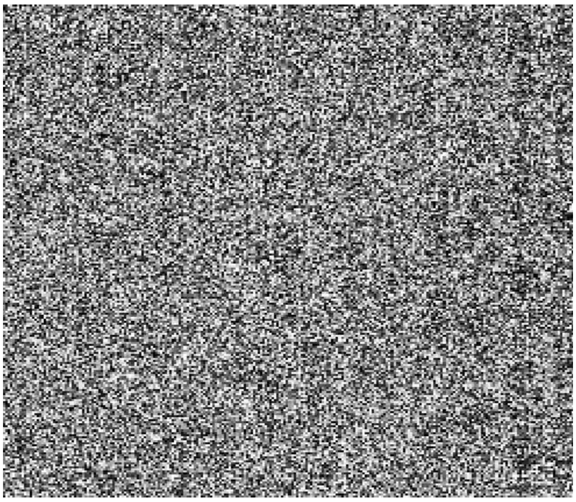
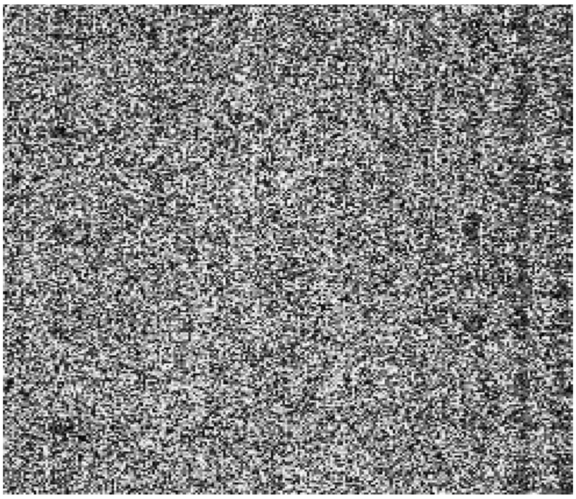
The advantage of the currently designed OFDM system is that, when the channel is under a high noise condition, the system outputs a worse image quality rather than completely loosing the transmitted image. This is depicted in the pictures of Table 5.13 with SNR value of 3 or 6 dB. This image transmission through the noisy channel has been simulated by using the same MATLAB code as for the bits transmission, where the signal to noise ratio (SNR) of the channel is varied from 1dB to 20 dB, with the image quality measured at 3 dB increments.

In this OFDM system, the FEC technique was also used with the 16 - QAM modulation technique which illustrate that:

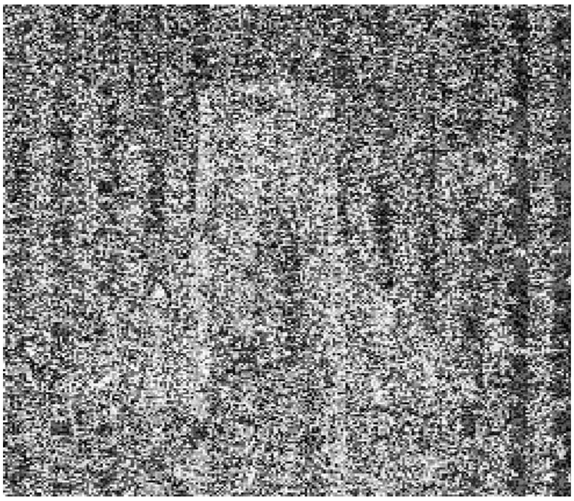
I. Using 16 – QAM carries higher data rates, which is essential when dealing with image transmission.

II. Modulation techniques such as 16QAM perform better than higher order modulation such as (256QAM) under high noise channel condition with SNR < 12 dB.

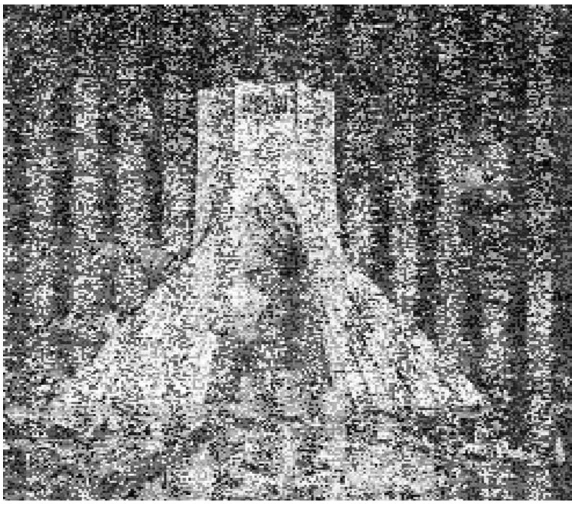
Table 5.13. The transmission of an image through an OFDM system, with channel of different noise level

Original Image	**Gray-scale Image**
	
SNR = 1 dB	**SNR = 3 dB**
	

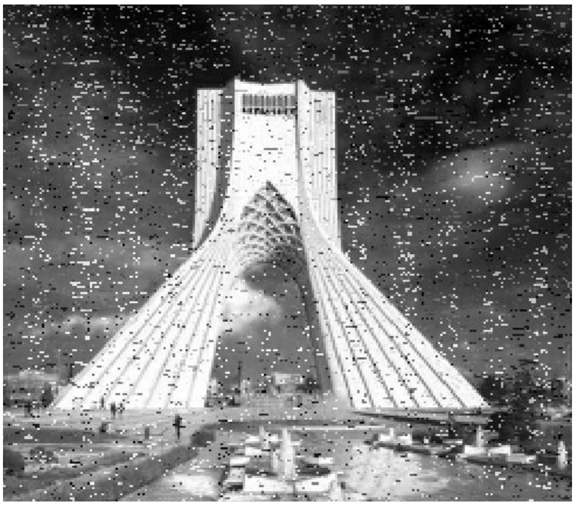
SNR = 6 dB



SNR = 9 dB



SNR = 12 dB



SNR = 15 dB

SNR = 18 dB

SNR = 20 dB

5.6. Summary

This chapter presented a brief theoretical background to techniques employed in design of full OFDM system followed by the simulation response and comparative performance studies on comprehensive OFDM modem. The results presented in this chapter are based on the three comparative performances for different modulation type, different modulation order and also application of forward error correction scheme. This comparative performance study was conducted to understand and recognise the most suitable technique for the transmission of message or image within a communication system.

