The Islamic University of Gaza
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Optical **O**rthogonal **F**requency **D**ivision **M**ultiplexing **D**irect **D**etection for **I**mproving **C**apacity of **R**adio over **F**iber **T**ransmission **S**ystem

تحسين سعة نظام التراسل لموجات الراديو عبر الألياف الضوئية باستخدام تقنية مضاعفة تقسيم الترددات المتعامدة الضوئية و الاكتشاف المباشر

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DEDICATION

To my parents
Who taught me the value of study and perseverance ethic and have given me endless support

To my wife, son and daughter
Who encouraged me through the work of this thesis

To my brothers and sister

To my faithful friends

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In the name of Allah S.W.T.

First of all, without the enlightenment of ALLAH, this work would not have been done successfully.

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Now, time has come to express full gratefulness to persons who educate me to be in this position, and continually doing this work; thanks to my parents, who first taught me how to think and reason, encouraged me to learn and excel, and planted in me ethics, principles and standards. Many thanks to my bothers, sister and uncles who continually encourage me. All thanks to anyone who prayed for me.

Ahmed Said Al Shantti
Palestine, Gaza

ABSTRACT

The next generation of access networks is rushing the needs for the convergence of wired and wireless services to offer end users greater choice, convenience and variety in an efficient way. This scenario will require the simultaneous delivery of voice, data and video services with mobility feature to serve the fixed and mobile users in a unified networking platform. In other words, new telecom systems require high-transmission bandwidths and reliable mobility. The Radio over Fiber (RoF) technology represents a key solution for satisfying these requirements, since it jointly takes advantage of the huge bandwidth offered by optical communications systems with the mobility and flexibility provided by wireless systems. RoF systems consist of heterogeneous networks formed by wireless and optical links. RoF technology provides the advantage of eliminating the gateways, since there is no need for analogous-digital or digital-analogous conversions. This simplifies the system complexity and reduces the operational costs. For these reasons, this proposed research will focus on improvement of data rate using Optical Orthogonal Frequency Division Multiplexing (OOFDM) and direct detection to achieve very high data rate with better Bit Error Rate (BER) and improving the capacity of the system. The Quadrature Amplitude Modulation (QAM), 4QAM, 16QAM and 64QAM Orthogonal Frequency Division Multiplexing (OFDM) RoF system describes with different number of subcarriers and shows a BER of value of zero. OptiSystem simulation program is used for the simulation and Bit Error Rate (BER) is obtained and verified.

ملخص الرسالة

يعتبر الجيل القادم من شبكات النفاذ، وتسارع الاحتياجات، و تقارب الخدمات السلكية واللاسلكية و ذلك من أجل تقديم خيارات أوسع و أشمل للمستخدمين النهائيين بطريقة فعالة و مريحة و متنوعة. وهذا السيناريو يتطلب الاتصال في وقت واحد من الصوت والبيانات وخدمات الفيديو مع ميزة التنقل لخدمة المستخدمين الثابتة والمتنقلة في منصة التواصل الموحدة ، حيث أن نظم الاتصالات الجديدة تتطلب عرض نطاق ترددي عالي النقل والتنقل موثوق به و الحماية.

يمثل نقل موجات الراديو عبر الألياف الضوئية (RoF) مفتاح الحل لتلبية هذه الاحتياجات، لأنه يأخذ ميزة مشتركة ضخمة من عرض النطاق الترددي التي تقدمها نظم الاتصالات الضوئية مع الحركة والمرونة التي توفرها الأنظمة اللاسلكية. تتكون نظم (RoF) من شبكات غير متجانسة تتكون من وصلات لاسلكية والبصرية، حيث أن نظام (RoF) يوفر ميزة لإزالة البوابات، لذك فإنه ليس هناك حاجة للتحويلات التماثلية إلى الرقمية أو الرقمية إلى التماثلية، و هذا يبسط تعقيد النظام ويقلل من التكاليف التشغيلية له.

لهذا الأسباب، فإن هذا البحث المقترح يركز على تحسين معدل البيانات و زيادة السعة باستخدام مضاعفة تقسيم الترددات المتعامدة الضوئية (OOFDM) و الاكتشاف المباشر لتحقيق معدل البيانات عالية جدا مع أفضل قيمة لمعدل الأخطاء (BER) وتحسين سعة النظام، حيث سيتم تناول عدة انواع من هذا النظام لدراسته دراسة تحليلة و توضيحية بالرسم مثل نظام 4QAM، و 16QAM، و 64QAM حيث سيتم عمل أنظمة محاكاة لها باستخدام برنامج OptiSystem و إظهار قيم معدل الخطأ المناسبة و كيفية زيادة السعة مع الحصول على قيمة مناسبة لمعدل الخطأ.

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LIST OF ABBREVIATIONS

APD: Avalanche Photodiode
ADC: Analogue-to- Digital Converter
AM: Amplitude Modulation
ASK: amplitude shift keying
BW: Bandwidth
BER: Bit Error rate
BS: Base Station
B-ISDN: Broadband Integrated Services Digital Network
CATV: Cable television
CD: Chromatic Dispersion
CNR: Carrier to Noise Ratio
CW: Continuous Wave
CS: Central Station
CP: Cyclic prefix
DWDM: Dense Wavelength Division Multiplexing
DFB: Distributed Feedback Laser
DSB- Double side Band
DVB-TV: Digital Video Broadcasting
DAC: Digital-to-Analogue Converter
DD: Direct Detection
DFT: Discrete Fourier Transform
DTFT: Discrete-time Fourier Transform
DR: Dynamic Range
DMT: discrete multitone
DFB: Distributed Feedback Laser
DPSK: Differential Phase Shift Keying
EAM: Electro Absorption Modulator
EDFA: Erbium Doped Fiber Amplifier
FFT: Fast Fourier Transform
FTTx: Fiber to The Home, curb, etc.

FP: Fabry Perot Laser
FM: Frequency Modulation
FSK: frequency shift keying
GRIN: Graded Index
GSM: Global System Mobile
IF: Intermediate Frequency
IDFT: Inverse discrete Fourier Transform
IFFT: Inverse Fast Fourier Transform
IM: Intensity Modulation
ISI: Inter-symbol Interference
IQ: In-phase and in-Quadrature
IVC: inter-vehicle communication
ITS: intelligent transport systems
LD: Laser Diode
LTE: Long Term Evolution
LAN: Local Area Network
LED: Light Emitting Diode
MMF: Multi mode Fiber
MZM: Mach-Zehnder Modulator
MH: Mobile Home
MAN: Metropolitan Area Network
MS: Mobile Station
MSC: Mobile Switching Center
MU: Mobile Unit
MVDS: Multipoint Video Distribution Services
MBS: Mobile Broadband System or Service
NRZ: Non return to Zero
NF: Noise Figure
OSSB: Optical Single Side Band
OTDM: Optical time Division Multiplexing
OFDM: Orthogonal Frequency Division Multiplexing
OOK: On Off Keying

OCDMA: Optical Code Division Multiple Access
OTR: Optical To RF
PD: Photo Detector
PM: phase modulation
PSK: phase shift keying
PMD: Polarization Mode Dispersion
PRBS: Pseudo Random Bit Sequence
PON: Passive Optical Network
SNR: Signal to Noise Ratio
SMF: Single Mode Fiber
RAU: Radio Access Unit
RF: Radio Frequency
RZ: Return to Zero
RoF: Radio over Fiber
RS: Remote Site
RVC: road-to-vehicle communication
RIN: Relative Intensity Noise
RTO: RF To Optical
SONET: Synchronous Optical Network
SDH: Synchronous Digital Hierarchy
SCM: Sub-carrier Multiplexing
TDM: Time division multiplexing
UMTS: Universal Mobile Telecommunication System
VCSEL: Vertical Cavity Surface Emitting Laser
WLAN: Wireless Local Area Network
WDM: Wavelength Division Multiplexing

1

Introduction

1.1 Introduction

Wireless communication is becoming an integral part of today's society. The spread of mobile and other wireless devices with increased demand for broadband services are putting pressure on wireless systems to increase capacity. To achieve this, wireless systems must have increased feeder network capacity, operate at higher carrier frequencies, and cope with increased user population densities.

However, raising the carrier frequency and thus reducing the radio cell size leads to costly radio systems while the high installation and maintenance costs associated with high bandwidth silica fiber render it economically impractical for in-home and office environments.

This research is focused on orthogonal division frequency multiplexing (OFDM) radio over fiber (RoF) applied in optical systems. Hence by incorporating OFDM along with the optical fiber, the RoF system can be used for both short distance as well as long-haul transmission at very high data rate. This improves the system flexibility and provides a very large coverage area without increasing the cost and complexity of the system very much.

RoF is a technology used to distribute radio frequency (RF) signals over analog optical links. In such RoF systems, broadband microwave data signals are modulated onto an optical carrier at a central station (CS), and then transported to remote sites or base station (BS) using optical fiber. The base-stations then transmit the RF signals over small areas using microwave antennas.

OFDM is a well-known technique in communication systems, since it is used in different applications, for example in wire copper with digital subscriber lines (DSL), digital video broadcasting television (DVB-TV), in RF systems such as wireless local area network (WLAN), and in the new next generation of mobile system, long term evolution (LTE).

The increasing popularity of internet based services, fiber-optic access is presently regarded as the only technology with potential to cope with the expected bit rate demand of home connections. For these reasons, the next generation optical networks are expected to require more advanced modulation formats, such as for example OFDM modulation.

Nowadays the digital processing technology has matured to the point where OFDM signal processing could be performed in a complementary metal-oxide semiconductor (CMOS) integrated circuit to digitalize the information at the high bit rates typical of fiber optic communication systems.

OFDM has been already established in long haul high bit data rate fiber applications as a technique to compensate the chromatic dispersion of standard single mode fiber (SSMF).

1.2 Problem Statement

Indeed, bandwidth-hungry services will require upgraded capacity through increased bit rate. Higher bit rates are being targeted fuelled by the progress in the component industry. In order to meet the twin constraints of low-cost and high performance for the access network, external modulation seems the most convenient way provided that the propagation penalties that distort the signal are diminished.

For above reasons this research presents a new approach for enhancing and improving the performance of RoF transmission systems using OOFDM techniques. OFDM is seen as the modulation technique for future broadband wireless communications because it provides increased robustness against frequency selective fading and narrowband interference, and is efficient in dealing with multipath delay spread. While RoF is the next generation communications system that can utilize the high capacity of optical networks along with the mobility of wireless networks.

1.3 Objectives

There are many objectives of this thesis; these objectives are presented as the following:

- Analyzing the design of optical OFDM systems for RoF systems.
- Analyzing in full details the multi-stage structures of optical OFDM when applying to RoF.
- Evaluating the performance of the system using eye diagram and minimum bit error rate (Min BER) tools.
- Try to obtain a new low complexity optical OFDM which operate under RoF systems.
- Publishing the research results as possible in prestigious journals and in proceedings of highly reputed and refereed international conferences.

1.4 Organization of the Dissertation

The remaining part of this dissertation is divided into five chapters as detailed below:

Chapter 2 surveys the state of the art on RoF technologies with a special emphasis devoted to RoF system, and shows the benefits, applications and the limitations of RoF technology, and also describes the OFDM RoF system. *Chapter 3* describes the background material that is necessary to understand the work, and deals with the OFDM issues such as definition of orthogonality and OFDM signal and OFDM RoF. It shows the advantages and disadvantages of OFDM, and covers the coded OFDM and optical OFDM. *Chapter 4* covers the basic optical fiber communication link such as optical fiber, laser, modulation, detection and photodiode, and describes the optical OFDM RoF system. In *chapter 5* simulation results and performance analysis are presented and discussed. *Chapter 6* draws conclusions, summarizes the main contributions of this dissertation, and finally describes the possible future works.

2

Literature Review
Radio over Fiber

2.1 Introduction

To meet the accelerating demands in communication systems, the integration of optical network and wireless radio is a promising solution. ROF means the optical signal is being modulated at radio frequencies and transmitted via the optical fiber.

The RoF technology is transport systems have the potential to serve both fixed and mobile customers with offer large transmission capacity, significant mobility, flexibility, large bandwidth and increased mobility in a cost-effective way.

This chapter highlights the literature cited on the RoF technology, and it is consist of four parts, first part covers about general explanation of RoF systems, the benefits and RoF link configuration. The second part deals with applications of RoF technology. The third part discusses the limitations of RoF technology. The fourth part covers the OFDM system for RoF.

2.2 Radio over Fiber Technology

Radio over fiber (RoF) technology has emerged as a cost effective approach for reducing radio system costs because it simplifies the remote antenna sites and enhances the sharing of expensive radio equipment located at appropriately sited switching centers (SC) or otherwise known as central sites/stations (CS). On the other hand, graded Index polymer optical fiber (GIPOF) is promising higher capacity than copper cables, and lower installation and maintenance costs than conventional silica fiber [1-2].

There are so many previous research papers and works that have been done by several people recently in terms of using OFDM modulation technique or multicarrier transmission for sending and receiving data through Radio over Fiber Networks.

For example a study about multiplexing carrier used for RoF Network Technology, and their result of this study that the outcomes of bandwidth was increased to 60 GHz by applying of 16 channel of SCM combined with WDM in optical fiber link [3]. Another study about OFDM for a RoF system for WLAN, this study the analysis of theoretical performance for OFDM using different technique of digital modulation such as phase shift keying (PSK), binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) and QAM. This study shows that QAM provide better spectral efficiency and lower detection error probability [4].

During study of the analysis of OFDM signal through optical fiber for RoF transmission it has investigated the impact of fiber dispersion on the transmission performance of OFDM based IEEE 802.11.g, WLAN signal for different distances. The results of study show that using different fiber length it is clear that significant coverage extension is possible with very minimum penalty [5].

And another work which studied a RoF link for OFDM transmission without RF amplification. This work is to increase OFDM signal transmission quality over the optically amplified link by joint optimization of the photo detector (PD) impedance matching and Mach-Zender modulator (MZM) bias. The result show that the amplification can be moved from electrical to optical, which allows having an optical amplifier at the central office and simplifying the base station [6].

Based on those previous papers and studies, there are so many researches and works in the field of using multicarrier transmission technique especially OFDM to transmitted and received data through optical link in Radio over Fiber Networks.

2.2.1 Overview

First RoF systems were mainly used to transport microwave signals, and to achieve mobility functions in the central office or exchange (CO). That is, modulated microwave signals had to be available at the input end of the RoF system, which subsequently transported them over a distance to the Remote Site (RS) in the form of optical signals. At the RS the microwave signals are regenerated and radiated by antennas. Figure 2.1 shows a general RoF architecture.

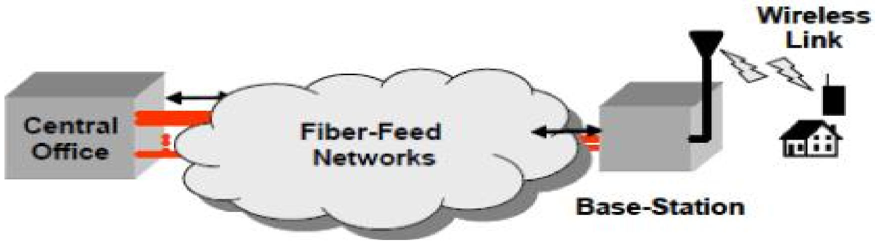

Figure 2.1: General RoF system concept.

At a minimum, a RoF link consists of all the hardware required to impose an RF signal on an optical carrier, the fiber-optic link, and the hardware required to recover the RF signal from the carrier.

The optical carrier's wavelength is usually selected to coincide with either the 1.3 µm window, at which standard single-mode fiber has minimum dispersion, or the 1.55 µm window, at which its attenuation is minimum [7-10].

The RoF systems are designed to perform added radio system functionalities besides transportation and mobility functions. These functions include data modulation, signal processing, and frequency conversion (up and down). For a multifunctional RoF system, the required radio signal at the input of the RoF system depends on the RoF technology and the functionality desired.

Figure 2.2 shows a typical RF signal (modulated by analog or digital modulation techniques) being transported by an analog fiber optic link. The RF signal may be baseband data, modulated IF, or the actual modulated RF signal to be distributed. The RF signal is used to modulate the optical source in transmitter. The resulting optical signal is launched into an optical fiber. At the other end of the fiber, we need an optical receiver that converts the optical signal to RF again [1, 11].

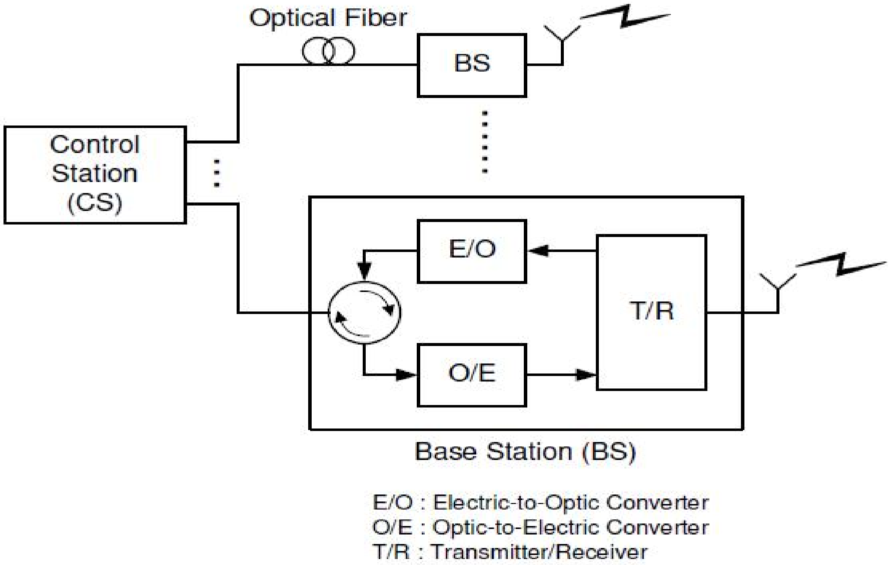

Figure 2.2: RoF communication system architecture [11].