This chapter has specifically covered the theoretical background on the basic concept of channel encoding such as FEC, CCE, BCE and also the Interleaving Technique. Later, the simulation response and analysis of the above mentioned techniques were presented. Therefore, a conclusion drawn from this chapter containing the notable points:

- The results of comparison between different modulation orders indicated that BPSK is the simplest modulation order to implement, as it offers lower data rates. This simple modulation order provides a very good performance in the communication system and it is more robust and resilient in presence of noise and interferences. After BPSK, 4-QAM in comparison to higher order QAM modulation, showed a better performance. Although it produced a very similar results to 4-PSK, but a better performance in the system was observed, due to its lower data rates and its robustness in presence of noise.
- The results of comparison between different modulation types was achieved by studying and examining 4-PSK, 4-FSK and 4-QAM, out of which PSK and QAM demonstrated a better performance. The 4-PSK and 4-QAM modulation types are similarly simple to implement. Such modulation types showed a high performance in communication system as they offer a lower data rates and are more robust in presence of noise. It is also important to note that when faster data rates are required, 4-QAM is a better option. In fact, this method of comparison between the different modulation types proved to be a useful method of testing these modulations.

- The results of comparison between different encoding techniques revealed that ‘convolutional channel soft encoding’ and ‘block channel soft encoding’ present a better performance in comparison to the other channel encoding techniques. Moreover, this comparison has also suggested that when the two mentioned encoding techniques are applied to BPSK modulation; it provides a considerable improvement in the OFDM system.
- The comparison result of convolutionally encoded link and un-coded link, when applied to AWGN modelled channel, illustrated that BER value of 10-2, needs about 5 dB less compared with that of the un-coded link. This coding gain converged to a value of about 5.3 dB for BER value of 10-3. The BER value under BPSK modulation, over AWGN channel, with encoder produces SNR value of 10.7 dB but in the case of un-coded system the SNR is 15 dB. This suggests that the encoder has accurately detected and corrected the present noise in the channel and hence produced an improvement on the performance of the system.
- In addition to the transmission of the bits, the transmission of an image was presented using the 16 – QAM modulation technique, which carries higher data rates, an essential requirement when dealing with image transmission. The image was transmitted through an OFDM system with different channel noise level. It was observed that when the channel is under a high noise condition, the system outputs a worse image quality rather than completely loosing the transmitted image. In addition, the transmitted image with SNR of 12 dB was received with small amount of noise, in other hand the transmitted image with SNR of 20 dB was received as a very clean image.

Chapter 6

Conclusion and Future Work

6.1. Conclusion

The main aim of conducting this research project was to design and implement an OFDM system for powerline-based communication, by simulating the operation of virtual transmitter and receiver. More specifically, the overall aim of this research was to design an OFDM modem for a powerline-based communication in order to propose and examine a novel approach in comparing the different modulation order, different modulation type, application of FEC scheme and also application of different noise types and applying them to the two modelled channels (AWGN and Powerline modelled channel) in an attempt to understand and recognise the most suitable technique for the transmission of message or image within a communication system. For the purpose of simulating an OFDM that its signal could be corrupted by powerline type of noise the nearest model in this field was adoption of Powerline coloured background noise, however most of the simulations in this project are the result of AWGN only.

This principal aim was achieved by setting and completing number of objectives. The first was to design a basic OFDM modem by using BPSK and the second was to design a more comprehensive OFDM modem for the purpose of simulation. This was followed by investigating the functioning of the communication link with respect to OFDM by utilising Cyclic Prefix, with the aim of counteracting the effects of delay such as ISI and ICI. The performance of this OFDM modem was then examined by using the AWGN channel. An additional comparative performance studies were conducted by plotting the BER graphs for numerous simulations for different modulation types, different modulation orders and also different types of channel coding, as planned. Moreover, additional analysis was carried out in order to examine the overall performance of the OFDM modem. This was primarily achieved by using AWGN and subsequently with Powerline coloured background noise. Finally, the full functioning OFDM modem was examined through the transmission of an image.

Towards this aim, a high-level technical computing language called MATLAB® was used in order to design and implement the outlined OFDM communication system. The simulation, synthesis, results, analysis and discussions presented in Chapters 3, 4 and 5, resulted in the creation of an overall comparison presented in Chapter 5, Table 5.12. This table contains the techniques used in the current research, most important results obtained, the best selected techniques and finally some advantages and disadvantages of these techniques.

The results of comparison between different modulation orders in Chapter 5 indicate that BPSK is the simplest modulation order to implement, as it offers lower data rates. This simple modulation order provides a very good performance in the communication system and it is more robust and resilient in presence of noise and interferences. After BPSK, 4-QAM in comparison to higher order QAM modulation, showed a better performance. Although it produced a very similar results to 4-PSK, but a better performance in the system was observed, due to its lower data rates and its robustness in presence of noise.

Research on the performance of different modulation types was accomplished by studying and examining 4-PSK, 4-FSK and 4-QAM, out of which PSK and QAM demonstrated a better performance. The 4-PSK and 4-QAM modulation types are similarly simple to implement. Such modulation types showed a high performance in communication system as they offer a lower data rates and are more robust in presence of noise. It is also important to note that when faster data rates are required, 4-QAM is a better option. In fact, this method of comparison between the different modulation types proved to be a useful method of testing these modulations.

The results of comparison between different encoding techniques revealed that ‘convolutional channel soft encoding’ and ‘block channel soft encoding’ present a better performance in comparison to the other channel encoding techniques. Moreover, this comparison has also suggested that when the two mentioned encoding techniques are applied to BPSK modulation; it provides a considerable improvement in the OFDM system.

As it has been discussed in Chapter 5, application of Convolutional Channel Encoding (CCE) results in an improvement of 6.2 dB in comparison to when Forward Error Correction (FEC) is not applied. It was observed that for a BER of 10^{-5}, the CCE needs about 5.5 dB less in the E_b/N_0 value compared to when no FEC is applied. This value converges to a maximum of about 6.2 dB for lower BER. The results of such comparative study also prove that application of CCE has resulted in considerable improvement of performance. In addition, CCE allows the receiver to correct errors without demanding a reverse channel to request re-transmission of data. However, if re-transmission of data is required due to applying CCE, recovery of the corrupted data is necessary.

Application of Block Channel Encoding soft; showed an approximate improvement of about 3 dB in comparison to No-FEC. In Block Channel Encoding (BCE), as explained in Chapter 5, the added redundancy within the encoding system enables the receiver to reliably detect and correct errors over communication channel. It is worth mentioning that soft-decision FEC algorithms, unlike hard-decision, process analogue signals allowing for much higher error-correction performance as presented when applying the CCE-Soft and BCE-Soft.

The comparison between un-coded and convolutionally encoded models of AWGN and Powerline coloured background (using BPSK modulation technique) has assisted in determining the need for such encoding in that particular channel. The comparison result of convolutionally encoded link and un-coded link, when applied to AWGN modelled channel, illustrated that BER value of 10^{-2}, needs about 5 dB less compared with that of the un-coded link. This coding gain converged to a value of about 5.3 dB for BER value of 10^{-3}. As noted in Chapter 5, the BER value under BPSK modulation, over AWGN channel, with encoder produces SNR value of 10.7 dB but in the case of un-coded system the SNR is 15 dB. This suggests that the encoder has accurately detected and corrected the present noise in the channel and hence produced an improvement on the performance of the system.

Similarly, for the modelled powerline channel, convolutionally encoded link with BER value of $10^{-1.7}$, needed about 3.5 dB less compared with that of the un-coded link. This coding gain converged to a value of about 6 dB for BER value of 10^{-2}.

The BER value under BPSK modulation, over powerline channel modelled, with encoder produces a SNR value of 8.8 dB but in the case of un-coded system the SNR value is 15 dB. This indicates that the encoder has accurately detected and corrected the present noise in the channel and hence produced an improvement on the performance of the system.

In conclusion, the simulation results presented in this project suggest that BPSK and 4-QAM, are the most preferred modulation techniques (in both type and order) for their considerable performance. Also, CCE-Soft and BCE-Soft are by far the best encoding techniques (in FEC type) for their best performance in error detection and correction. Indeed, applying these techniques to the two modelled channels has proven very successful and will be accounted as a novel approach for the transmission of message or image within a powerline based communication system.

6.2. Future Work

The results' summary presented above and contributions made by this research have shown that although presence of AWGN and Powerline coloured background noise cause a significant impairment in the performance and subsequently to the transmission of the system, various framing techniques such as the use of appropriate modulation and error correction techniques, can reduce the impact of the noise and interference.

However, existence of certain assumptions and limitations in this study restrict the outcome and contributions of this work from providing a more accurate comparison between the techniques, and also a precise estimation of the errors in real powerline systems. It is important to highlight and suggest some of the areas where if given time and facilities; further research, investigation and improvements would be worthwhile. Following is a list of scope for further research:

Although having an ideal channel and perfect timing synchronisation between the transmitter and receiver is not the case in most of the real communication systems, nevertheless the imperfect conditions present within the communication system can be compensated by utilising specific digital signal processing (DSP) techniques in both transmitter and receiver end. It is also worth mentioning that the use of such digital signal processing techniques is application dependent, as change in specific parameter of the DSP techniques produces a different performance. The idea of synchronisation for OFDM communication systems presented in [95,103] can be taken forward and applied to the system presented in the current research.

- An attempt can be made in measuring the powerline noise in a real life scenario, and examine how best can the signal be recovered as a result of such noise.
- Another point which can be added to the current research is to apply the discussed different modulation schemes (BPSK, 4QAM etc.) to some other

fading channels that are not covered in this study, such as ‘Rayleigh’, ‘Rician’, ‘Weibull’ and ‘Beckmann’ channel.

- This research concentrated on applying the ‘forward error correction’, ‘convolutional channel encoding’ and ‘block channel encoding’ to improve the system performance. Although these encoding systems are the most suitable encoding system for practical implementation, but additional performance analysis can be completed by using different types of encoding techniques. This could be done by employing ‘Hamming’, ‘Golay’ and ‘Reed–Muller’ encoding and decoding techniques, and comparing their performance with the currently used encoding techniques.
- The OFDM modem designed in the present research may be used for further study in this field at higher level research, through the use of programming languages such as C or platforms such as MATLAB, which will help implement customer-based configurable integrated circuits such as Field-programmable Gate Array (FPGA), to be very flexible and reconfigurable. In 2003, a similar research was completed by initially suppressing the complexity of Neural Networks (NN) for peak to average power ratio (PAPR) reduction of OFDM signal and later implementing it on a FPGA [150], idea of which could be further explored.
- The channel estimation is another research area that would be worth investigating, or improving the already proposed algorithms, as it is imperative for the implementation of OFDM. Many related research were involved in the use of both neural network and the Cyclic Prefix (CP) based block Recursive Least Squares (RLS) algorithm, as an approach to investigate the channel estimation in an OFDM and MIMO-OFDM systems [64-69, 76]. Although there have been number of algorithm proposed, there remains a great potential for this technique to be explored and improved.
- Although some recent investigation have been completed on the channel equalisation by using ‘feedback equalisation’, ‘blind adaptive equalisation’ and neural network [93, 106], the research area relating to the equalisation using the cyclic prefix concept could be another point of interest is to extend.
- Some researchers have concentrated on improving the OFDM weakness [105, 151-153]; yet additional analysis can be done by initially considering the already completed research and attempting to further improve the system.

- Another point of interest would be to attempt analysing the performance of the currently designed OFDM system in a multi-user environment and also to establish a protocol with the ability to conduct acknowledge and re-transmissions.
- In the current research, different modulation order and modulation type such as 2PSK, 4PSK, 8PSK, 4FSK, 4QAM, 8QAM and 16-QAM were investigated and later compared. For future research, depending on the type of data being transmitted, the modulation order and modulation type can dynamically be selected. This would help improving the overall performance, as the most suitable modulation technique for that particular data has been selected.
- Further research could also be done on the 'coding and modulation for powerline communication'. Although A.J. H. Vinck and J. Haring, G. Lindell [73 - 75] have tried to explore the knowledge in this area, but there seem to be a great potential for this technique to be explored.

- Applying the Artificial Neural Network (ANN) to an OFDM system with the aim of improving the performance of the system, have been observed in number of researches and studies [77 - 84]. Detailed explanations to such network and its operation can be found in [154-156]. This method can therefore be further implemented and applied to different components within the OFDM communication system to improve its performance.

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List of Publications

1. N. Karimian and J. Yazdani, "Design and Analysis of OFDM System for Powerline Based Communication," 5th Workshop on Power Line Communications (WSPLC) – For the Grid of the Future, 22-23 September 2011.
2. N. Karimian and J. Yazdani, "Design and Analysis of OFDM System for Powerline Based Communication," International Symposium on Power Line Communication, March 2012.

Appendices:

A: Publication 1

B: Publication 2

C: Compact Disk of MATLAB codes attached

Design and Analysis of OFDM System for Powerline Based Communication

Miss N. Karimian and Dr. J. Yazdani
JYazdani@uclan.ac.uk

Abstract - Research on digital communication systems has been greatly developed in the past few years and offers a high quality of transmission in both wired and wireless communication environments. Coupled with advances in new modulation techniques, Orthogonal Frequency Division Multiplexing (OFDM) is a well-known digital multicarrier communication technique and one of the best methods of digital data transmission over a limited bandwidth [1].
In this paper, design and analysis of OFDM system for powerline based communication is proposed. In doing so, MATLAB and embedded Digital Signal Processing (DSP) systems are used to simulate the operation of virtual transmitter and receiver. The performance of the system design is then analysed by adding noise (additive white Gaussian noise, Powerline coloured background noise and Middleton Class A noise) in an attempt to corrupt the signal.
In this paper results will show that performance is improved by using lower order modulation formats e.g. Binary Phase Shift Keying (BPSK), QPSK, etc. compared to the higher modulation schemes e.g. 64 Quadrature Amplitude Modulation (QAM); as they offer lower data rates but are more robust in the presence of noise. The performance study of OFDM scheme is also examined with and without presence of noise and application of forward error correction (FEC).