The generated electrical signal must meet the specifications required by the wireless application be it global system for mobile (GSM), universal mobile telecommunication system (UMTS), wireless LAN, Worldwide Interoperability for Microwave Access (WiMax) or other. By delivering the radio signals directly, the optical fiber link avoids the necessity to generate high frequency radio carriers at the antenna site. Since antenna sites are usually remote from easy access, there is a lot to gain from such an arrangement [11].

Usually a single fiber can carry information in one direction only (simplex) which means that we usually require two fibers for bidirectional (duplex) communication However, the main advantage of RoF systems is the ability to concentrate most of the expensive, high frequency equipment at a centralized location, thereby making it possible to use simpler remote sites. Furthermore, RoF technology enables the centralizing of mobility functions such as macro-diversity.

2.2.2 RoF link configurations

There are several approaches to transporting radio signals over optical fiber in RoF systems, which is classified based on the kinds of frequency bands (RF bands, IF baseband (BB)) transmitted over an optical fiber link. The three fundamental techniques as shown in Figure 2.3 RoF analog photonic links are typically multichannel in nature and require high power compared to digital schemes because of the increased carrier to noise ratio (CNR) requirements [12-14].

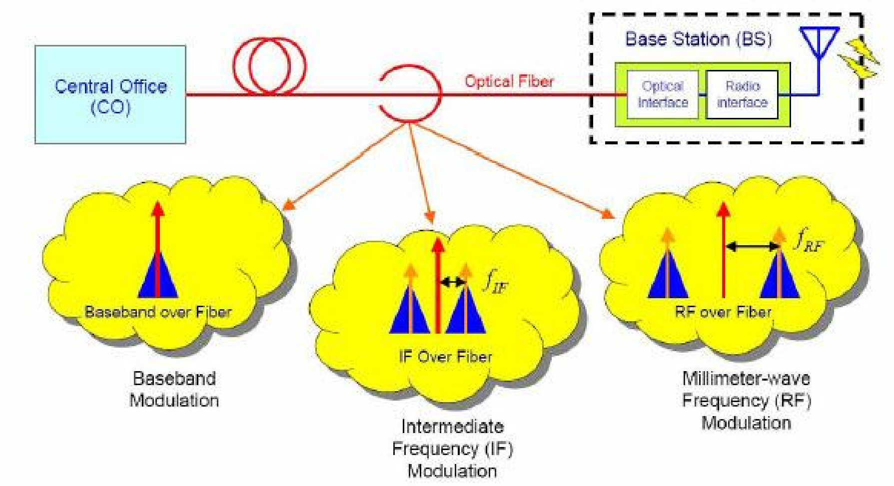

Figure 2.3 Radio signal transport schemes for RoF systems [9].

The wireless signals are transported directly over the fiber at the radio carrier transmission frequency without the need for any subsequent frequency up or down conversion at the remote antenna BSs. The key optical and RF devices required at the CO and the BS for downstream signal transmission in a RoF system based on RF over fiber.

The wireless data obtained from the trunk network are modulated onto a number of lower intermediate frequency (IF) carriers, which are then combined to form a SCM signal. This SCM signal is up converted to the radio transmission frequency using a local oscillator (LO) source located at the CO and then modulated onto an optical carrier.

At the remote BS, the analog optical signal is detected, amplified, filtered, and directed to an antenna for free space transmission. Upstream radio transmission to the BS and subsequently back to the CO will require a mechanism for modulating an optical source located at the BS at the radio carrier frequency, and photo detection of this signal back at the CO.

For downstream signal transmission in a RoF system based on the distribution of the radio signal at a lower IF, the so called ‘‘IF over fiber’’. IF signal transport schemes offer the advantage that the readily available mature microwave hardware can be utilized at the BS, IF radio signal transport allows transmission over low cost multimode fiber (MMF) and several commercial RoF products are based on the distribution of radio signals over MMF since many buildings have legacy optical fiber infrastructure networks based on multimode fibers.

2.3 Benefits of RoF Technology

Some of the advantages and benefits of the RoF technology compared with electronic signal distribution are given below.

2.3.1 Large Bandwidth

Optical fibers offer huge bandwidth. There are three transmission windows, which offer low attenuation, the first window 850 nm, the second window 1310 nm, and the third window 1550 nm wavelengths. For a single SMF optical fiber, the combined bandwidth of the three windows is in the excess of 50 THz [15]. However, today’s state-of-the-art commercial systems utilize only a fraction of this capacity (1.6 THz). But developments to exploit more optical capacity per single fiber are still continuing.

The main driving factors towards unlocking more and more bandwidth out of the optical fiber include the availability of low dispersion (or dispersion shifted) fiber, the erbium doped fiber amplifier (EDFA) for the 1550 nm window, and the use of advanced multiplex techniques namely optical time division multiplexing (OTDM) in combination with dense wavelength division multiplex (DWDM) techniques.

The huge bandwidth offered by optical fibers has other benefits apart from the high capacity for transmitting microwave signals. The high optical bandwidth enables high speed signal processing that may be more difficult or impossible to do in electronic systems. That means, some of the demanding microwave functions such as filtering, mixing, and up- and down-conversion, can be implemented in the optical domain [16]. Furthermore, processing in the optical domain makes it possible to use cheaper low bandwidth optical components such as laser diodes and modulators, and still be able to handle high bandwidth signals [17].

The utilization of the huge bandwidth offered by optical fibers is severely hampered by the limitation in bandwidth of electronic systems, which are the primary sources and receivers of transmission data. This problem is referred to as the “electronic bottleneck”. The solution around the electronic bottleneck lies in effective multiplexing. OTDM and DWDM techniques mentioned above are used in digital optical systems.

In analogue optical systems including RoF technology, SCM is used to increase optical fiber bandwidth utilization. In SCM, several microwave subcarriers, which are modulated with digital or analogue data, are combined and used to modulate the optical signal, which is then carried on a single fiber [18, 19]. This makes RoF systems cost-effective.

2.3.2 Low Attenuation Loss

It is problematic and costly either in free space or through transmission lines for electrical distribution of high frequency microwave signals. In free space, losses due to absorption and reflection increase with frequency [20]. In transmission lines, impedance rises with frequency as well, leading to very high losses [21]. Therefore, distributing high frequency radio signals electrically over long distances requires expensive regenerating equipment.

For mm-waves (30 to 300 gigahertz), their distribution via the use of transmission lines is not possible even for short distances. The alternative solution to this problem is to distribute baseband signals or signals at low IF from the switching center (headend) to the BS. The baseband or IF signals are up-converted to the required microwave or mm-wave frequency at each base station, amplified and then radiated. However, since optical fiber offers very low loss, RoF technology can be used to achieve both low-loss distribution of mm-waves, and simplification of radio access unit (RAU) at the same time.

Single mode fibers (SMFs) made from glass (silica) has attenuation losses below 0.2 dB/km and 0.5 dB/km in the 1550 nm and the 1300 nm windows, respectively. Polymer optical fibers (POFs), a more recent kind of optical fiber exhibits higher attenuation ranging from 10 – 40 dB/km in the 500 – 1300 nm regions [22, 23]. These losses are much lower than those encountered in, say coaxial cable, whose losses are higher by three orders of magnitude at higher frequencies. For instance, the attenuation of a ½ inch coaxial cable is >500 dB/km for frequencies above 5 GHz [24]. Therefore, by transmitting microwaves in the optical form, transmission distances are increased several folds and the required transmission powers reduced greatly.

2.3.3 Easy Installation and Maintenance

A complex and expensive equipment is kept at the headend in RoF systems, because of that making the RAUs simpler. For example, most RoF techniques eliminate the need for a LO and related equipment at the RAU. In such cases a photodetector, an RF amplifier, and an antenna make up the RAU. Modulation and switching equipment is kept in the headend and is shared by several RAUs. This arrangement leads to smaller and lighter RAUs, effectively reducing system installation and maintenance costs.

Easy installation and low maintenance costs of RAUs are very important requirements for mm-wave systems, because of the large numbers of the required RAUs. In applications where RAUs are not easily accessible, the reduction in maintenance requirements leads to major operational cost savings [25]. Smaller RAUs also lead to reduced environmental impact.

2.3.4 Immunity to Radio Frequency Interference

Immunity to electromagnetic interference (EMI) is considered as a very attractive property of optical fiber communications, especially for microwave transmission. This is so because signals are transmitted in the form of light through the fiber. Because of this immunity, fiber cables are preferred even for short connections at mm-waves.

Related to EMI immunity is the immunity to eavesdropping, which is an important characteristic of optical fiber communications, as it provides privacy and security.

2.3.5 Reduced Power Consumption

Reduced power consumption is considered as a consequence of having simple RAUs with reduced equipment. Most of the complex equipment is kept at the centralized headend. In some applications, the RAUs are operated in passive mode. For example, some 5GHz Fiber-Radio systems employing pico-cells can have the RAUs operate in passive mode. Reduced power consumption at the RAU is significant considering that RAUs are sometimes placed in remote locations not fed by the power grid [25].

2.3.6 Operation Flexibility

RoF offers system operational flexibility. Depending on the microwave generation technique, the RoF distribution system can be made signal-format transparent. For instance the intensity modulation and direct detection (IM-DD) technique can be made to operate as a linear system and therefore as a transparent system. This can be achieved by using low dispersion fiber (SMF) in combination with pre-modulated RF subcarriers (SCM). In that case, the same RoF network can be used to distribute multi-operator and multi-service traffic, and resulting in huge economic savings [26].

The principle of optical frequency multiplication (OFM) can also be used to achieve multi-service operation in combination with either WDM or SCM, because it is tolerant to chromatic dispersion.

2.3.7 Dynamic Resource Allocation

It is possible to allocate capacity dynamically because the switching, modulation, and other RF functions are performed at a centralized headend. For instance in a RoF distribution system for GSM traffic, more capacity can be allocated to an area during peak times and then re-allocated to other areas when off peak (e.g. to populated residential areas in the evenings). This can be achieved by allocating optical wavelengths through WDM as need arises [27].

Allocating capacity dynamically as need for it arises obviates the requirement for allocating permanent capacity, which would be a waste of resources in cases where traffic loads vary frequently and by large margins [26]. Furthermore, having the centralized headend facilitates the consolidation of other signal processing functions such as mobility functions, and macro diversity transmission [27].

2.3.8 Radio System Functionalities

RoF technology is not only used for distributing RF signals but for radio system functionalities as well. However, application of RoF technology for radio system functionalities goes beyond modulation and frequency conversion to encompass signal processing at very high frequencies. These functions include filtering, attenuation control and signal processing in high frequency phased array antenna systems, just to name but a few. These functions are also referred to as microwave functions.

Many of these functions are difficult to achieve in the electrical domain due to limited bandwidth and other electromagnetic wave propagation limitations. However, if the processing is done in the optical domain, unlimited signal processing bandwidth becomes available.

Many microwave functions can be performed by optical components without needing electrical to optical conversion for processing by microwave components and vice versa [28].

2.3.9 Millimeter Waves

Although millimeter waves offer several benefits, it cannot be distributed electrically due to high RF propagation losses.

In addition, generating mm-wave frequencies using electrical devices is challenging. These issues describe the electronic bottleneck already discussed above.

The solution to the problem is to use optical means. Low attenuation loss and large bandwidth make the distribution of mm-waves cost effective. Furthermore, some optical based techniques have the ability to generate unlimited frequencies. For instance, microwave frequencies that can be generated by remote heterodyning and detection (RHD) methods are limited only by the bandwidth of photodetectors.

2.4 Applications of RoF Technology

Some of the applications of RoF technology include satellite communications, mobile radio communications, broadband access radio, Multipoint Video Distribution Services (MVDS), Mobile Broadband System (MBS), vehicle communications and control, and wireless LANs over optical networks. The main application areas are briefly discussed below.

2.4.1 Cellular Networks

The field of mobile networks is an important application area of RoF technology. The ever-rising number of mobile subscribers coupled with the increasing demand for broadband services have kept sustained pressure on mobile networks to offer increased capacity.

Therefore, mobile traffic (GSM or UMTS) can be relayed cost effectively between the SCs and the BSs by exploiting the benefits of SMF technology.

Other RoF functionalities such as dynamic capacity allocation offer significant operational benefits to cellular networks.

2.4.2 Satellite Communications

Satellite communications was one of the first practical uses of RoF technology. One of the applications involves the remoting of antennas to suitable locations at satellite earth stations. In this case, small optical fiber links of less than 1km and operating at frequencies between 1GHz and 15GHz are used. The second application involves the remoting of earth stations themselves.

With the use of RoF technology the antennae need not be within the control area (e.g. Switching Center). They can be sited many kilometres away for the purpose of, for instance improved satellite visibility or reduction in interference from other terrestrial systems. Switching equipment may also be appropriately sited, for say environmental or accessibility reasons or reasons.

2.4.3 Video Distribution Systems

The video distribution is one of the major promising application areas of RoF systems. A case in point is the multipoint video distribution services (MVDS). MVDS is a cellular terrestrial transmission system for video (TV) broadcast. It was originally meant to be a transmit-only service but recently, a small return channel has been incorporated in order to make the service interactive. MVDS can be used to serve areas the size of a small town. Allocated frequencies for this service are in the 40 GHz band. At these frequencies, the maximum cell size is about 5km. To extend coverage, relay stations are required.

In MVDS the coverage area is served by a transmitter, which is located either on a mast or a tall building. The rooftop equipment can be simplified by employing RoF techniques. In addition, a single optical fiber could feed the transmitter unit from a distance of several hundred meters.

2.4.4 Mobile Broadband Services

The mobile broadband system or service (MBS) concept is intended to extend the services available in fixed broadband integrated services digital network (B-ISDN) to mobile users of all kinds. Future services that might evolve on the BISDN networks must also be supported on the MBS system. Since very high bit rates of about 155 Mbps per user must be supported, carrier frequencies are pushed into mm-waves. Therefore, frequency bands in the 60 GHz band have been allocated.

The 62-63 GHz band is allocated for the downlink while 65-66 GHz is allocated for the uplink transmission. The size of cells is in diameters of hundreds of meters (micro-cells). Therefore, a high density of radio cells is required in order to achieve the desired coverage. The micro-cells could be connected to the fixed B-ISDN networks by optical fiber links. If RoF technology is used to generate the mm-waves, the base stations would be made simpler and therefore of low cost, thereby making full scale deployment of MBS networks economically feasible [7].

2.4.5 Wireless LANs

The demand for mobile broadband access to LANs will be on the increase because of the portable devices and computers become more and more powerful as well as widespread. This will lead, to higher carrier frequencies in the bid to meet the demand for capacity. For instance current wireless LANs operate at the 2.4 GHz ISM bands and offer the maximum capacity of 11 Mbps per carrier (IEEE 802.11b). The broadband wireless LANs are offered up to 54 Mbps per carrier, and will require higher carrier frequencies in the 5 GHz band (IEEE802.11a/D7.0) [29].

Higher carrier frequencies in turn lead to micro- and Pico-cells, and all the difficulties associated with coverage discussed above arise. A cost effective way around this problem is to deploy RoF technology.

A wireless LAN at 60 GHz has been realized by first transmitting from the BS, a stable oscillator frequency at an IF together with the data over the fiber [8]. The oscillator frequency is then used to up-convert the data to mm-waves at the transponders (Remote Stations). This greatly simplifies the remote transponders and also leads to efficient base station design.

2.4.6 Vehicle Communication and Control

The vehicle control is considered as potential application area of RoF technology. Frequencies between 63-64 GHz and 76-77 GHz have already been allocated for this service within Europe. The objective is to provide continuous mobile communication coverage on major roads for the purpose of intelligent transport systems (ITS) such as road-to-vehicle communication (RVC) and inter-vehicle communication (IVC).

ITS systems aim to provide traffic information, improve transportation efficiency, reduce burden on drivers, and contribute to the improvement of the environment [9]. In order to achieve the required (extended) coverage of the road network, numerous base stations are required. These can be made simple and of low cost by feeding them through RoF systems, thereby making the complete system cost effective and manageable.

2.5 Limitations of RoF Technology

Since RoF involves analogue modulation, and detection of light, it is fundamentally an analogue transmission system. Therefore, signal impairments such as noise and distortion, which are important in analogue communication systems, are important in RoF systems as well. These impairments tend to limit the Noise Figure (NF) and Dynamic Range (DR) of the RoF links [30]. DR is a very important parameter for mobile communication systems such as GSM because the power received at the BS from the MUs varies widely. That is, the RF power received from a mobile unit (MU) which is close to the BS can be much higher than the RF power received from a MU which is several kilometres away, but within the same cell.

The noise sources in analogue optical fiber links include the laser's relative intensity noise (RIN), the laser's phase noise, the photodiode's shot noise, the amplifier's thermal noise, and the fiber's dispersion.

In SMF based RoF systems, chromatic dispersion may limit the fiber link lengths and may also cause phase de-correlation leading to increased RF carrier phase noise [20]. In MMF based RoF systems, modal dispersion severely limits the available link bandwidth and distance. It must be stated that although the RoF transmission system itself is analogue, the radio system being distributed need not be analogue as well, but it may be digital (e.g. WLAN, UMTS), using comprehensive multi-level signal modulation formats such as QAM, or OFDM.

2.6 OFDM Technique in RoF System

The basic building blocks for an OFDM transceiver system for RoF are shown in Figure 2.4 [32, 33].

Firstly, the user data is converted into symbols by m-ary signaling. These symbols are the converted into frames of N parallel rows. Also pilot symbol is added at the starting of each frame, which is used at the receiver for synchronization and also for channel equalization. The N sub symbols are then sent to an inverse fast Fourier transform (IFFT) block that performs an N-point inverse fast Fourier transform. Hence, the original input data is treated by OFDM as though it is in the frequency-domain. The output of the inverse fast Fourier transform block is N time-domain samples. This complex signal is transmitted on orthogonal carriers at RF frequency. The RF signal then carried by optical modulation in RoF transmitter to be sent over single mode fiber.

At the RoF receiver the optical signal received would convert back onto electrical domain signal by photodetector. In the receiver the pilot symbol is used for synchronization at the starting stage and the same symbol is used for equalization at the later stage. All the other processes at the receiver are the reverse process of the transmitter.

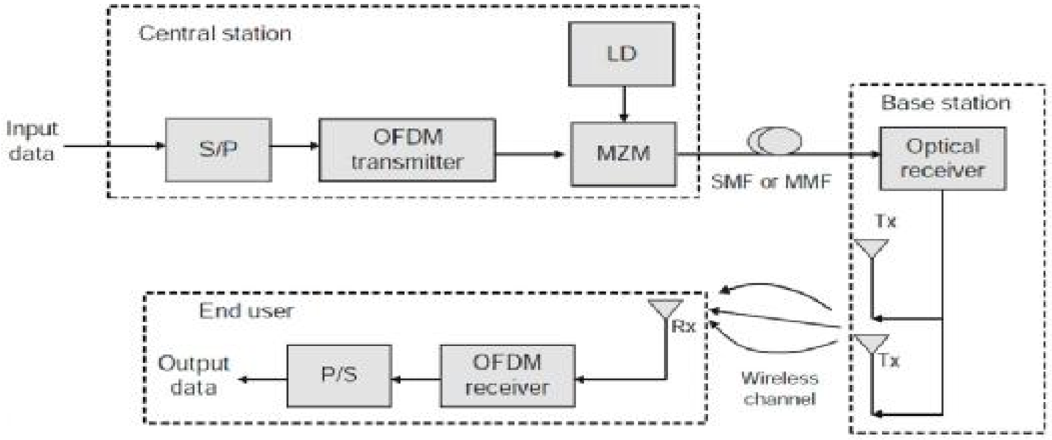

Figure 2.4: OFDM model for RoF Network BS, base station; LD, laser diode; MZM, Mach–Zehnder modulator; Rx, wireless receiver; Tx, wireless transmitter.

2.7 Summary

In this chapter a brief description and explanation of the basic theory about Radio over Fiber technology are presented and discussed. The basic theories are about the overview of RoF technologies nowadays, link configuration and the benefits of RoF. The applications of RoF in nowadays communication technologies also have been described, but only tell some of them. The limitations of RoF were described. Also a brief description of the OFDM technique is discussed.

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3

Orthogonal Frequency Division Multiplexing Techniques

3.1 Introduction

Orthogonal frequency division multiplexing (OFDM) is a modulation technique which belongs to a broader class of multicarrier modulation (MCM) in which the data information is carried over many lower rate subcarriers. Two of the fundamental advantages of OFDM are its robustness against channel dispersion and its ease of phase and channel estimation in a time-varying environment. With the advancement of powerful silicon DSP technology.

OFDM is now used in most new and emerging broadband wired and wireless communication systems because it is an effective solution to intersymbol interference caused by a dispersive channel. Very recently a number of researchers have shown that OFDM is also a promising technology for optical communications.

In this chapter, a historical perspective of OFDM will be presented and then discussed the definitions of orthogonality and OFDM signal, and then provided a description for OFDM system, including its basic unit description such as series to parallel, modulation techniques, and discrete Fourier transform implementation, guard internal and digital to analog converter. The advantages and disadvantages of OFDM will be discussed, after that discussed coded OFDM and finally comparison between wireless OFDM and optical OFDM will be shown.

3.2 OFDM History

The concept of OFDM was first introduced by Chang in a seminal paper in 1966[1]. The scheme was soon analyzed by Saltzberg in 1967 [2]. The term "OFDM" in fact is first appeared in a separate patent of his in 1970 [3]. The proposal to generate the orthogonal signals using an FFT came in 1969 [4]. The cyclic prefix (CP), which is an important aspect of almost all practical OFDM systems, was proposed in 1980 [5].

OFDM began to be considered for practical wireless applications in the mid–1980s. Cimini of Bell Labs published a paper on OFDM for mobile communications in 1985 [6]. In 1987, Lassalle and Alard based in France considered the use of OFDM for radio broadcasting and noted the importance of combining forward error correction (FEC) with OFDM [7]. Because of this interrelationship, OFDM is often called Coded OFDM (C-OFDM) by broadcast engineers.

The field of OFDM had long been developed as a peripheral interest in military applications because there was a lack of broadband applications for OFDM and powerful integrated electronic circuits to support the complex computation required by OFDM.

OFDM is now the basis of many practical telecommunications standards including WLAN, fixed wireless [8] and television and radio broadcasting in much of the world [9]. OFDM is also the basis of most DSL standards, though in DSL applications the baseband signal is not modulated onto a carrier frequency and in this context OFDM is usually called discrete multitone (DMT).

The application of OFDM to optical communications has only occurred very recently, but there are an increasing number of papers on the theoretical and practical performance of OFDM in many optical systems including optical wireless [10, 11].

Figure 3.1 below shows the summary of the historical development of both the theoretical basis of OFDM and its practical application across a range of communication systems [12].

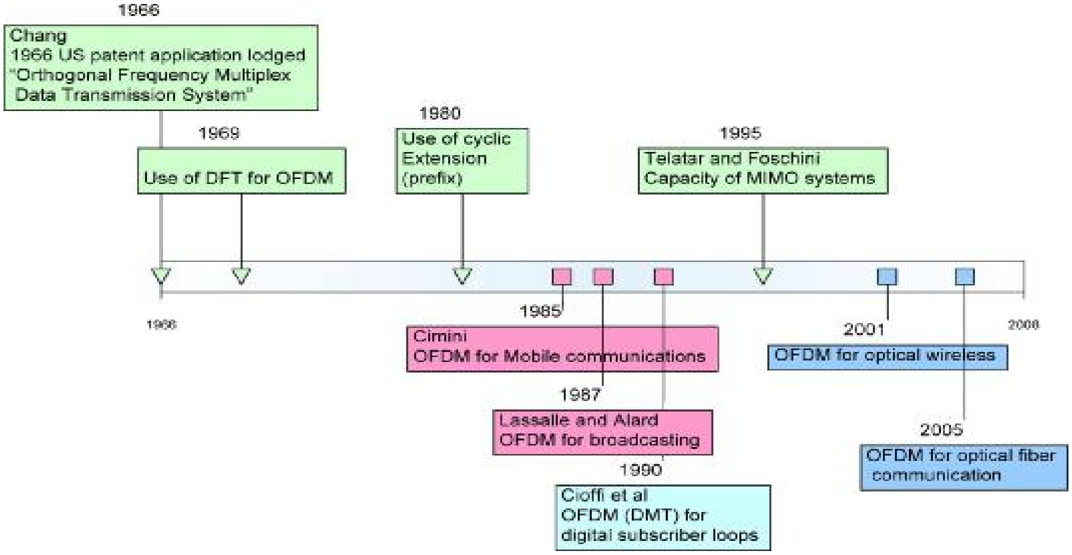

Figure 3.1: Historical development of the underlying theory of OFDM and its practical implementation [12].

3.3 Orthogonality

Orthogonality is considered as a property that allows multiple information signals to be transmitted perfectly over a common channel and detected without interference. OFDM achieves Orthogonality in the frequency domain by allocating each of the separate information symbols onto different orthogonal subcarriers.

OFDM signals are generated from a sum of sinusoids, with each corresponding to a subcarrier. Subcarriers can be mathematically represented as [13]:

$$s_K(t) = \begin{cases} \sin(2p\,k\,\Delta f t), & 0 < t < T,\ k = 1, 2, \ldots, N \\ 0, & otherwise \end{cases} \tag{3.1}$$

where Δf is the subcarrier spacing, N is the number of subcarriers, and T is the data symbol period. Since the highest frequency component is $N\Delta f$, the transmission bandwidth is approximately $N\Delta f$. Signals are orthogonal if they are mutually independent of each other.

These subcarriers are orthogonal to each other because they satisfy the following condition:

$$\int_0^T S_i(t) S_j(t) dt = \begin{cases} C, i = j \\ 0, i \neq j \end{cases} \tag{3.2}$$

The orthogonality property of OFDM signals is to look at its spectrum. In the frequency domain each OFDM subcarrier has a sinc, (*sin(x)/x*), spectrum, as shown in Figure 3.2. Rectangular windowing of transmitted pulses in the time domain results in a *sinc* shape frequency response for each channel. The sinc shape has a narrow main lobe, with many side-lobes that decay slowly with the magnitude of the frequency difference away from the center. Each carrier has a peak at the centre frequency and nulls evenly spaced with a frequency gap equal to the carrier spacing. The orthogonal nature of the transmission is a result of the peak of each subcarrier corresponding to the nulls of all other subcarriers.

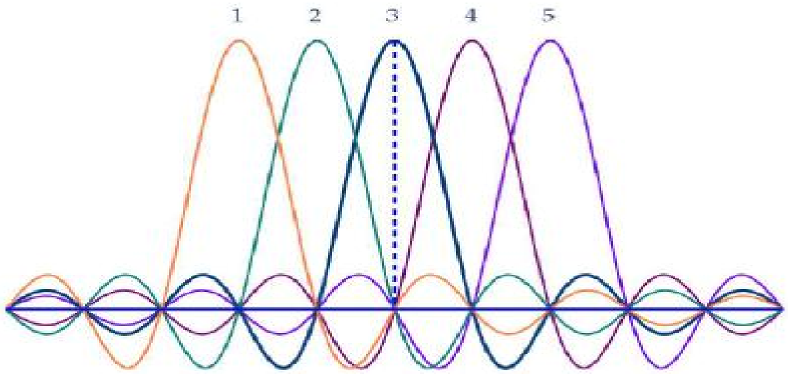

Figure 3.2: Spectrum of orthogonal OFDM.

3.4 OFDM Signal

A generic implementation of OFDM signal is depicted in Figure 3.3. The structure of a complex multiplier (IQ modulator/demodulator), which is commonly used in MCM systems.

The MCM transmitted signal *s(t)* is represented as [14]:

$$s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{N_{sc}} C_{ki} S_k (t - Ts) \tag{3.3}$$

$$S_k(t) = \prod(t) e^{j2pf_k t} \tag{3.4}$$

$$\prod(t) = \begin{cases} 1, & 0 < t < T_s \\ 0, & t \leq 0, t > T_s \end{cases} \tag{3.5}$$

where C_{ki} is the ith information symbol at the k^{th} subcarrier, S_k is the waveform for the k^{th} subcarrier, N_{sc} is the number of subcarriers, f_k is the frequency of the subcarrier, T_s is the symbol period, and *Π(t)* is the pulse shaping function. The optimum detector for each subcarrier could use a filter that matches the subcarrier waveform or a correlator matched to the subcarrier as shown in Figure 3.3.

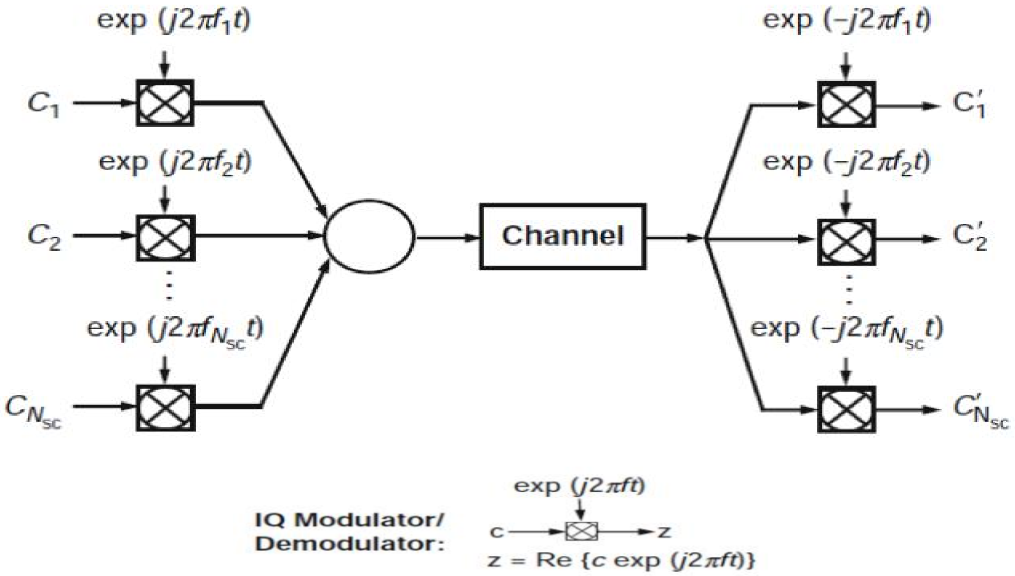

Figure 3.3: Conceptual diagram for a generic multicarrier modulation system [14].

Therefore, the detected information symbol C'ik at the output of the correlator is given by

$$C'_{ki} = \frac{1}{T_s} \int_0^{T_s} r(t - iT_s) S^*_k dt = \frac{1}{T_s} \int_0^{T_s} r(t - iT_s) e^{-j2pf_k t} dt \tag{3.6}$$

where *r(t)* is the received time domain signal.

The major disadvantage of MCM is that it requires excessive bandwidth. This is because to design the filters and oscillators cost-effectively, the channel spacing has to be a multiple of the symbol rate, greatly reducing the spectral efficiency.

A novel approach, OFDM, was investigated by employing overlapped yet orthogonal signal sets. [15] This orthogonality originates from a straightforward correlation between any two subcarriers, given by [14]

$$d_{kl} = \frac{1}{T_s}\int_0^{T_s} S_k S^*_l dt = \frac{1}{T_s}\int_0^{T_s} \exp(j\,2p\,(f_k - f_l)t)dt = \exp(j\,p\,(f_k - f_l)T_s)\frac{\sin(p\,(f_k - f_l)T_s)}{p\,(f_k - f_l)T_s} \quad (3.7)$$

It can be seen that if the condition

$$f_k - f_l = m\frac{1}{T_s} \quad (3.8)$$

is satisfied, then the two subcarriers are orthogonal to each other. This signifies that these orthogonal subcarrier sets, with their frequencies spaced at multiples of inverse of the symbol periods, can be recovered with the matched filters in Eq. (3.6) without intercarrier interference (ICI), despite strong signal spectral overlapping.

3.5 OFDM System Description

Figure 3.4 shows the block diagram of transmission system using OFDM. At the transmitter as shown in Figure 3.4, the high rate digital data stream is split into N parallel streams. Each stream is mapped to a symbol stream using some modulation scheme (QAM, PSK, etc). The symbols are modulated onto the subcarriers using the inverse discrete Fourier transform (IDFT). IDFT operation is a transformation of the OFDM symbol from the frequency domain to time domain. The inverse fast Fourier transform (IFFT) performs the same operation as an IDFT, except that it is much more computationally efficiency. After the IDFT operation, a cyclic prefix is added to the OFDM symbol prior to digital- to-analogue converter (DAC). The DAC output is a baseband analog signal which is then up-converted in frequency and transmitted.

At the receiver as shown in Figure 3.4, the received signal is down-converted to baseband. Then the signal is converted from analog to digital using an analogue-to-digital converter (ADC). After removing guard interval, the samples are fed into the discrete Fourier transform (DFT) to be converted to frequency domain. Finally, data is detected.

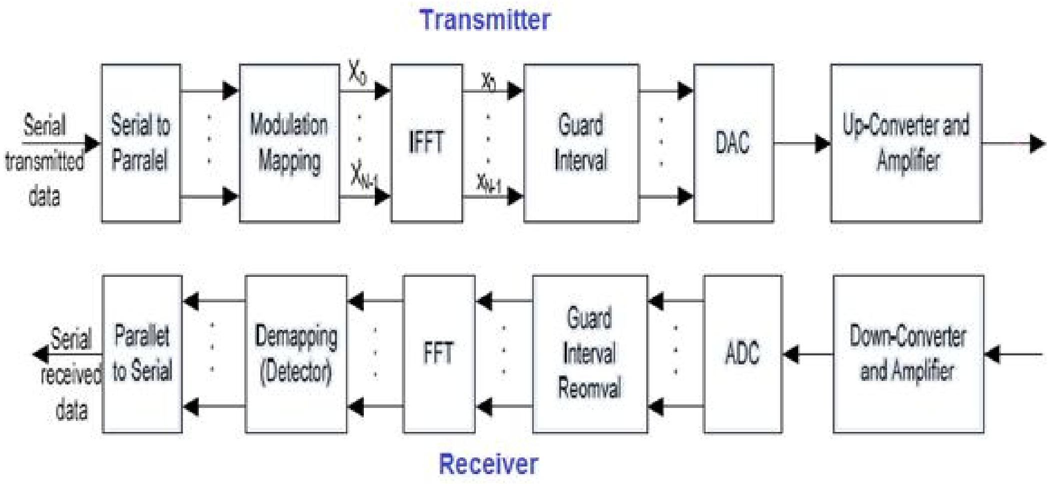

Figure 3.4: Block diagram showing a basic OFDM system.

3.5.1 Serial to Parallel Conversion

The input data stream is formatted into the word size required for transmission in each OFDM symbol. For example, for a subcarrier modulation of 4-QAM, each subcarrier carries 2 bits of data, 16-QAM has 4 bits and 64-QAM has 6 bits of data. So for a transmission using 100 subcarriers using 16-QAM, the number of bits per OFDM symbol would be 400, while the number of parallel symbols entering the IFFT block is 100.

3.5.2 Modulation Techniques

The modulation scheme is a mapping of data words to a real (In phase) and imaginary (Quadrature) constellation, also known as an IQ constellation. For example, 64-QAM involves 6 bits in each symbol (data word). Each data word is mapped to one unique IQ location in the constellation. A large number of modulation schemes are available allowing the number of bits transmitted per subcarrier per symbol to be varied. In the receiver, the received IQ symbol demapped back to data words. This is called demodulation [16].