Keywords: Digital communication, OFDM, Powerline, DSP, PSK, QAM, FEC

1. Introduction

Multicarrier modulation has long been known as an efficient modulation scheme for band-limited channels. OFDM is considered as one of the most promising modulation methods for powerline communications [2].

The research aim of this paper is to design and implement an OFDM communication link for Powerline Communication (PLC), using MATLAB and embedded DSP systems to simulate the operation of virtual transmitter and receiver. The performance of the system design is then analysed by adding noise such as additive white Gaussian noise (AWGN), Powerline background noise and Middleton Class A noise, in an attempt to corrupt the signal.

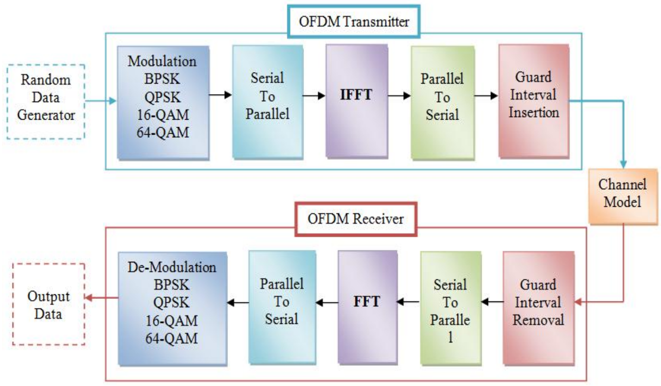


Figure 1 depicts the block diagram of OFDM modem which is designed in this research paper.

Figure 1. OFDM Block diagram

Despite wide use of the OFDM in conjunction with (or without) other techniques, there is a great potential for this technique to be employed in PLCs, and the author has therefore diverted the main focus of the current research to this goal.

In this research, a basic structure of a modem, using BPSK was initially designed and tested. Later a more comprehensive OFDM modem was designed, for which a comparative performance studies using the Bit Error Rate (BER) plots was conducted for numerous simulations scenarios. These simulation scenarios include the use of different modulation types, with and without use of encoding and use of different types of noise.
In addition to comparative studies, the functioning of communication link with respect to OFDM was also investigated by utilising guard time/cyclic prefix to assist in counteracting the effects of delay, Inter-Symbol Interference (ISI) and Inter-Channel Interference (ICI).

I. OFDM Background

OFDM systems have been widely recognised as an efficient transmission technique for wireless communications and are extensively used in the standards for digital audio/video broadcasting.

OFDM is a frequency-domain approach to communications, and has important advantages when dealing with the frequency-selective nature of high data rate communication channels. As the demand for operating with higher data rates has increased, OFDM systems have emerged as an effective physical-layer solution in their environment [3].

The paper is organised as follows. Section 2 describes the classification of powerline noise and presents the mathematical algorithms and characteristics of the noises used in this paper; Section 3 describes the simulation response and noise modelling; Finally, Section 4 contains the concluding remarks.

2. Powerline Noise

It is well known that the data transmission over powerlines provide many attractive properties. However, like all other communication systems, PLC systems are also at risk of internal or external noise and disturbances. Powerline noises can be classified into 5 categories as follows [4]:

- Coloured background noise with a relatively low power spectral density (PSD), which is caused by summation of numerous noise sources of low power.
- Narrow band noise, mostly amplitude modulated sinusoidal signals caused by ingress of radio broadcasting stations.
- Periodic impulsive noise asynchronous to the mains frequency, which is mostly caused by switched-mode power supplies.
- Periodic impulsive noise synchronous to the mains frequency, which is mainly caused by switching actions of rectifier diodes found in many electrical appliances.
- Asynchronous impulsive noise, which is by switching transients in the power network.

This paper offers an insight into the influence of different types of powerline noise (e.g. Coloured background noise and Impulsive Noise) as well as AWGN.

a) Coloured background noise

A statistical analysis method is usually employed to understand the random behaviour of the noise in the time domain. In [4], an extensive study of the noise amplitude spectrums taken from the laboratory and residential house measurements, was done and it was suggested that the probability distribution of the time-domain noise amplitudes resembles the Nakagami-m distribution. The Nakagami-m probability density functions (PDF) can be written as:

$$p(r) = \frac{2}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^m r^{2m-1} e^{-\frac{mr^2}{\Omega}} \qquad (1)$$

Where r is the random variable, p is the probability of the corresponding random variable, $\Gamma(.)$ is the Gamma function and m is the ratio of the moments i.e. the closeness between the Nakagami and Rayleigh distribution. Simulation response of this research shows that the Nakagami PDF is exactly the same as the Rayleigh PDF when $m = 1$. However, when $m > 1$, the Nakagami PDF has smaller variance and larger mean than the Rayleigh PDF, and reverse is true when $m < 1$.

b) Impulsive Noise – Class A Noise

By means of statistical analysis method, the performance of OFDM system is analysed through an impulsive noise to corrupt the channel. The starting point for deriving the impulsive noise model is the assumption that a large number of statistical independent interferers contribute to the noise. According to the bandwidth of the noise emitted by each of the interferers, Middleton classifies the noise in 3 general classes of A, B and C [5]. This paper considers focusing on the Class A noise model. It is worth mentioning that the noise bandwidth is assumed to be comparable or less than the bandwidth of the disturbed communication system and so transient effects in the analogue receiver stages can be neglected.
As this paper is partly concentrated on the influence of impulsive noise on OFDM transmission, the channel modelling for the additive impulsive noise channel will be kept simple as (2).

$$\boldsymbol{r} = \boldsymbol{s} + \boldsymbol{n} \qquad (2)$$

- S = The transmitted symbol
- n = Class A distributed random variable
- r = The received value

Additionally, a Gaussian noise component is added to model the (almost) always present thermal receiver noise. The Class A noise PDF is given by (3) [6].

$$p_n(\eta) = e^{-A} \sum_{m=0}^{\infty} \frac{A^m}{m!2\pi\sigma_m^2}\, exp\left(-\frac{\eta^*\eta}{2\sigma_m^2}\right) \qquad (3)$$

With η^* denotes the complex conjugate of η.

$$\sigma_m^2 = \frac{\frac{m}{A} + T}{1 + T}$$

The parameter A is the impulsive index given by the product of the average number of impulses per unit time and the mean duration of the emitted impulses entering the receiver. For $A \rightarrow \infty$ the noise gets Gaussian distributed and small A produces more structured/impulsive noise. The parameter T is the ratio between the mean power of the Gaussian and the mean power of the impulsive noise component [6].