3.5.3 Discrete Fourier Transform Implementation

At the transmitter of an OFDM system, data are apportioned in the frequency domain and an IFFT is used to modulate the data into the time domain. The FFT output data are guaranteed to be real-valued if conjugate symmetry is imposed on the input data.

In the receiver, an FFT is used to recover the original data. The FFT allows an efficient implementation of modulation of data onto multiple carriers [11]. Due to the similarity between the forward and inverse transform, the same circuitry, with trivial modifications, can be used for both modulation and demodulation in a transceiver.

A fundamental challenge with OFDM is that a large number of subcarriers are needed so that the transmission channel affects each subcarrier as a flat channel. This leads to an extremely complex architecture involving many oscillators and filters at both transmit and receive ends. Weinsten and Ebert first revealed that OFDM modulation/demodulation can be implemented by using inverse discrete Fourier transform (IDFT)/discrete Fourier transform (DFT) [17].

Let $\{X_n\}_{n=0}^{N-1}$ be the complex symbols to be transmitted using OFDM. The modulated OFDM signal can be expressed in the time domain as [18-20]

$$x(t) = \sum_{n=0}^{N-1} X_n e^{j2pf_n t} \tag{3.9}$$

where $f_n = f_o + n\Delta f$, $n = 0,1,.....,N-1$, T_s and Δf are called the symbol duration and the subchannel spacing, respectively, and N is the number of subcarriers. Δf is usually chosen to make the subcarriers orthogonal.

If $x(t)$ is sampled at an interval of $T_{sa}=T_s/N$ then:

$$x_k = x(kT_{sa}) = \sum_{n=0}^{N-1} X_n e^{j2pf_n\frac{kT_s}{N}} \tag{3.10}$$

Without loss of generality, setting $f_o=0$, then $T_s.f_n=n$, then Eq.(3.10) becomes:

$$x_k = \sum_{n=0}^{N-1} X_n e^{j2p\frac{kn}{N}} = IDFT\left\{X_n\right\} \tag{3.11}$$

where, IDFT denotes the inverse Discrete Fourier Transform. Therefore, the OFDM transmitter can be implemented using the IDFT. For the same reason, the receiver can be also implemented using DFT.

There are two fundamental advantages of DFT/IDFT implementation of OFDM. First, because of the existence of an efficient IFFT/FFT algorithm, the number of complex multiplications for IFFT and FFT is reduced from N^2 to $N/2log2N$ [19] almost linearly with the number of subcarriers, N. Second, a large number of orthogonal subcarriers can be generated and demodulated without resorting to much more complex RF oscillators and filters. This leads to a relatively simple architecture for OFDM implementation when large numbers of subcarriers are required.

3.5.4 Guard Interval for OFDM

The system bandwidth in OFDM systems is broken up into N bands, for the purpose of eliminating ISI completely; a guard interval can be added to the start of each OFDM symbol. This guard interval is longer than the maximum delay spread of the channel. The guard interval preserves orthogonality between the subcarriers by keeping the OFDM symbol periodic over the extended symbol duration, therefore avoiding inter-carrier interference (ICI).

Cyclic prefix is added as a guard interval. The cyclic prefix is copying the last part of the OFDM symbol and prefixing it as a guard interval at the beginning of the

OFDM symbol. If the OFDM symbol consists of N symbols with observation period (the output of the IFFT), the cyclic prefix is made up of the last few, say N_g, symbols of the original OFDM symbol as shown in Figure 3.5 and Figure 3.6 [21].

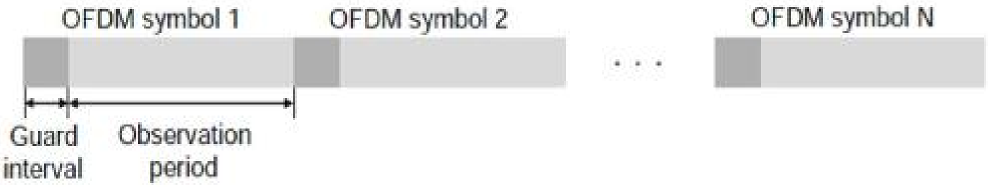

Figure 3.5: *N* OFDM symbols with guard interval.

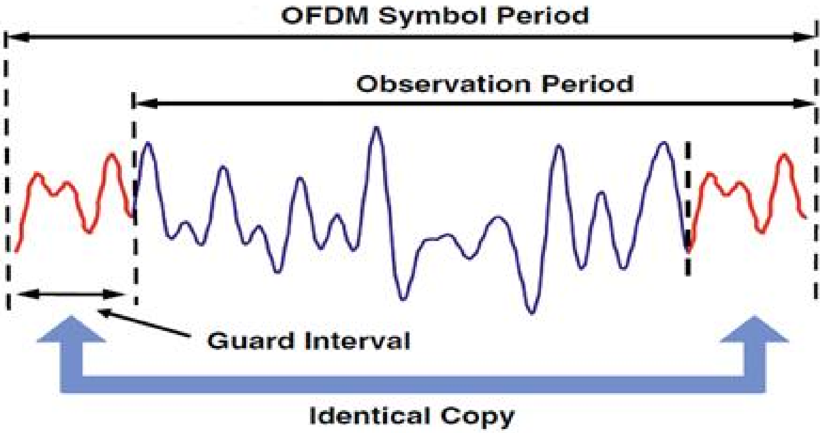

Figure 3.6: Cyclic prefix in an OFDM symbol (time domain sequence).

Since the cyclic prefix is an extension of the OFDM symbol, it does not carry any new information. This reduces the efficiency of the system by a factor of $N_g/(N + N_g)$ [22]. For an OFDM system employing a large number of subcarriers, this loss will not be significant.

It can be seen that to recover the OFDM information symbol properly, there are two critical procedures that need to be carried out: (1) selection of an appropriate DFT window, called DFT window synchronization, and (2) estimation of the phase shift for each subcarrier, called channel estimation or subcarrier recovery.

3.5.5 D/A and A/D conversion

As it can be seen from Figure 3.4, a digital-to-analogue converter (DAC) is needed to convert the discrete value of (sample) to the continuous analogue value, and an analogue-to-digital converter (ADC) is needed to convert the continuous received signal to discrete sample.

In order to build a real system, the fact of being able to use commercial off-the-shelf converters at both ends of the transmission scheme becomes one of the main issues. This is why many techniques are available to take advantage from the digital signal processing stages and simplify the analogue processing, lowering the requirements for both the DAC and the ADC.

3.6 Advantages of OFDM

OFDM has several advantages such as high data rate in mobile wireless channel and it is conveniently implemented using IFFT and FFT operations. OFDM also has good tolerance to inter symbol interference (ISI). The advantages of OFDM are shown below:

- Can easily adapt to severe channel conditions without complex equalization.
- Robust against narrow-band co-channel interference.
- Robust against intersymbol interference (ISI) and fading caused by multipath propagation.
- High spectral efficiency.
- Efficient implementation using FFT.
- Low sensitivity to time synchronization errors.
- Tuned sub-channel receiver filters are not required (unlike conventional FDM).
- Facilitates Single Frequency Networks, i.e. transmitter macro diversity.

3.7 Disadvantages of OFDM

In the other hand, OFDM has some disadvantages. The most effective disadvantage of OFDM is the complexity, where OFDM is a multicarrier modulation which is more complex than single-carrier modulation as well as OFDM requires a more linear power amplifier. The disadvantages of OFDM are shown below and the explanation of some of these disadvantages in next sections below:

- Sensitive to Doppler shift.
- Sensitive to frequency synchronization problems.
- High peak-to-average-power ratio (PAPR).

3.7.1 Peak-to-Average Power Ratio

High peak to average power ratio (PAPR) has been recognized as one of the drawbacks of the OFDM modulation. An OFDM signal is formed by adding a number of data modulated independent subcarriers. This can produce a large PAPR when all subcarriers added up coherently as shown in Figure 3.7 at time (t=0.23). When *N* signals are added with the same phase, they produce a peak power that is N times the average power.

To avoid the relatively “peaky” OFDM signal is to operate the power amplifier at where the signal power is much lower than the amplifier saturation power. Unfortunately, this requires an excess large saturation power for the power amplifier, which inevitably leads to low power efficiency.

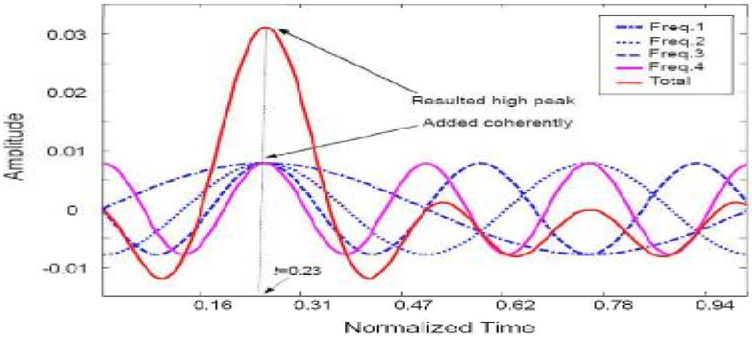

Figure 3.7: High Peak on OFDM System [14].

In the following, consider the transmitted time domain waveform for one OFDM symbol can be written as [14]

$$s(t) = \sum_{k=1}^{Nsc} C_k e^{j2pf_kt}, \qquad f_k = \frac{k-1}{T_s} \tag{3.12}$$

The PAPR of the OFDM signal is defined as

$$PAPR = \frac{\max\left\{|s(t)|^2\right\}}{E\left\{|s(t)|^2\right\}}, \qquad t \in [0, T_s] \tag{3.13}$$

For simplicity, assume that an M-PSK encoding is used, where $|C_k|=1$. The theoretical maximum of PAPR is $10log_{10}(N_{sc})$ in dB, by setting $C_k=1$ and $t=0$ in Eq. (3.12). For OFDM systems with 256 subcarriers, the theoretical maximum PAPR is 24 dB, which obviously is excessively high.

A better way to characterize the PAPR is to use the complementary cumulative distribution function (CCDF) of PAPR, P_c, which is expressed as

$$P_c = \mathrm{P_r}\left\{PAPR > z_p\right\} \tag{3.14}$$

where, P_c is the probability that PAPR exceeds a particular value of ζ_P.

CCDF with varying numbers of subcarriers shows in Figure 3.8. We have assumed QPSK encoding for each subcarrier. It can be seen that despite the theoretical maximum PAPR of 24 dB for the 256-subcarrier OFDM systems, for more likely probability regimes, such as a CCDF of 10^{-3}, PAPR is approximately 11.3 dB, which is much less than the maximum value of 24 dB. A PAPR of 11.3 dB is still very high because it implies that the peak value is approximately one order of magnitude stronger than the average, and some form of PAPR reduction should be used. It is also interesting to note that the PAPR of an OFDM signal increases slightly as the number of subcarriers increases. For instance, PAPR increases by approximately 1.6 dB when the subcarrier number increases from 32 to 256.

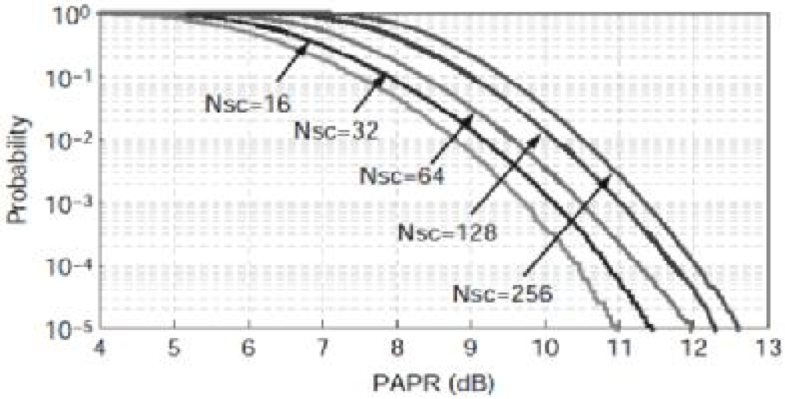

Figure 3.8: CCDF for the PAPR of OFDM signal with varying numbers of subcarriers [14].

There are different solutions to the PAPR problem. The PAPR reduction algorithms proposed so far allow for trade-offs among three figures of merits of the OFDM signal: PAPR, bandwidth efficiency, and computational complexity. These solutions can be broadly classified into techniques involving coding, techniques involving multiple signal representation (MSR), and techniques involving non linear distortion, such as clipping.

The most two popular PAPR reduction approaches are firstly, *PAPR reduction with signal distortion* in this approach hard clipping the OFDM signal. The consequence of clipping is increased BER and out-of band distortion. The out-of-band distortion can be mitigated through repeated filtering. The second, *PAPR reduction without signal distortion* in this approach map the original waveform to a new set of waveforms that have a PAPR lower than the desirable value, most often with some bandwidth reduction. This algorithm include selection mapping, optimization approaches.

3.7.2 Frequency Offset and Phase Noise Sensitivity

Frequency offset and phase noise sensitivity has been recognized as two major disadvantages of OFDM. Both frequency offset and phase noise lead to ICI. Because of its relatively long symbol length compared to that of the single carrier. Frequency offset sensitivity can be mitigated through frequency estimation and compensation [14].

This offset is usually compensated by using adaptive frequency correction (AFC) [19] and phase noise sensitivity is resolved primarily via careful design of RF local oscillators that satisfy the required phase noise specification [14].

3.7.3 Time Offset error

The time offset error is caused by the incorrect identification of the OFDM symbol boundary at the receiver introducing ISI and ICI. The inclusion of the cyclic prefix makes OFDM relatively more robust to time offset errors. The time offset may vary over an interval equal to the length of the CP without causing ICI or ISI. On the other hand, OFDM is relatively more sensitive to frequency offset errors [19].

The objective of time synchronization is to estimate where the symbol boundary lines, so that an uncorrupted portion of the received OFDM symbol can be sampled for FFT.

3.8 Coded OFDM

Coded OFDM (COFDM) is one of the widely used transmission techniques for overcoming the frequency selectivity of the channel.

The basic idea of coded OFDM is to encode input data and interleave the coded symbols. The interleaved symbols are split into several sub channels to achieve frequency diversity. Even though the uncoded symbol error rate is high for the subcarriers with low channel gains, with the channel coding and interleaving it is possible to correct the errors in the low gain channels. With the channel coding and interleaving, coded OFDM provides a robust communication link for many wireless channel environments.

This technique is very effective for channels with narrow coherence bandwidth. However, if the coherence bandwidth is large, then the channel gains of neighboring sub channels are highly correlated and this may limit the diversity gain of coded OFDM systems [23].

An example of a coded OFDM system is the 802.11a Wireless Local Area Network (W-LAN) system in the 5GHz band [24]. The IEEE 802.11a standard uses a coded OFDM scheme which demultiplexes coded symbols into 52 separate subcarriers. Data rates of the 802.11a system are 6, 9, 12, 18, 24, 36 and 48 Mbps. Data rates below 24 Mbps are mandatory.

A pseudo-random sequence is transmitted through the pilot subcarriers to avoid spectral lines. The receiver knows the signal sent on the pilot subcarriers and uses the pilot subcarriers for channel estimation.

3.9 Optical OFDM

Despite OFDM widespread use in wireless communications, OFDM has only recently been applied to optical communications. OFDM is an attractive modulation format that recently received a lot of attention in the fiber-optic community. The main advantage of optical OFDM is that it can cope with virtually unlimited amount of ISI.

In high-speed optical transmission systems, ISI is caused for instance by chromatic dispersion and polarization mode dispersion (PMD) [12, 14, 25], which are serious issues in long-haul systems whose bit rate is higher than 40 Gbit/s, Table 3.1 show the comparison between wireless OFDM and Optical OFDM.

As discussed basics of OFDM, the division of a high bit rate data stream into several low bit rate streams, which are simultaneously modulated onto orthogonal subcarriers.

In general, the subcarriers are generated in the digital domain, therefore these systems typically consist of many subcarriers. In these systems, channel estimation is realized by periodically inserting training symbols. In fiber-optic transmission systems, the OFDM systems where the subcarriers are generated in the optical domain are also proposed.

Table 3.1: Comparison between Wireless and Optical OFDM.

	Wireless OFDM	Optical OFDM
Mathematical Model	Time domain multiple discrete Rayleigh fading	Continuous frequency domain dispersion
Nonlinearity	None	Significant
Speed	Can be fast for mobile environment	Medium
Detection	Coherent Reception	Direct Detection
Information Carried	On electrical field	On optical intensity
Local Oscillator	At receiver	At receiver
polarity	Bipolar	Unipolar

Optical OFDM solutions can be divided into two groups. The first group includes techniques for multi modes are received, for instance, optical wireless and multimode fiber systems. The second group includes techniques for single mode fiber, where only one mode of the signal is received [25].

3.10 Summary

OFDM has emerged as the leading modulation technique in the RF domain. An OFDM transmitter and receiver are described and the roles of the main signal processing blocks explained, the main advantages of OFDM such as high data rate, conveniently implemented using IFFT and FFT operations and has good tolerance to inter symbol interference (ISI), and also the main drawbacks of OFDM are its high peak to average power ratio and its sensitivity to phase noise and frequency offset. The impairments that these cause are described.

Finally, OFDM is a very promising technology for optical communications, but the very different constraints introduced open up many new interesting avenues for research.

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4

The OOFDM RoF System Model

4.1 Introduction

In this system the OFDM modulation technique is incorporated into RoF system. Because the advantages of both, while OFDM could distribute the data over a large number of carriers that are spaced apart at precise frequencies with overlapping bands and RoF is a next generation communication systems that can utilize the high capacity of optical networks along with the mobility of wireless networks.

Hence by incorporating OFDM along with RoF, the system can be used for both short distance as well as long-haul transmission at very high data rate. This improves the system flexibility and provides a very large coverage area without increasing the cost and complexity of the system very much.