3. Simulation Response and Noise Modelling

This section concentrates on presenting the simulation response for different simulation scenarios, considering the comparison for different modulation types and orders, BER comparison curves for AWGN channel with/ without convolutional channel coding.

Figure 2 depict the different Bit Error Rate (BER) curves for different orders of PSK and QAM modulation types in an AWGN channel.

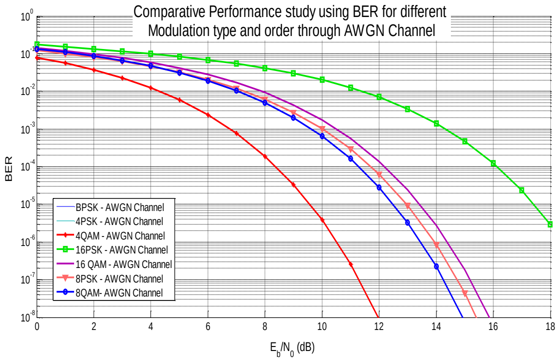


Figure 2. Comparative performance study using BER for different order of PSK and QAM through AWGN Channel

As it is shown Figures 2, the performance is improved by using lower order modulation formats e.g. BPSK, 4PSK, 4QAM etc. compared to the higher modulation schemes e.g. 64PSK, 64QAM etc; as they offer lower data rates but are more robust in the presence of noise.

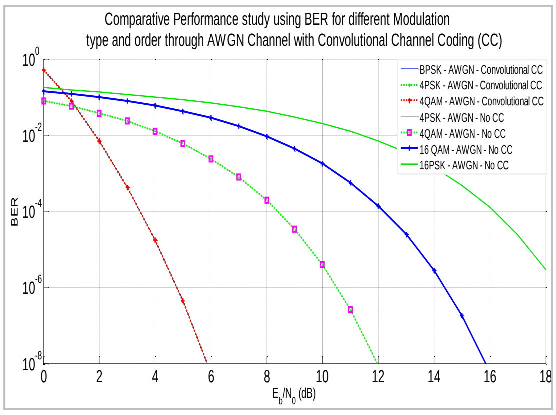


Figure 3. Comparative performance study using BER for PSK and QAM with/without convolutional channel coding

The performance study of OFDM scheme is also examined with and without presence of noise and application of forward error correction (FEC) and it can be seen that the performance of the system is greatly improved when FEC, in this case convolutional coding, is used.

Figures 4 and 5 depicts the steps and comparison of noise modelling.

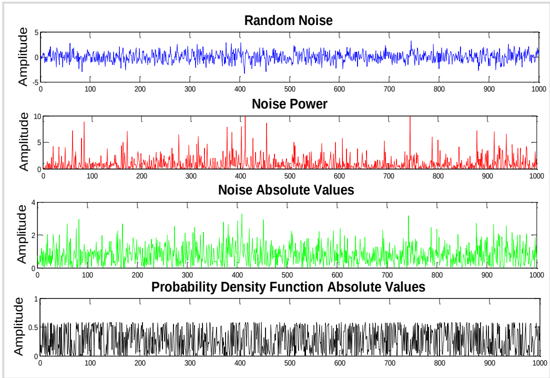


Figure 4. Graphs of random input noise, its power, absolute value and absolute value of its PDF

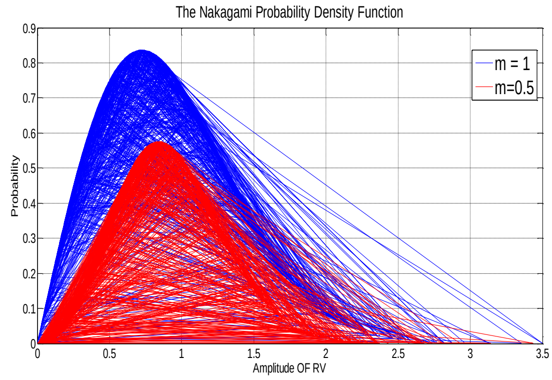
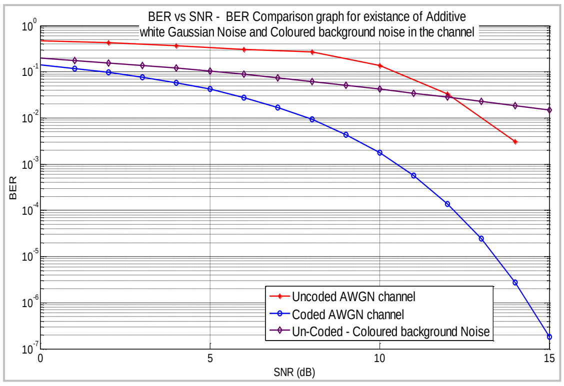


Figure 5. The Nakagami Probability Density Function for different m = 1 and m = 0.5

As illustrated in Figure 6, the modelled coloured



background noise does not have rational effect on the performance of the channel and hence the system.

Figure 6. BER comparison graph for different channel scenarios, Un-coded AWGN, convolutionaly coded AWGN and Channel affected by the modelled coloured background noise.

4. Conclusion

In this paper, design and analysis of OFDM system for powerline based communication was presented. In doing so, MATLAB was used to simulate the operation of virtual transmitter and receiver.

The performance of the system design was then analysed by adding AWGN and powerline coloured background noise and in an attempt to corrupt the signal.

This research is currently carried out for degree of Masters by Research. More results (e.g. Image transmission through the OFDM system and Middleton Class A noise modelling, etc) will be obtained on-time for the presentation date of this workshop.

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Design and Analysis of OFDM System for Powerline Based Communication

Noushin Karimian and Javad Yazdani
School of Computing, Engineering and Physical Sciences, University of Central Lancashire, PR1 2HE, UK
Email: NKarimian@uclan.ac.uk

***Abstract* - Research on digital communication systems has been greatly developed in the past few years and offers a high quality of transmission in both wired and wireless communication environments. Coupled with advances in new modulation techniques, Orthogonal Frequency Division Multiplexing (OFDM) is a well-known digital multicarrier communication technique and one of the best methods of digital data transmission over a limited bandwidth.**

In this paper, design and analysis of OFDM system for powerline based communication is proposed in an attempt to understand and recognise the most suitable technique for the transmission of message or image within a communication system. This is achieved by examining a novel approach in comparing the different modulation order, different modulation type, application of Forward Error Correction (FEC) scheme and also application of different noise types and applying them to the two modelled channels (AWGN and Powerline modelled channel). In doing so, MATLAB and embedded Digital Signal Processing (DSP) systems are used to simulate the operation of virtual transmitter and receiver. The performance of the system design is then analysed by adding noise (additive white Gaussian noise and Powerline coloured background noise) in an attempt to corrupt the signal. In the present paper, results will show that performance is improved by using lower order modulation formats e.g. Binary Phase Shift Keying (BPSK) and Quadrature Amplitude Modulation (4-QAM), compared to the higher modulation schemes e.g. 64-QAM; as they offer lower data rates but are more robust in the presence of noise. The performance study of OFDM scheme is also examined with and without presence of noise and application of FEC.