This chapter highlights the literature cited on the optical transmission link with more details about optical fiber, optical transmitter, optical modulation, optical receiver and optical amplifier, and covers about the OOFDM-RoF system model.

4.2 Optical Transmission Link

A general optical transmission link, shown in Figure 4.1 below is briefly described for which assumed that a digital pulse signal is transmitted over optical fiber unless otherwise specified.

The optical link consists of an optical fiber transmitter, receiver, and amplifier each of which is dealt with in the subsequent subsections.

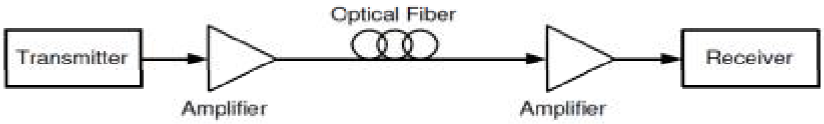

Figure 4.1: Optical transmission link.

4.2.1 Optical Fiber

Optical fiber is a dielectric medium for carrying information from one point to another in the form of light. Unlike the copper form of transmission, the optical fiber is not electrical in nature. To be more specific fiber is essentially a thin filament of glass that acts as a waveguide. A waveguide is a physical medium or path that allows the propagation of electromagnetic waves, such as light. Due to the physical phenomenon of total internal reflections, light can propagate following the length of a fiber with little loss.

Optical fiber has two low-attenuation regions [2]. Centered at approximately 1300 nm is a range of 200 nm in which attenuation is less than 0.50dB/km. The total bandwidth in this region is about 25 THz. Centered at 1550 nm is a region of similar size with attenuation as low as 0.2 dB/km. Combined, these two regions provide a theoretical upper bound of 50 THz of bandwidth. By using these large low attenuation areas for data transmission, the signal loss for a set of one or more wavelengths can be made very small, thus reducing the number of amplifiers and repeaters actually needed. In single channel long-distance experiments, optical signals have been sent over hundreds of kilometers without amplification.

Besides its enormous bandwidth and low attenuation, fiber also offers low error rates. Communication systems using an optical fiber typically operate at BER's of less than10^{-11}. The small size and thickness of fiber allows more fiber to occupy the same physical space as copper, a property that is desirable when installing local networks in buildings. Fiber is flexible, reliable in corrosive environments, and deplorable at short notice. Also, fiber transmission is immune to electromagnetic interference and does not cause interference. Basically there are two types of optical fiber, first so called as step-index fiber and second graded-index fiber.

4.2.1.1 Multimode versus Single-Mode Fiber

A mode in an optical fiber corresponds to one of the possible multiple ways in which a wave may propagate through the fiber. It can also be viewed as a standing wave in the transverse plane of the fiber. More formally, a mode corresponds to a solution of the wave equation that is derived from Maxwell's equations and subject to boundary conditions imposed by the optical fiber waveguide.

If more than one mode propagates through a fiber, then the fiber is called multimode. In general, a larger core diameter or high operating frequency allows a greater number of modes to propagate.

The advantage of multimode fiber is that, its core diameter is relatively large; as a result, injection of light into the fiber with low coupling loss can be accomplished by using inexpensive, large-area light sources, such as light-emitting diodes (LED's).

The disadvantage of multimode fiber is that it introduces the phenomenon of intermodal dispersion. In multimode fiber, each mode propagates at a different velocity due to different angles of incidence at the core-cladding boundary. This effect causes different rays of light from the same source to arrive at the other end of the fiber at different times, resulting in a pulse that is spread out in the time domain. Intermodal dispersion increases with the distance of propagation, so that it limits the bit rate of the transmitted signal and the distance that the signal can travel. Thus, in RoF networks multimode fiber is not utilized as much as possible, instead, single-mode fiber is widely used.

Single-mode fiber allows only one mode and usually has a core size of about 10μm, while multimode fiber typically has a core size of 50-100 μm. It eliminates intermodal dispersion and hence can support transmission over much longer distances. However, it introduces the problem of concentrating enough power into a very small core. LED's cannot couple enough light into a single-mode fiber to facilitate long-distance communications. Such a high concentration of light energy may be provided by a semiconductor laser, which can generate a narrow beam of light.

4.2.1.2 Attenuation in Fiber

Attenuation in an optical fiber leads to a reduction of the signal power as the signal propagates over some distance. When determining the maximum distance that a signal can propagate for a given transmitter power and receiver sensitivity, one must consider attenuation. Let *P(L)* be the power of the optical pulse at distance *L* km from the transmitter and *A* be the attenuation constant of the fiber (in dB/km).
Attenuation is characterized by

$$P(L) = 10^{-AL/10} P(0) \tag{4.1}$$

where *P(0)* is the optical power at the transmitter.

4.2.1.3 Dispersion in Fiber

Dispersion is the widening of pulse duration as it travels through a fiber. As a pulse widens, it can broaden enough to interfere with neighboring pulses (bits) on the fiber, leading to intersymbol interference.

Dispersion thus limits the bit spacing and the maximum transmission rate on a fiber-optic channel. As described earlier, one form of the dispersion is an *intermodal dispersion*. This is caused when multiple modes of the same signal propagate at different velocities along the fiber. Intermodal dispersion does not occur in a single-mode fiber.

Another form of dispersion is *material* or *chromatic dispersion*. In a dispersive medium, the index of refraction is a function of the wavelength. Thus, if the transmitted signal consists of more than one wavelength, certain wavelengths will propagate faster than other wavelengths. Since no laser can create a signal consisting of an exact single wavelength, chromatic dispersion will occur in most systems.

A third type of dispersion is *waveguide dispersion*. Waveguide dispersion is caused as the propagation of different wavelengths depends on waveguide characteristics such as the indices and shape of the fiber core and cladding.

At 1300 nm, chromatic dispersion in a conventional single-mode fiber is nearly zero. Luckily, this is also a low-attenuation window (although loss is higher than 1550 nm). Through advanced techniques such as *dispersion shifting*, fibers with zero dispersion at a wavelength between 1300-1700 nm can be manufactured.

4.2.1.4 Nonlinearities in Fiber

Nonlinear effects in fiber may potentially have a significant impact on the performance of WDM optical communications systems. Nonlinearities in fiber may lead to attenuation, distortion, and cross-channel interference. In a WDM system, these effects place constraints on the spacing between adjacent wavelength channels, limit the maximum power on any channel, and may also limit the maximum bit rate. The details of the optical nonlinearities are very complex and beyond the scope of the dissertation. It should be emphasized that they are the major limiting factors in the available number of channels in a WDM system [3].

4.2.2 Optical Laser Transmitters

Laser is an acronym for light amplification by stimulated emission of radiation. The key word is stimulated emission, which is what allows a laser to produce intense high-powered beams of coherent light (light that contains one or more distinct frequencies). There are three main types of laser that can be considered for this type of application:

1. VCSEL (vertical cavity surface emitting laser): these lasers operate at 850 nm and are predominantly multi (transverse) mode. Cost is very low because they are produced in high volume for data communications applications.
2. FP (fabry perot laser): these lasers are edge emitters and predominantly operate at longer wavelength (1310 or 1550 nm windows) with multiple longitudinal modes. Cost is intermediate between VCSELS and DFBs.
3. DFB (distributed feedback laser): these lasers are edge-emitters and predominantly operate at longer wavelength (1310 or 1550nm windows) with a single longitudinal mode. Cost is higher than for VCSEL or FP.

4.2.3 Optical Modulation

To transmit data across an optical fiber, the information must first be encoded, or modulated, onto the laser signal. Analog techniques include amplitude modulation (AM), frequency modulation (FM), and phase modulation (PM). Digital techniques include amplitude shift keying (ASK), frequency shift keying (FSK), and phase shift keying (PSK). Of all these techniques, binary ASK currently is the preferred method of digital modulation because of its simplicity. In binary ASK, also known as on-off keying (OOK), the signal is switched between two power levels. The lower power level represents a 0 bit, while the higher power level represents a 1 bit.

In systems employing OOK, modulation of the signal can be achieved by simply turning the laser on and off (direct modulation). In general, however, this can lead to chirp, or variations in the laser's amplitude and frequency, when the laser is turned on. A preferred approach for high bit rates (≥10 Gb/s) is to have an external modulator that modulates the light coming out of the laser. To this end, the Mach Zehnder interferometer or electroabsorption modulation are widely utilized [4, 5].

4.2.3.1 Electro-optic Modulation System

There are two primary methods for modulating light in telecommunication systems: direct and external modulation. Direct modulation refers to the modulation of the source, i.e.: turning a laser on and off to create pulses, while external modulation uses a separate device to modulate the light. External modulation has become the dominant method for high-speed long haul telecommunication systems.

External modulators can be implemented using a variety of materials and architectures although typically electro-optic materials the permitivity of the material is affected by the presence of electric fields. Many electro-optic materials are also birefringent. Since the indexes of the refraction are refraction are related to the permitivities of the materials, the phase velocities of the light inside the materials can changed by the application of electric fields. These changes are exploited in various ways to achieve optical modulation.

A material used in many commercial electro-optic modulators is lithium niobate, LiNbO3. Lithium niobate is a crystalline material that is optically transparent as well as birefringent. Currently most 10 GHz per channel long-haul telecommunication systems are based on lithium niobate modulators. Several companies are now offering 40 GHz modulators in anticipate the development of higher bandwidth systems. As products are developed to meet future needs there is an emphasis on higher operating speeds and greater levels of device integration.

Many electro-optic materials are currently being investigated for use in developing optoelectronic devices. Several groups are working with nonlinear optical polymers such as NLOPs to create electro-optic devices like optical modulators. NLOPs have various characteristics that may facilitate that development of high speed, low voltage electro-optic devices.

4.2.3.2 Electro-Optic Mach Zehnder Modulator

The electro-optic Mach-Zehnder modulator has become a ubiquitous device for high speed optical communication systems. It is customarily used as an intensity modulator for typical systems making use of the non return-to-zero (NRZ) or return to-zero (RZ) modulation formats, and has recently demonstrated its potential for phase modulation in future systems making use of the differential phase-shift keying (DPSK) format. Such modulators are made from an electro-optic crystal (typically lithium niobate, LiNbO3), who's refractive index depends on the electric field, hence voltage, which is applied to it.

The electrical data can thus modulate the refractive index of the crystal, hence the phase of the incoming light wave. Incorporating the crystal into an interferometric structure (Mach-Zehnder interferometer) in turn converts the phase modulation into intensity modulation [6, 7].

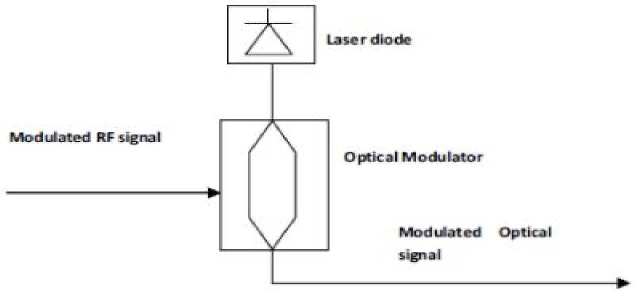

Figure 4.2: Basic configuration of optical modulator.

Although the principle of such a modulator is fairly simple, its operation can present many degrees of freedom and resulting trade-offs. One particular task will be to establish relations between the extinction ratio (defined as the ratio of the power transmitted into a binary `1´ and `0´) of the modulated optical signal and its frequency chirping, depending on the chirp generation mechanism (optical or electrical imbalance of the Mach-Zehnder modulator) [6, 7].

4.2.4 Optical Photodetector Receivers

In receivers employing direct detection a photodetector (PD) converts the incoming photonic stream into a stream of electrons. The electron stream is then amplified and passed through a threshold device. Whether a bit a logical zero or one is depends on whether the stream is above or below a certain threshold for bit duration. In other words the decision is made based on whether or not light is present during the bit duration.

The basic detection devices for direct detection optical networks are the PN photodiode (a p-n junction) and the Pm photodiode (an intrinsic material is placed between p- and n- type material). In its simplest form, the photodiode is basically a reverse biased p-n junction. Through the photoelectric effect light incident on the junction will create electron-hole pairs in both the “n” and the “p” regions of the photodiode. The electrons released in the “p” region will cross over to the “n” region, and the holes created in the “n” region will cross over to the “p” in a region, thereby resulting in a current flow [8].

4.2.5 Optical Amplifiers

Although an optical signal can propagate a long distance before it needs amplification, both long-haul and local light wave networks can benefit from optical amplifiers. All-optical amplification may differ from optoelectronic amplification in that it may act only to boost the power of a signal, not to restore the shape or timing of the signal. This type of amplification is known as 1R (regeneration), and provides total data transparency (the amplification process is independent of the signal's modulation format). 1R amplification is emerging as the choice for the transparent all-optical networks of tomorrow.

Digital networks [e.g., synchronous optical network (SONET) and synchronous digital hierarchy (SDH)], however, use the optical fiber only as a transmission medium, the optical signals are amplified by first converting the information stream into an electronic data signal and then retransmitting the signal optically.

Such amplification is referred to as 3R (regeneration, reshaping, and reclocking). The reshaping of the signal reproduces the original pulse shape of each bit, eliminating much of the noise. Reshaping applies primarily to digitally modulated signals but in some cases it may also be applied to analog signals. The reclocking of the signal synchronizes the signal to its original bit timing pattern and bit rate. Reclocking applies only to digitally modulated signals.

Another approach to amplification is 2R (regeneration and reshaping), in which the optical signal is converted to an electronic signal, which is then used to modulate a laser directly.

The 3R and 2R techniques provide less transparency than the 1R technique, and in future optical networks, the aggregate bit rate of even just a few channels might make 3R and 2R techniques less practical.

Optical amplification uses the principle of stimulated emission, similar to the approach used in a laser. The two basic types of optical amplifiers are semiconductor laser amplifiers and rare-earth-doped-fiber amplifiers.

4.2.5.1 Doped-Fiber Amplifier

Optical doped-fiber amplifiers as shown in Figure 4.3 are lengths of fiber doped with an element (rare earth) that can amplify light. The most common doping element is erbium, which provides gain for wavelengths of 1525 and 1560nm. At the end of the length of fiber, a laser transmits a strong signal at a lower wavelength (referred to as the pump wavelength) back up the fiber. This pump signal excites the do pant atoms into a higher energy level. This allows the data signal to stimulate the excited atoms to release photons. Most erbium doped fiber amplifiers (EDFA's) are pumped by lasers with a wavelength of either 980 or 1480 nm.

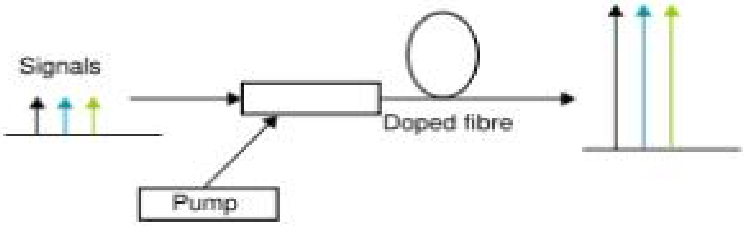

Figure 4.3: Schematic diagram of a simple Doped Fiber Amplifier.

A limitation to optical amplification is the unequal gain spectrum of optical amplifiers. While an optical amplifier may provide gain across a range of wavelengths, it will not necessarily amplify all wavelengths equally.

This characteristic accompanied by the fact that optical amplifiers amplify noise as well as signal and the fact that the active region of the amplifier can spontaneously emit photons, which also cause noise - limits the performance of optical amplifiers. Thus, a multiwavelength optical signal passing through a series of amplifiers will eventually result in the power of the wavelengths' being uneven.

4.3 The OOFDM-RoF System Model

The OFDM technique has several advantages for example the symbol duration is increased so that the relative amount of dispersion in time caused by multi-path delay spread is decreased significantly. The critical advantage of using OFDM in optical fiber communications includes better spectral efficiency, elimination of sub channel and symbol interference using the FFT for modulation and demodulation, which does not require any equalization and dispersion tolerance [1].

Figure 4.4 below describes the block diagram of OFDM – RoF system. From the figure, the digital data input first would be split into parallel streams data by OFDM transmitter, then this data would carry onto the optical fiber link. In the optical link, continues wave (CW) laser (transmitter) would emit a continuous beam or a train of short pulses of a laser. In the MZM (external modulator) the electrical wave signal from OFDM transmitter are combined with the continuous wave light from CW laser, this two waves are then modulated by MZM to form optical signal which would be sent through the optical fiber.

After sending through the optical fiber, then the data would be received first by photodetector (receiver). This photodetector converts the incoming photonic stream back into a stream of electrons, so the optical signals are converted back into electrical signals. The signal then would recombine again in the OFDM receiver to get the original data back.

As shown and discussed above the system consists of an optical fiber, transmitter, receiver, external modulator, and amplifier each of which is dealt with in the previous section 4.2.

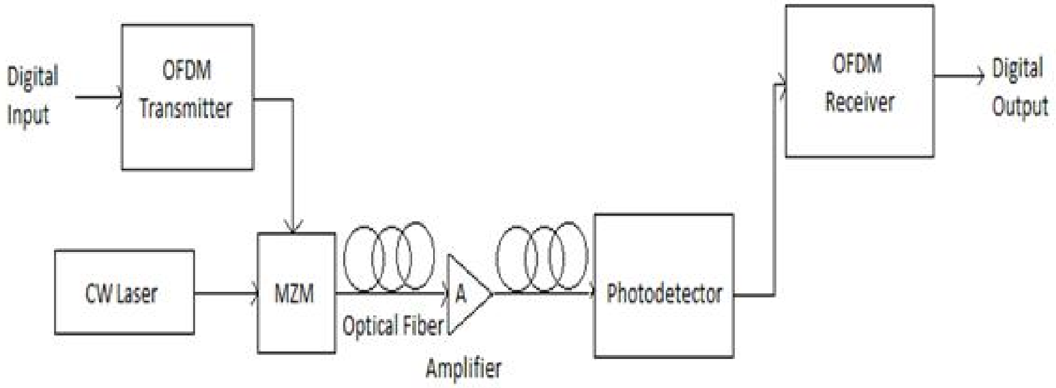

Figure 4.4: Block diagram of OFDM – RoF system.