***Keywords:* Digital communication, OFDM, Powerline, FEC, AWGN, DSP, BPSK, QAM.**

I. INTRODUCTION

Among the techniques that have been used to design a digital communication system; Orthogonal Frequency Division Multiplexing (OFDM) has been referred to as one of the most advantageous technique. OFDM systems have been widely recognised as a bandwidth efficient transmission technique for wireless communications. This multi-carrier transmission technique has been gaining more and more interest from communications and signal processing communities [1]. OFDM is also considered as one of the most promising modulation methods for powerline communications [2].

The research aim of this paper is to design and implement an OFDM communication link for Powerline Communication (PLC) system, using MATLAB and embedded DSP systems to simulate the operation of virtual transmitter and receiver. More specifically, the overall aim of this paper is to design an OFDM modem for a powerline-based communication in order to propose and examine a novel approach in comparing the different modulation order, different modulation type, application of FEC scheme and also application of different noise types (AWGN and Powerline coloured background noise) and applying them to the two modelled channels (AWGN and Powerline modelled channel) in an attempt to understand and recognise the most suitable technique for the transmission of message or image within a communication system. This principal aim is achieved by setting and completing number of objectives. The first is to design a basic OFDM modem by using BPSK and the second is to design a more comprehensive OFDM modem for the purpose of simulation. This will be followed by investigating the functioning of the communication link with respect to OFDM by utilising Cyclic Prefix, with the aim of counteracting the effects of delay such as ISI and ICI. The performance of this OFDM modem is then examined by using the AWGN channel. An additional comparative performance studies will be conducted by plotting the BER graphs for numerous simulations for different modulation types, different modulation orders and also different types of channel coding. Moreover, additional analysis will be carried out in order to examine the overall performance of the OFDM modem. This will be primarily achieved by using AWGN and subsequently with Powerline coloured background noise. Finally, the full functioning OFDM modem is examined through the transmission of an image.

Figure 1 depicts the block diagram of OFDM modem which is designed in this research paper.

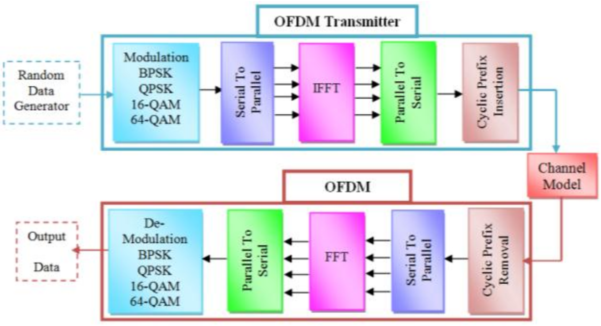


Figure 1. OFDM Block diagram.

Despite wide use of the OFDM in conjunction with (or without) other techniques, there is a great potential for this technique to be employed in PLCs, and the author has therefore diverted the main focus of the current research to this goal.

In this research, a basic structure of a modem, using BPSK was initially designed and tested. Later a more comprehensive OFDM modem was designed, for which a comparative performance studies using the Bit Error Rate (BER) plots was conducted for numerous simulations scenarios. These simulation scenarios include the use of different modulation types, with and without use of encoding and use of different types of noise. In addition to comparative studies, the functioning of communication link with respect to OFDM was also investigated by utilising guard time/cyclic prefix to assist in counteracting the effects of delay, Inter-Symbol Interference (ISI) and Inter-Channel Interference (ICI).

II. OFDM Background

OFDM is classified as a special type of multi-carrier transmission technique, where the transmission of individual data stream occurs over number of subcarriers which have lower rate. This fundamental idea was initially proposed and patented by Chang in the middle of 1960s [3], for which it was found that the bandwidth (W) is divided into number (N_c) of smaller sub-bands, generally referred to as subcarriers. The width of these subcarriers is:

$$\Delta f = {}^{W}/_{N_c} \qquad (1)$$

Figure 2 depicts the subdivision of the bandwidth into number of sub-bands (N_c) or subcarriers, indicated as the blue arrows [3].

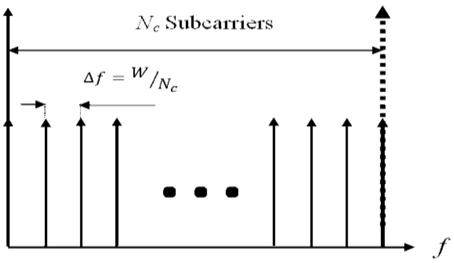


Figure 2. The subdivision of the bandwidth [3].

More specifically, a multicarrier system functions by partitioning the data stream into blocks of N_c data symbols, as illustrated in Figure 3.12, where the data symbols are communicated in a parallel format by modulating the N_c carriers.

Such multicarrier schemes have symbol duration of:

$$T_s = N_c / R \qquad (2)$$

Where:

- R: The baud rate
- T_s: The symbol duration
- N_c: subcarriers

A multicarrier signal has a general form containing set of modulated carriers as presented in Equation (3.10) [3] .

$$s(t) = \sum_{m=-\infty}^{+\infty}\left(\sum_{k=0}^{N_c-1} x_{k,m}\Psi_k(t-mT_s)\right) \qquad (3)$$

- $s(t)$: Multicarrier signal
- $x_{k,m}$: The data symbol modulating the k^{th} subcarrier in the m^{th} signalling interval
- Ψ_k : The waveform for the k^{th} subcarrier

A standard modulation of multicarrier scheme is depicted in Figure 3.

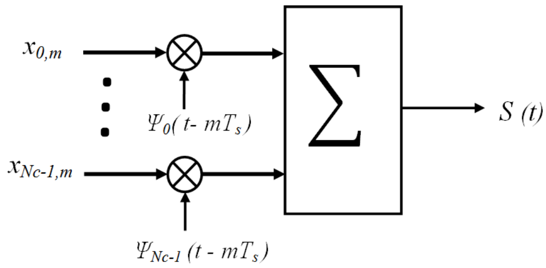


Figure 3. Modulation of multicarrier scheme [3].

In order to promise a high spectral efficiency, the signals for each sub-channel must present an overlapping transmit spectra. In other words, the sub-channel waveforms must appear as orthogonally overlapping, as this would ease the separation of such overlapping sub-channel at the receiver end [3]. The term ‘orthogonality’ refers to the existence of a specific “mathematical relationship between the frequencies of the carrier in the system” [1]. A general mathematical equation for orthogonal waveforms can be written as [1]:

$$\Psi_k(t) = \begin{cases} \frac{1}{\sqrt{T_s}} e^{jw_k t} & t \in [0, T_s] \\ otherwise & 0 \end{cases} \qquad (4)$$

With: $\omega_k = \omega_0 + k\omega_s$

Where:

$$k = 0, 1, \ldots N_c - 1 \qquad (5)$$

- f_k = Subcarrier frequency $f_k = {}^{\omega_k}/_{2\pi}$
- f_0 = Lowest frequency (k=0) $f_0 = {}^{\omega_0}/_{2\pi}$

The distance between each of the neighbouring subcarriers is:

$$\Delta f = {}^{\omega_s}/_{2\pi} = {}^{W}/_{N_c}$$

It is worth mentioning that as each of the sub-channel waveform ($\Psi_k(t)$) is limited to the time window $[0, T_s]$, the distance between each of the neighbouring subcarriers should also comply with:

$$\Delta f = {}^{1}/_{T_s} = {}^{R}/_{N_c}$$

Such windowing will result in a convolution with the equation below, in the frequency domain [3].

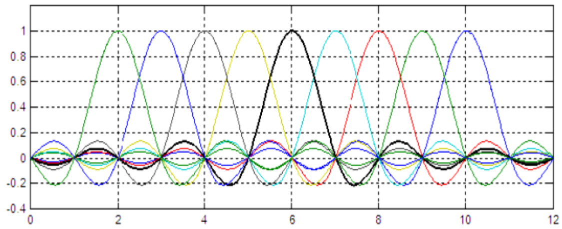
$$T_s.\exp(-j\pi f T_s).\frac{\sin(\pi f T_s)}{\pi f T_s}$$

As depicted in Figure 4, although the different sub-carriers overlap on each other, they don't interfere with each other at:

$$f = f_k; (k = 0,1, \dots . N_c - 1)$$

They are therefore known as orthogonal subcarrier or [1]:

$$\int_0^{T_s} \Psi_k(t)\, \Psi_l^*(t) dt = \delta(k-1) \qquad (6)$$



Time (Normalised by 1/*T- OFDM*)

Figure 4. Spectrum of an OFDM signal.

OFDM systems have been widely recognised as an efficient transmission technique for wireless communications and are extensively used in the standards for digital audio/video broadcasting. OFDM is a frequency-domain approach to communications, and has important advantages when dealing with the frequency-selective nature of high data rate communication channels. As the demand for operating with higher data rates has increased, OFDM systems have emerged as an effective physical-layer solution in their environment [4].

The paper is organised as follows. Section 3 describes the classification of powerline noise and presents the mathematical algorithms and characteristics of the noises used in this paper; Section 4 describes the simulation response and noise modelling; Finally, Section 5 contains the concluding remarks.

III. Powerline Noise

It is well known that the data transmission over powerlines provide many attractive properties. However, like all other communication systems, PLC systems are also at risk of internal or external noise and disturbances. Powerline noises can be classified into 5 categories as follows [4]:

- Coloured background noise with a relatively low power spectral density (PSD), which is caused by summation of numerous noise sources of low power.
- Narrow band noise, mostly amplitude modulated sinusoidal signals caused by ingress of radio broadcasting stations.
- Periodic impulsive noise asynchronous to the mains frequency, which is mostly caused by switched-mode power supplies.
- Periodic impulsive noise synchronous to the mains frequency, which is mainly caused by switching actions of rectifier diodes found in many electrical appliances.
- Asynchronous impulsive noise, which is by switching transients in the power network.

This paper offers an insight into the influence of different types of powerline noise (e.g. Coloured background noise) as well as AWGN.

A. *Powerline Coloured background noise*

A statistical analysis method is usually employed to understand the random behaviour of the noise in the time domain. In [4], an extensive study of the noise amplitude spectrums taken from the laboratory and residential house measurements, was done and it was suggested that the probability distribution of the time-domain noise amplitudes resembles the Nakagami-m distribution. The Nakagami-m probability density functions (PDF) can be written as:

$$p(r) = \frac{2}{\Gamma(m)}\left(\frac{m}{\Omega}\right)^m r^{2m-1} e^{-\frac{mr^2}{\Omega}} \qquad (7)$$

Where r is the random variable, p is the probability of the corresponding random variable, Γ(.) is the Gamma function and *m* is the ratio of the moments i.e. the closeness between the Nakagami and Rayleigh distribution. Simulation response of this research shows that the Nakagami PDF is exactly the same as the Rayleigh PDF when *m* = 1. However, when *m* > 1, the Nakagami PDF has smaller variance and larger mean than the Rayleigh PDF, and reverse is true when *m* < 1.

IV. Simulation Response and Noise Modelling

This section concentrates on presenting the simulation response for different simulation scenarios, considering the comparison for different modulation types and orders, BER comparison curves for application of FEC scheme and also application of different noise types and applying them to the two modelled channels (AWGN and Powerline modelled channel). However, prior to carrying out these comparative studies, the correct transmission and reception of the data and therefore perfect operation of the designed OFDM modem has been confirmed. Furthermore, this section will include analysing three different techniques listed below, for achieving better communication performance:

i) Different modulation order
ii) Different modulation type
iii) Application of Forward Error Correction scheme

Figure 5 depict the different Bit Error Rate (BER) curves for different modulation techniques, both type and order in an AWGN channel.

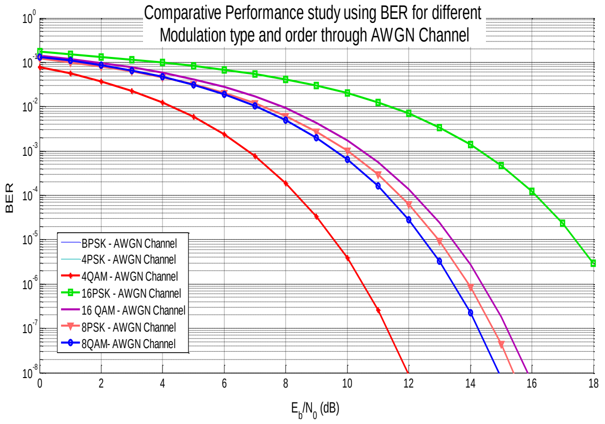


Figure 5. Comparative performance study using BER for different modulation type and modulation order through AWGN Channel.

Based on the comparison results for the different modulation type and order, a graph is designed and presented in Figure 6. This is achieved by having the different modulation types and orders versus the number of advantages. The factors that have been considered are the data rate, simple implementation, overall performance, robustness in presence of noise and reliability. As it is illustrated, the BPSK and 4QAM have the highest number of advantages; hence they are the most suitable and highly reliable modulation format for communication system.