One way to categorize OFDM generators would be to classify them depending on the type of subcarrier generation. This would give rise to two different transmitter categories: analogue and digital generation. While the first one requires a complex integrated modulation, the latter allows a simple optics design with flexible and adaptive constellations at the receiver side.

At the same time, optical OFDM systems with subcarriers generated in the digital domain can be classified according to many other parameters. The most important ones are the modulation technique used in the electrical to optical (E/O) conversion and the type of detection at the receiver in OFDM system.

4.3.1 Modulation Technique

The way in which data is allocated at the input sequence of the IFFT gives rise to many different transmitter configurations. Thus, different optical modulations should be applied depending on the type of electrical OFDM signal obtained at the transmitter output.

Here, an optical IQ MZM modulation is emphasized, which avoids the transmission impairments caused by dispersion by applying the optical single sideband technique, though they do it in different ways.

If an IQ MZM is used for the optical modulation of the electrical OFDM signal, only one complex optical OFDM band is obtained, so no optical filter is required at the transmitter end. The resulting schematic for this technique is depicted in Figure 4.5, where the real and imaginary components of the OFDM signal are directly fed to the IQ MZM. For simplicity, oversampling is neglected [9].

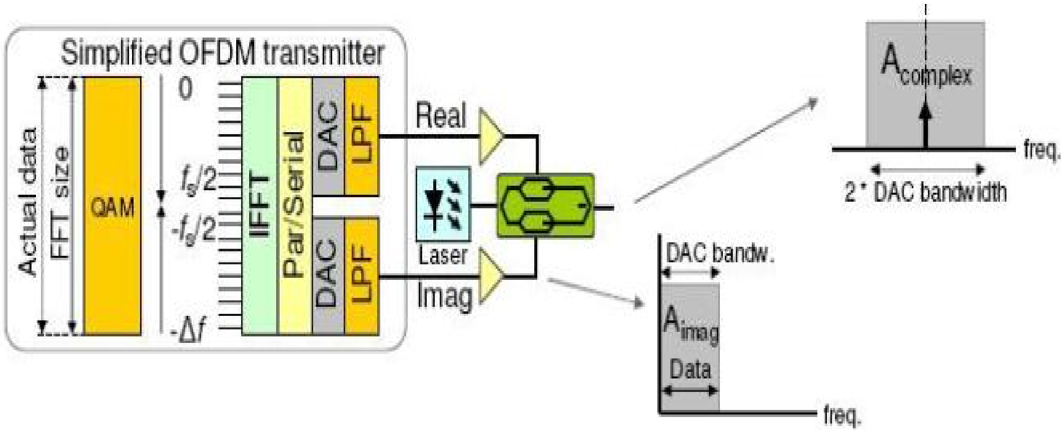

Figure 4.5: Optical IQ modulation schematic [9].

This scheme provides the possibility of a full-data IFFT input sequence and the complete DAC bandwidths usage (when no oversampling is applied). Moreover, few electronic devices are needed for the implementation of this scheme, though two DACs are required and three bias voltages have to be adjusted for the IQ MZM.

4.3.2 Detection Techniques

There are two basic kinds of techniques allowing the demodulation of an optical signal into the originally transmitted electrical signal: those are the direct and coherent detection. Both techniques have its pros and cons, and this subsection describes them. As the simulated transmission scenarios within this work use direct detection, this technique will be described in more detail than coherent detection.

4.3.2.1 Direct Detection Optical OFDM

There are many different forms of direct detection (DD) methods with some advantages over the others [10-13]. However, all of them share a very important characteristic, which is the use of a simple receiver.

Thus, the real valued electrical OFDM signal is available after upconversion and drives directly the E/O modulator. Figure 4.6 shows the schematic designed by Lowery and Armstrong in [14].

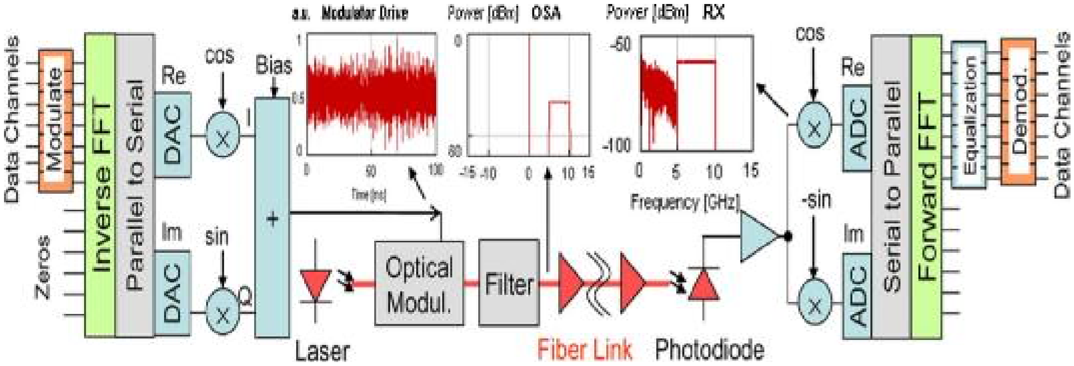

Figure 4.6: DDO-OFDM Long-haul optical communication system [14].

First, the received optical spectrum for an OSSB O-OFDM transmission is depicted in Figure 4.7.

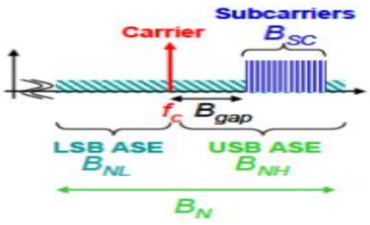

Figure 4.7: Received optical spectrum.

The OFDM subcarriers have a bandwidth B_{sc} and there is a gap, B_{gap}, between the carrier and the subcarriers, which can be produced by RF upconversion of the electrical OFDM signal or by zero padding at the input IFFT sequence, as explained in Chapter 3.

The amplified spontaneous emission (ASE) inherent to the laser is unpolarized and is band-limited by an optical filter, extending from B_{NL} below the carrier frequency (f_c) to B_{NH} above f_c as shown in Figure 4.7, being present in both the lower and the upper sideband zones [15].

The useful components in the electrical spectra (that is, the OFDM subcarriers) are the different terms which result from the mixing of the OFDM sideband and the optical carrier.

Figure 4.8 shows the optical spectra of the contributions to this mixing and the resulting electrical spectra after downconversion [15].

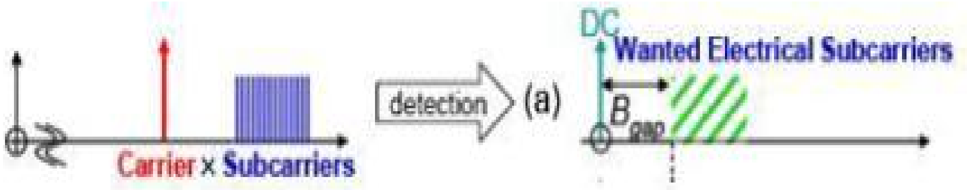

Figure 4.8: Useful components in the electrical spectra.

When a frequency guard band is used ($B_{gap} > B_{sc}$) all of the results of the mixing products between OFDM subcarriers will fall out of band, not degrading performance. This way, the unwanted out of band noise will be avoided as shown in Figure 4.9[15].

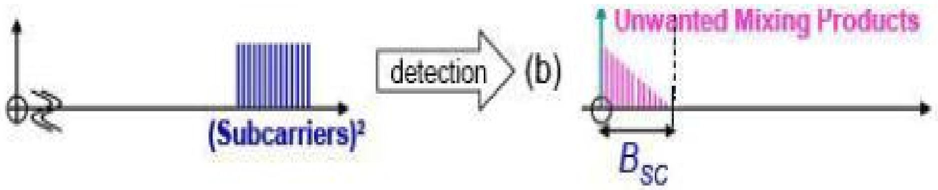

Figure 4.9: Unwanted out of band noise.

However, other undesired mixing products resulting from the square law detection will fall inside the OFDM band. Those are called the unwanted inband terms.

The single tap equalizer function in the OFDM receiver corrects for the amplitude distortions caused by frequency roll-off of the components and the phase distortions caused by CD and OFDM symbol timing offsets. It should be taken into account that there may be other mixing products because of nonlinearities in the system or I/Q imbalance in the transmitter.

Figure 4.10 represents a typical DD receiver used in optical OFDM, where the optical and electrical spectrums before and after the photodetector are also represented.

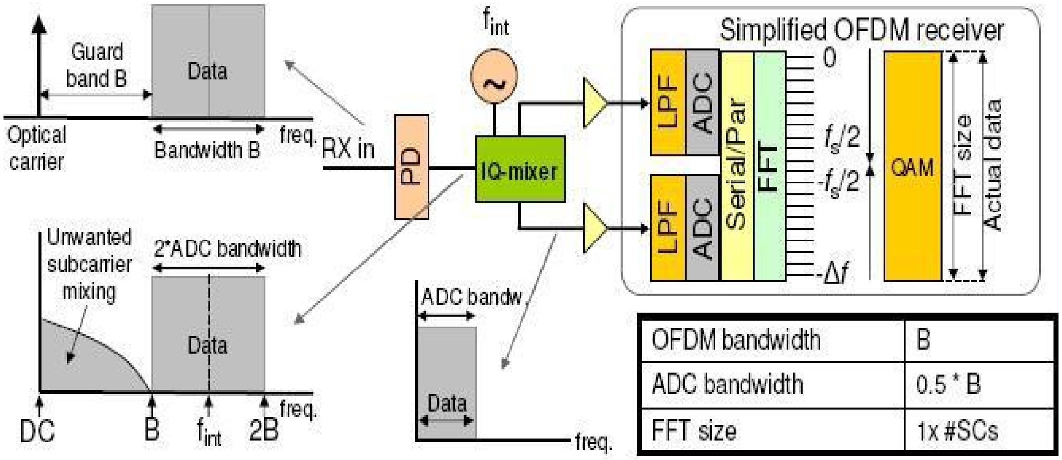

Figure 4.10: Direct detection at the receiver [9].

It can be seen that the second-order intermodulation is located in the guard band from DC to the OFDM signal bandwidth B, whereas the OFDM spectrum spans from B to 2B. Then, the RF spectrum of the intermodulation does not overlap with the OFDM signal, meaning that the intermodulation does not cause detrimental effects after proper electrical filtering.

Once photodetected, the electrical signal is downconverted to baseband in the opposite way as it was done at the transmitter, before applying the FFT to ideally recover the original subcarriers.

Thus, if the optical OFDM band is located close to the optical carrier in the frequency domain, the intra mixing products are located in the same frequency range as the electrical OFDM signal leading to performance degradation.

Taking all this into account, it can be said that the optical bandwidth requirements for direct detection optical OFDM are determined both by the OFDM band and the gap between the OFDM band and the optical carrier, always omitting one optical sideband. Typically the width of gap is equal to the width of the OFDM band in minimum.

4.3.2.2 Coherent Detection Optical OFDM

Coherent optical OFDM (CO-OFDM) represents the best performance in receiver sensitivity, spectral efficiency and robustness against polarization dispersion, but it requires the highest complexity in the transmitter design.

There are two main advantages coming from the combination of coherent optical communications and OFDM: OFDM brings coherent systems computation efficiency and ease of channel and phase estimation, and the coherent systems bring OFDM a much needed linearity in E/O upconversion and O/E downconversion, since a linear transformation is the key goal for the OFDM implementation. Moreover, there is no need to create a gap between the OFDM signal and the DC component as in the DD receiver setups.

The principle of coherent OFDM is depicted in Figure 4.11:

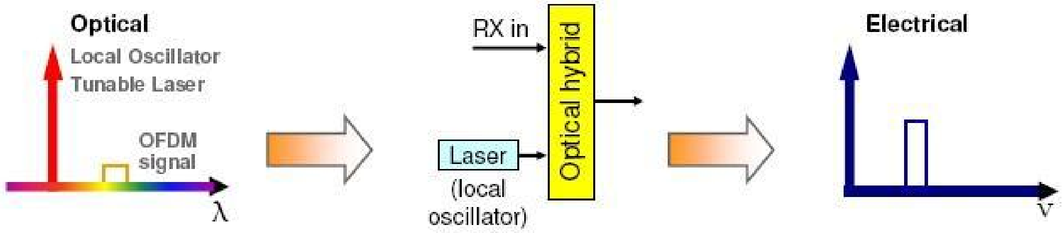

Figure 4.11: Principle of coherent OFDM receivers [9].

In coherent OFDM systems, the optical carrier is not transmitted with the optical OFDM signal, but generated locally by a laser. This makes this kind of system to require less transmitted optical power than DD-OOFDM, though it is more sensitive to phase noise.

As shown in Figure 4.11, a local oscillator (LO) is mixed with the OFDM signal by means of a 90º hybrid that performs the optical IQ detection. If both signals are aligned in polarization, the mixing of the optical OFDM signal with the LO signal results in the desired electrical OFDM signal. In case of orthogonal polarizations there are no mixing products available. There are two frequently used configurations regarding to coherent receivers for optical OFDM. Those are homodyne and heterodyne CO-OFDM receivers [9].

The optical bandwidth requirements for CO-OFDM are much lower compared to DD optical OFDM because there is no need to transmit an optical carrier with the required gap to the OFDM band in addition to the modulated subcarriers. This leads to a spectral efficiency of nearly twice the one in DD-OFDM for any type of subcarrier modulation.

4.3.3 Equalization

In order to obtain an OFDM signal without errors at the receiver, the use of cyclic prefix is essential. This will eliminate ISI when a temporal dispersion affects the channel. However, the effect of chromatic dispersion causes the information symbols to still be affected by amplitude and phase changes when arriving to the receiver, as shown in Figure 4.12 [9]:

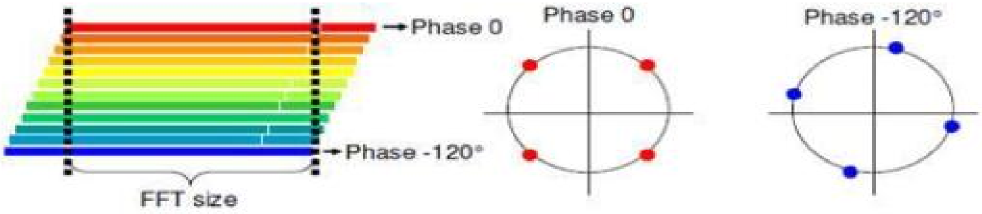

Figure 4.12: Phase distortions on the received constellation.

Consequently, an N-level equalizing stage has to be introduced right after the FFT operation at the receiver in order to correct the phase and amplitude levels, where N is the number of received subcarriers.

The design parameters for this stage should be obtained through a channel estimation, which is usually performed with training sequences. These sequences are added by using pilot subcarriers in each OFDM symbol, so the channel transfer function can be approximated.

However, this equalization will be not enough to obtain the ideal received constellation, as a constant phase shift will still affect the received symbols due to the choice of the reference frequency for the fiber.

4.4 Summary

In this chapter a brief description and explanation of the basic theory about optical transmission link is presented and discussed, optical fiber, optical transmitter, optical modulation, optical receiver and optical amplifier are explained. The OFDM-ROF system model has been described with some techniques which used in this model such as modulation technique, detection technique and equalization.

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5

Simulation Results and Performance Analysis

5.1 Introduction

This chapter presents the simulation results of OOFDM-RoF system. The RoF system designed in OptiSystem software. In this system the Quadrature Amplitude Modulation (QAM) OFDM modulation technique is incorporated into RoF system. This system can be used for both short distance as well as long-haul transmission at very high data rate. This improves the system flexibility and provides a very large coverage.

In this chapter an OptiSystem software will be described, a brief description and explanation of the basic theory about QAM technique will be presented and discussed. The OFDM-RoF system model will be explained and discussed, the 4QAM OFDM, 16QAM OFDM, 64QAM OFDM system will be explained and described by all simulation results for all parts of system.

5.2 OptiSystem Simulation Software

OptiSystem is a comprehensive software design suite that enables users to plan, test, and simulate optical links in the transmission layer of modern optical networks. The professional design environment of OptiSystem can simulate emerging PON technologies, such as the various optical code-division multiple-access (OCDMA) techniques for OCDMA-PON architectures and OFDM. The robust simulation environment enables users to plan, test and simulate optical links in the physical layer of a variety of passive optical networks [1].

Being a system level simulator based on realistic modeling of fiber-optic communication systems, it possesses a powerful new simulation environment and a truly hierarchical definition of components and systems. A robust graphical user interface controls the optical component layout and netlist, component models, and presentation graphics. An extensive library of active and passive components includes realistic, wavelength dependent parameters. Parameter sweeps allow the user to investigate the effect of particular device specifications on system performance.

5.2.1 Applications

OptiSystem enables users to simulate/design:

- Next Generation optical networks
- Current optical networks
- SONET/SDH ring networks
- Amplifiers, receivers, transmitters

5.2.2 Analysis Tools

- Eye diagrams, BER, Q-Factor, Signal chirp.
- Polarization state, Constellation diagrams.
- Signal power, gain, noise figure, OSNR
- Data monitors, report generation

5.3 QAM-OFDM RoF System

In this project the OFDM Signal generation and decoding using QAM as the modulation technique, 4QAM, 16QAM and 64QAM schemes are used. QAM is both an analog and a digital modulation scheme. It conveys two analog message signals, or two digital bit streams, by changing (modulating) the amplitudes of two carrier waves, using the ASK digital modulation scheme or AM analog modulation scheme. The two carrier waves, usually sinusoids, are out of phase with each other by 90° and are thus called quadrature carriers or quadrature components. The modulated waves are summed, and the resulting waveform is a combination of both PSK and ASK, or (in the analog case) of PM and AM.

In the digital QAM case, a finite number of at least two phases and at least two amplitudes are used. PSK modulators are often designed using the QAM principle, but are not considered as QAM since the amplitude of the modulated carrier signal is constant.

Figure 5.1 shows the constellation diagrams which show the different positions for the states within different forms of QAM, from 4QAM, 16QAM and 64QAM. As the order of the modulation increases.

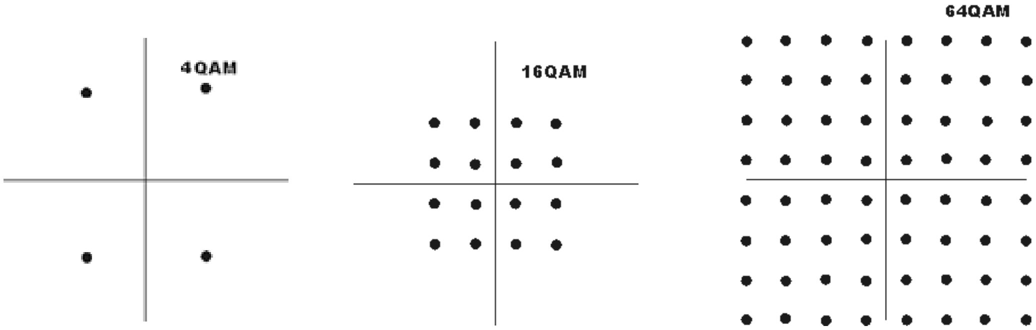


Figure 5.1: Constellation diagram for different forms of QAM.

Three forms of QAM are used to encode and generate the OFDM signal that is 4QAM, 16QAM and 64QAM. For every form of QAM-OFDM, the number of subcarrier is changed to achieve the increase in capacity of system with best value of bit error rate (BER).

Firstly, in 4QAM-OFDM system the 512 subcarrier is used to achieve a value of BER of zero, then in 16QAM-OFDM system the changes of number of subcarriers started from 128 subcarrier to 256 to 512 to 1024 subcarrier with BER of zero, then in 64QAM-OFDM system the 512 and 1024 subcarrier are used to get the best value of

BER, these simulations to show the how we can increase the capacity with very small value of BER, the 16QAM-OFDM system will discussed with more details and explanations.

5.3.1 The Transmitter Model

In OOFDM RoF system, the transmitter model is consisted of two parts, the first part is the radio frequency (RF) transmitter and the second one is optical transmitter. In the following subsection those parts will discussed and explained.

5.3.1.1 Radio Frequency Transmitter

The RF transmitter is consisted of four blocks the Figure 5.2 show all blocks of RF transmitter system as the following:

The first block is a pseudo random number generator; it generates a bit sequence of 0 and 1 with equal probability. In this simulation the sequence of length is 16384 bits with Non Return to Zero (NRZ) format.

The second block is QAM sequence generator, which is to generate the bits per symbol for all forms of QAM that used in the thesis simulation (4QAM, 16QAM and 64QAM).

The third block is OFDM modulation block system, which consists of important parameters such as number of subcarriers (see chapter 3) and low pass roll off filter with roll off factor (i.e. a parameter that governs the bandwidth occupied by the pulse and the rate at which the tails of the pulse decay and it's ranges from 0 to 1) equal 0.2.

Finally the quadrature modulator, which is used to up convert the signal at high RF frequency, in this system the 7.5 GHz frequency is used for different application in this bands of frequencies.

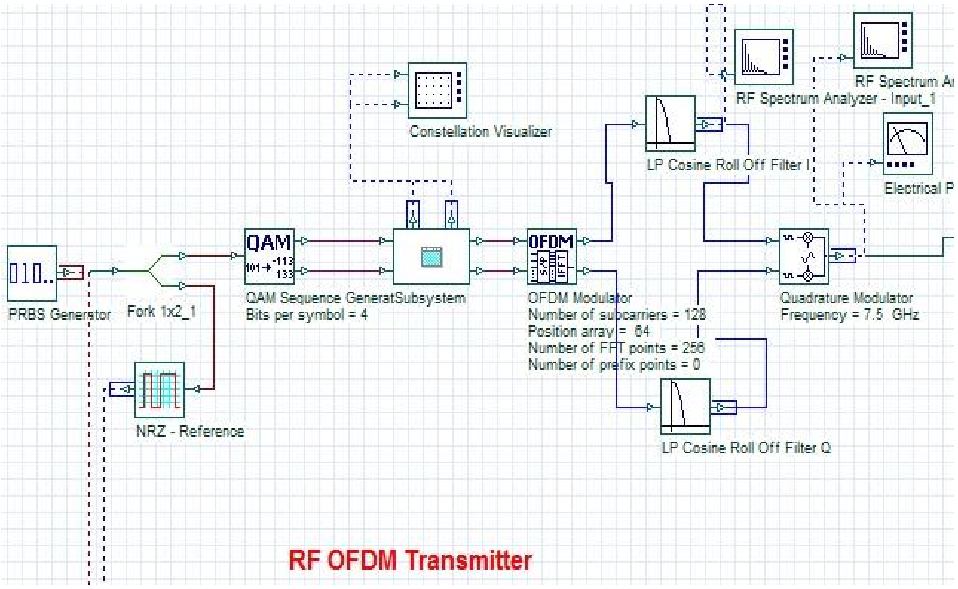


Figure 5.2: Radio Frequency Transmitter.

The global parameter setup that using in this simulation are shown in table 5.1 below:

Table 5.1: Global Parameter Setup.

Parameter	Value
Bit rate	10 Gbps
Time window	1.6384e-006 s
Sample rate	40 GHz
Sequence length	16384 bits
Sample per bit	4
Number of samples	65536

5.3.1.2 Optical Transmitter

The role of the optical transmitter is to convert the electrical signal into optical form, and launch the resulting optical signal into the optical fiber and also can called RF to optical upconverter (RTO). The optical transmitter consists of the following components, optical source, electrical pulse generator and optical modulator as shown in Figure 5.3.

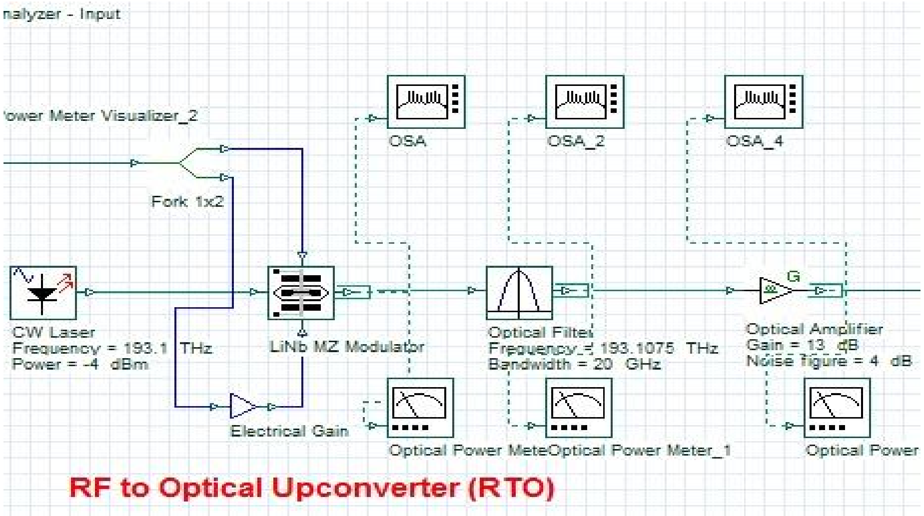


Figure 5.3: Optical Transmitter.

The launched power is an important design parameter, as indicates how much fiber loss can be tolerated, which is -4 dBm with 0.5 MHz line width at 1550 nm window (193.1 THz) in this simulation, then the light signal which was generated by laser and the OFDM symbols modulated with an optical modulator, which is used in this simulation is LiNb MZM (see chapter 4) after that the optical modulated signal is filtered by optical filter at the same window at 193.1 THz frequency with bandwidth of 20 GHz, then to keep signal strong the optical amplifier is used with gain 13 dBm.

5.3.2 The Optical Transmission Link Model

The transmission link as shown in Figure 5.4 part is consisted of optical fiber with length of 50 km and attenuation 0.2 dB/km, which work as transmission media, optical amplifier to amplify the weak signals and optical signal with the same window of laser, this transmission link is repeated twice.

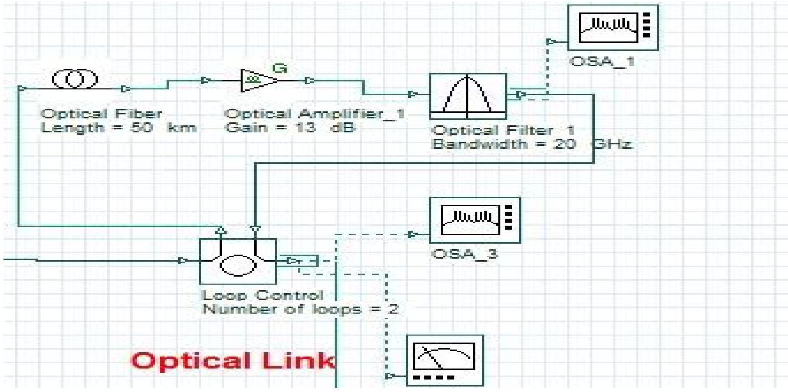


Figure 5.4: Optical Transmission Link.

5.3.3 The Receiver Model

The receiver model of this OOFDM RoF system is consisted of two parts, the first is optical receiver, and the second one is RF receiver.

5.3.3.1 Optical Receiver

The optical receiver is consisted of two blocks as show in Figure 5.5 and also called optical to RF downconverter (OTR). When the optical signal sent from laser to receiver by fiber the first block is received the signal is photodetector, which is Positive Intrinsic Negative detector with responsivity 1 A/W. The second part is band pass filter, which used to eliminate the noise that added from fiber, this filter has a frequency of the RF signal at 7.5 GHz and bandwidth of half of bit rate.

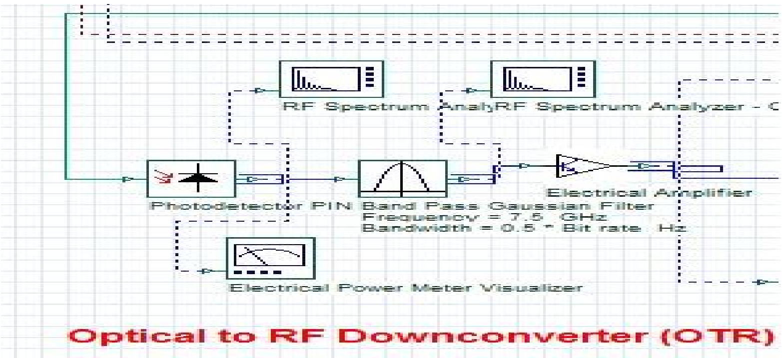


Figure 5.5: Optical to RF Receiver.

5.3.3.2 RF Receiver

In Figure 5.6 the RF receiver is shown, after the optical signal converted to electrical signal and all noise is eliminated, the signal will be demodulated at the same RF frequency which was modulated, then the signal will demodulated with OFDM demodulator to extract the symbols and then decoded to get the original bits.

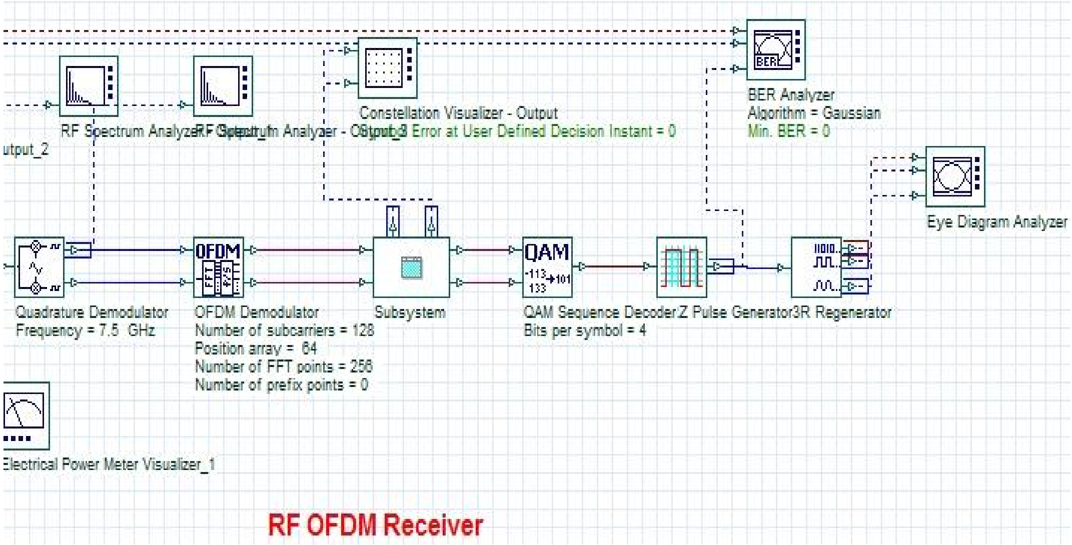


Figure: 5.6: RF Receiver.

5.4 4QAM-OFDM RoF System Simulation Results

In 4QAM-OFDM RoF system the bit generator will generate a sequence of 0 and 1 of NRZ form signal with 16384 bits, then those bits encoded with 4QAM decoder, which will use 2 bit per symbol. All of the figures below from Figure 5.6 to Figure 5.13 describe the results of simulations.

5.4.1 The Transmitter Model Simulation Results

The result for the transmitter part which is in electrical, frequency and optical domain was shown in the figures below from Figure 5.7 to Figure 5.11, these results show the original signal, the constellation diagram for 4QAM encoder output, time and frequency domain OFDM signal, the signal after MZM modulator and the optical signal in time and optical domain in fiber link media.

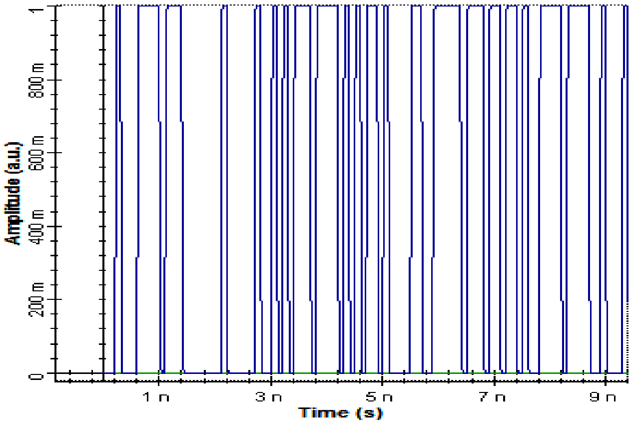


Figure 5.7: Original signal for 4QAM system.

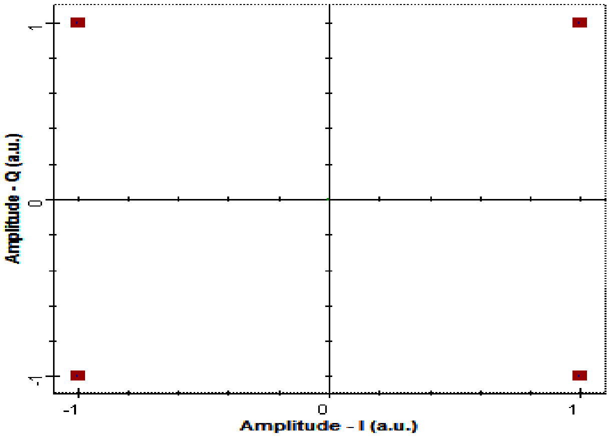
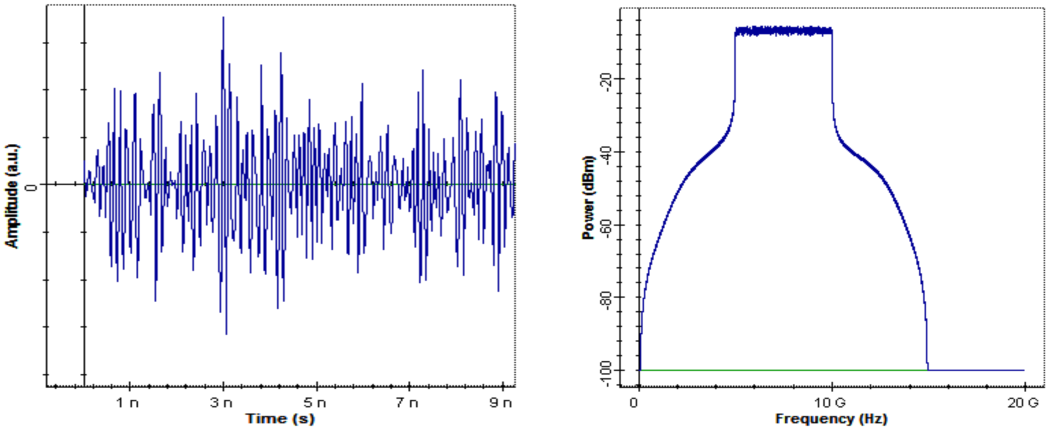


Figure 5.8: 4QAM Encoder Constellation Diagram



(a) **(b)**

Figure 5.9: Modulated OFDM Signal. a) Time Domain, b) Frequency Domain.