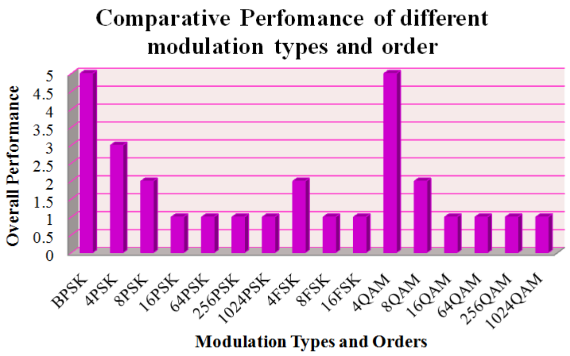


Figure 6. Different modulation types and orders versus the number of advantages.

As it is shown Figures 5 and 6, the performance is improved by using lower order modulation formats e.g. BPSK, 4PSK, 4QAM etc. compared to the higher modulation schemes e.g. 64PSK, 64QAM etc; as they offer lower data rates but are more robust in the presence of noise.

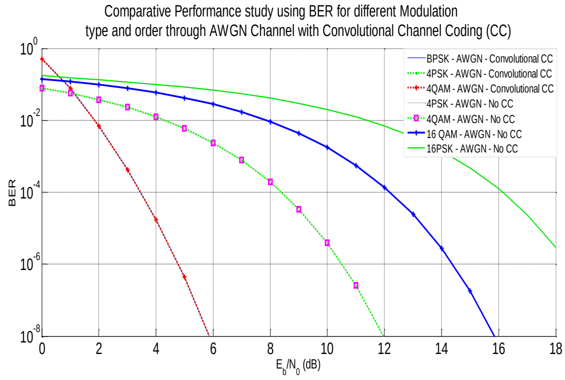


Figure 7. Comparative performance study using BER for PSK and QAM with/without convolutional channel coding.

As illustrated in Figure 7, convolutionally encoding the system has proved to make a considerable improvement for both BPSK and 4QAM modulation system. In addition, Convolutional Channel Encoding (CCE) allows the receiver to correct errors without demanding a reverse channel to request retransmission of data. After the CCE-soft technique, the next suitable technique is the Block Channel Encoding-soft (BCE) technique, with E_b/N_o of 9 dB, i.e. the second lowest E_b/N_o value. Soft-decision algorithms in FEC, unlike hard-decision, process analogue signals allowing for much higher error-correction performance (CCE-Soft and BCE-Soft). In BCE also, the added redundancy enables the receiver to reliably detect and correct errors over communication channel.

In order to investigate the performance of the designed OFDM system, analysis is conducted to examine the effects of noise, initially using AWGN and subsequently with powerline coloured background noise.

Figures 8-10 depicts the steps and comparison of noise modelling.

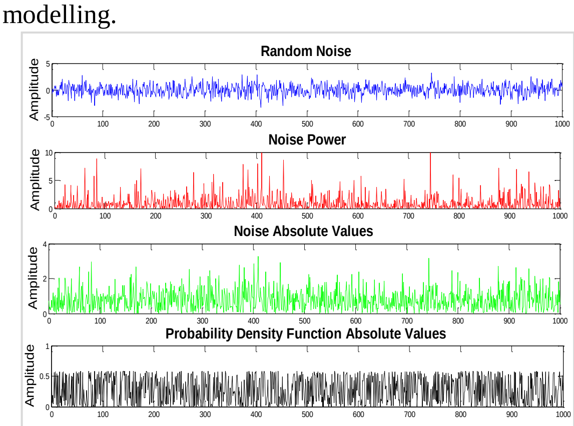


Figure 8. Graphs of random input noise, its power, absolute value and absolute value of its PDF.

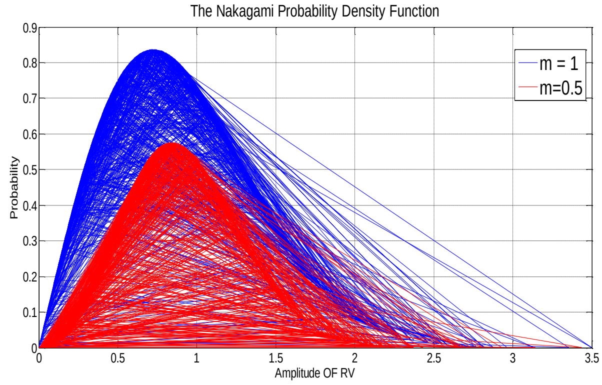


Figure 9. The Nakagami Probability Density Function for different m = 1 and m = 0.5.

As illustrated in Figure 10, the modelled coloured background noise does not have rational effect on the performance of the channel and hence the system.

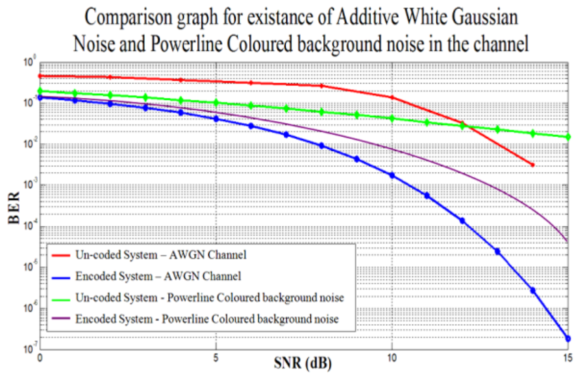


Figure 10. BER comparison graph for different channel scenarios, Un-coded and convolutionaly encoded AWGN, uncoded and convolutionaly encoded powerline coloured background noise.

It can be observed that the convolutionally encoded link with BER of 10^{-2}, needs about 5 dB less compared with that of the un-coded link. It is also clear that for BER of 10^{-3} coding gain converges to a value of about 5.3 dB. The BER under BPSK modulation technique over AWGN, with encoder produces a SNR value of 10.7 dB but in the case of un-coded system the SNR is 15dB. In the other hand, for modelled powerline channel, convolutionally encoded link with BER of $10^{-1.7}$, needs about 3.5 dB less compared with that of the un-coded link. It is also observable that for BER of 10^{-2} coding gain converges to a value of about 6 dB. The BER under BPSK modulation technique over modelled powerline channel, with encoder produces a SNR value of 8.8 dB but in the case of un-coded system the SNR is 15dB. Therefore encoding has accurately detected and corrected the present noise in the channel and produced an improvement on the performance of the system.

V. Conclusions

In this paper, design and analysis of OFDM system for powerline based communication was presented. In doing so, MATLAB was used to simulate the operation of virtual transmitter and receiver.
The performance of the system design was then analysed by adding AWGN and powerline coloured background noise and in an attempt to corrupt the signal.
The simulation results presented in this project suggest that lower order modulation formats (BPSK and 4-QAM), are the most preferred modulation techniques (in both type and order) for their considerable performance. The results also indicated that, CCE-Soft and BCE-Soft are by far the best encoding techniques (in FEC type) for their best performance in error detection and correction. Indeed, applying these techniques to the two modelled channels has proven very successful and will be accounted as a novel approach for the transmission of message or image within a powerline based communication system.

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