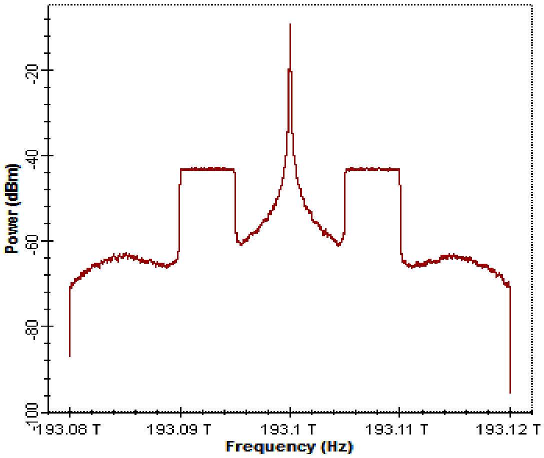
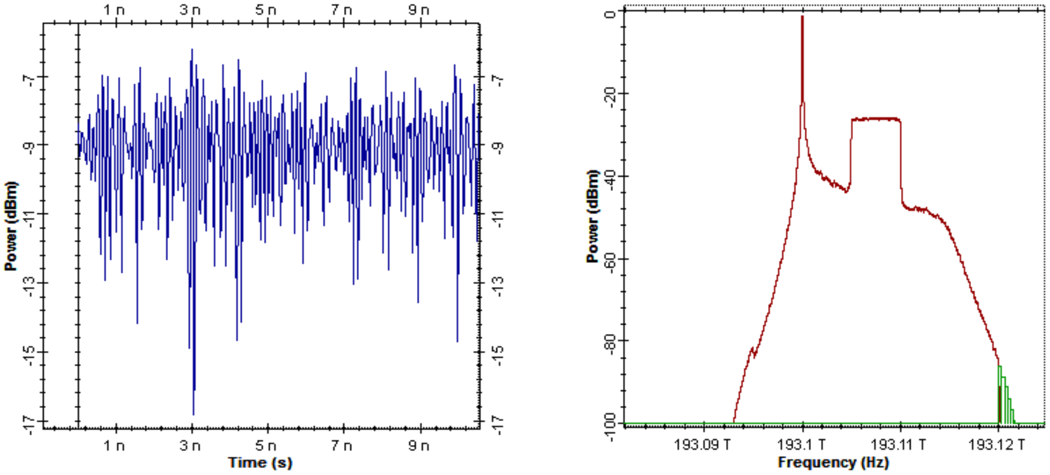


Figure 5.10: Optical Signal after MZM.

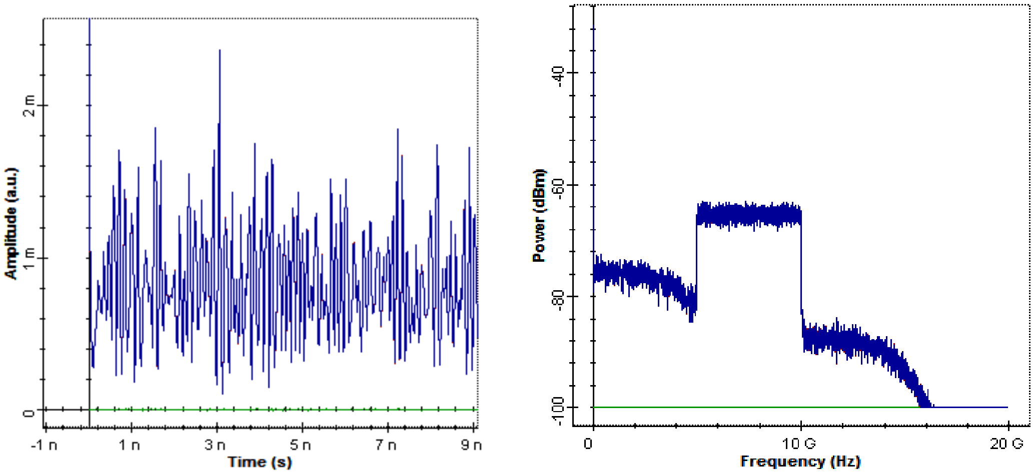


(a) **(b)**

Figure 5.11: Optical signal in the Fiber. a) Time Domain, b) Frequency Domain.

5.4.2 The Receiver Model Simulation Results

The result for the receiver part which is in electrical, frequency and optical domain was shown the figures below Figure 5.12 and Figure 5.13, these results show the received signal, output constellation diagram.



a) **b)**

Figure 5.12: Received signal after PD. a) Time Domain, b) Frequency Domain.

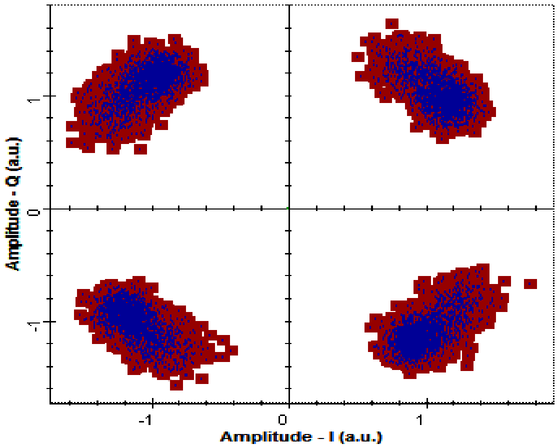


Figure 5.13: Final 4QAM Decoder Constellation Diagram.

5.5 16QAM-OFDM RoF System Simulation Results

In 16QAM-OFDM RoF system the bit generator will generate a sequence of 0 and 1 of NRZ form signal with 16384 bits, then those bits encoded with 16QAM decoder, which will use 4 bit per symbol. All of the figures below from Figure 5.14 to Figure 5.23 describe the results of simulations for 512 subcarrier OFDM signal, but another different number of subcarriers 128, 256 and 1024 subcarriers will show as figure comparison in Figure 5.24 to 5.30, so that 512 subcarriers OFDM-RoF system will discussed with more details in the two subsections below.

5.5.1 The Transmitter Model Simulation Results for 512 Subcarriers

In Figure 5.14 and Figure 5.15 above the original NRZ signal and the 16QAM encoded signal constellation diagram are shown, the 16QAM constellation diagram show the 4 bit per symbol to generate the OFDM signal.

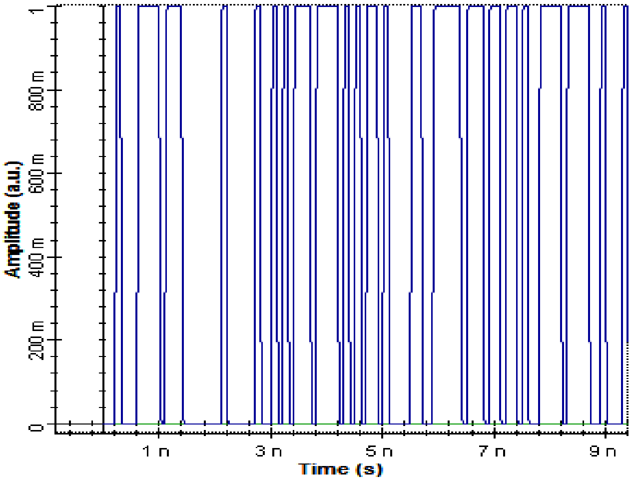


Figure 5.14: Original signal for QAM-OFDM system.

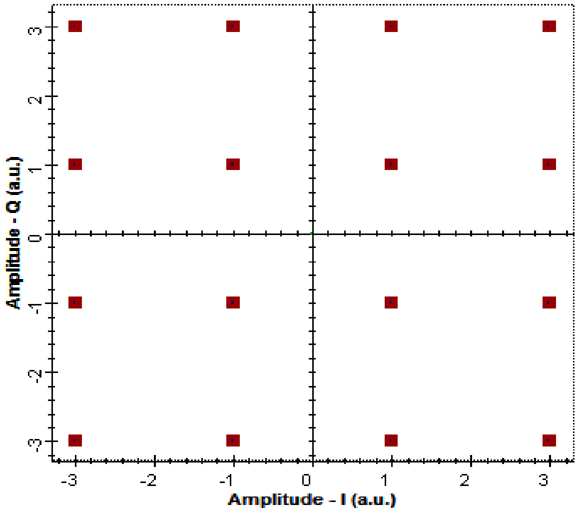


Figure 5.15: 16QAM Encoder Constellation Diagram.

After OFDM signal is generated, it will be modulated by quadrature modulator. Before modulation the OFDM signal is filtered by low pass (LP) cosine roll off to achieve the RF 7.5 GHz frequency with as shown Figure 5.16.

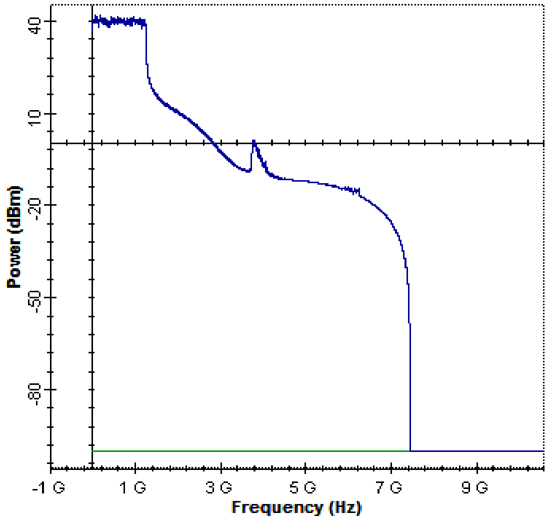
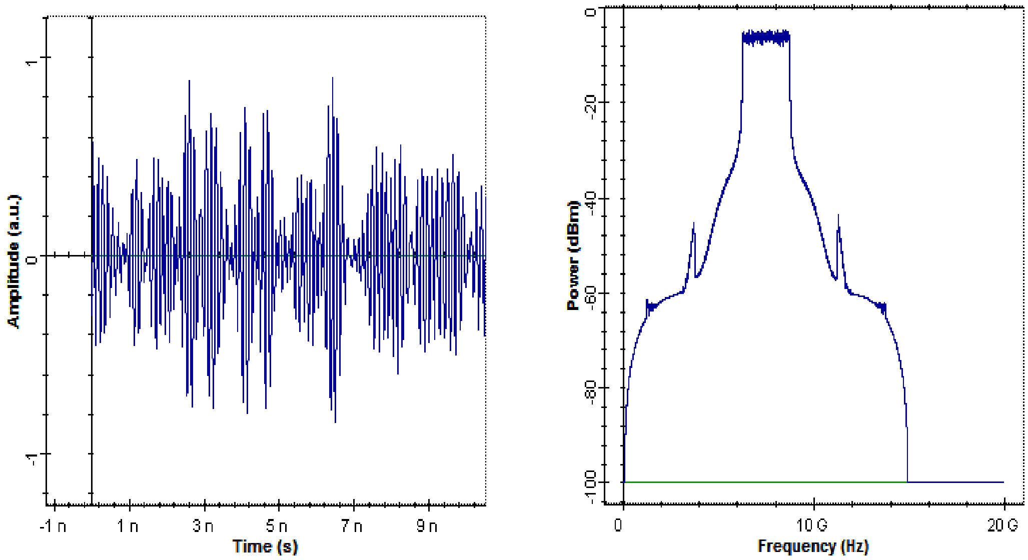


Figure 5.16: Filtered OFDM signal by LP filter.

In Figure 5.17 the modulated signal at time and frequency domain is shown. The power of modulated OFDM signal is equal -6 dBm and bandwidth of 15 GHz and the main OFDM part of signal is 3 GHz from two sides of the center of frequency.



a) **b)**

Figure 5.17: OFDM Signal. a) Time Domain, b) Frequency Domain.

The next operation is to upconvert the RF OFDM signal to optical signal at window of 1550 nm (193.1 THz) using MZM external modulator with small power value of -8 dBm, the resulted signal in time and frequency domain is shown in Figure 5.18.

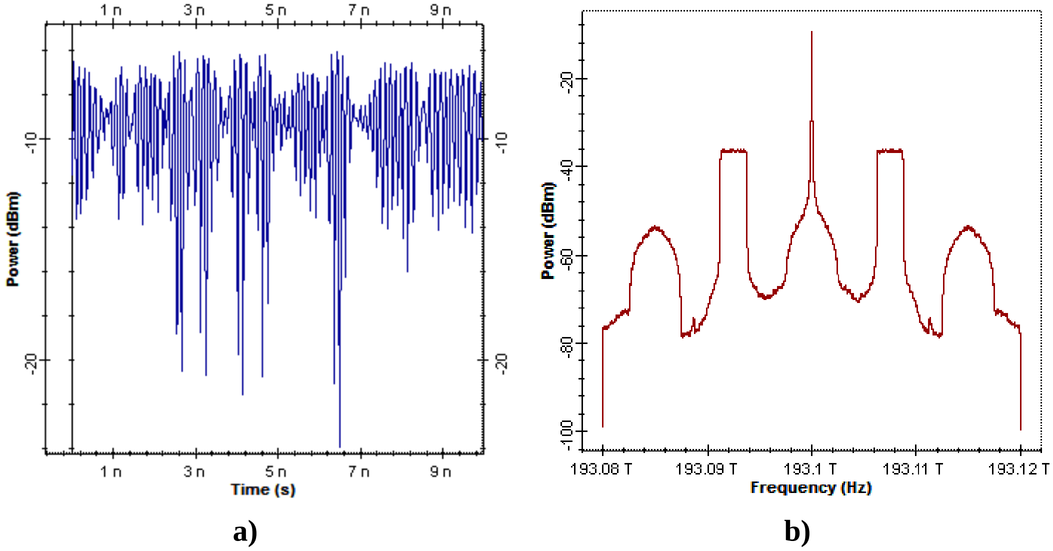


Figure 5.18: Modulated optical Signal. a) Time Domain, b) Frequency Domain.

After that the signal will be transmitted over fiber to be received in the end of fiber after two loops of 100 km length of fiber, the received optical signal at PD is shown in Figure 5.19, it is 8 dBm and power this high of power of received optical signal is because of optical amplifier in the fiber link.

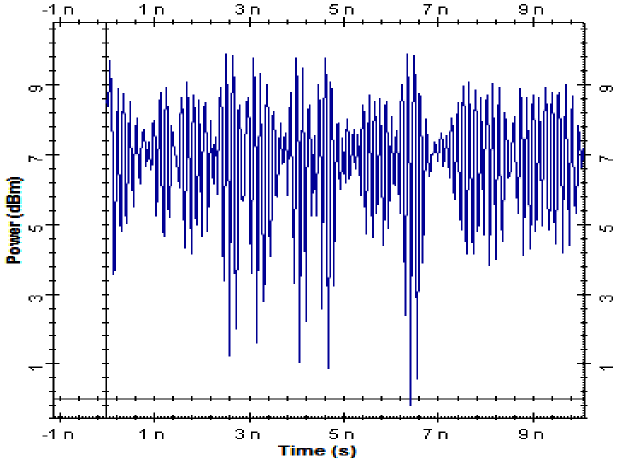
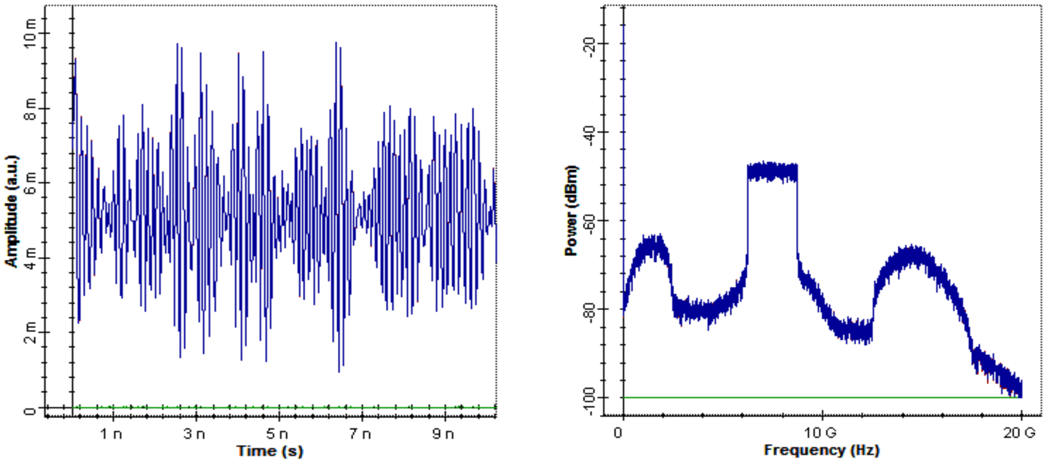


Figure 5.19: Received optical signal at PD.

5.5.2 The Receiver Model Simulation Results for 512 Subcarriers

In the receiver side, there are two parts to analyze the optical received signal. First part is the optical receiver which consists of PD, in Figure 5.20 the RF signal after converted from optical form, which is in time and frequency domain. The power of RF signal is equal -50 dBm with side noise.



a) **b)**

Figure 5.20: Received RF Signal. a) Time Domain, b) Frequency Domain.

To get the base OFDM signal without side noise to achieve the best BER, the band pass filter (BPF) is used. The resulted signal after BPF with 3 GHz bandwidth from two sides of the center frequency at 7.5 GHz is shown in Figure 5.21.

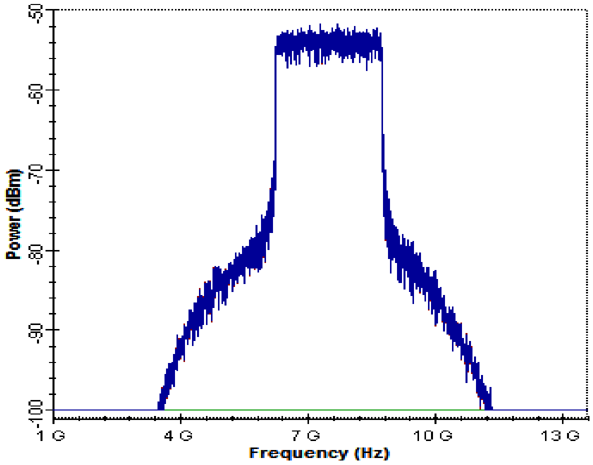


Figure 5.21: RF signal after BPF.

After the clarified RF OFDM signal is achieved at OFDM demodulator and the demodulation operation is done, the output of the demodulator will analyze to achieve desired value of BER, the final constellation diagram is shown in Figure 5.22, and the minimum BER and BER pattern are shown in Figure 5.23.

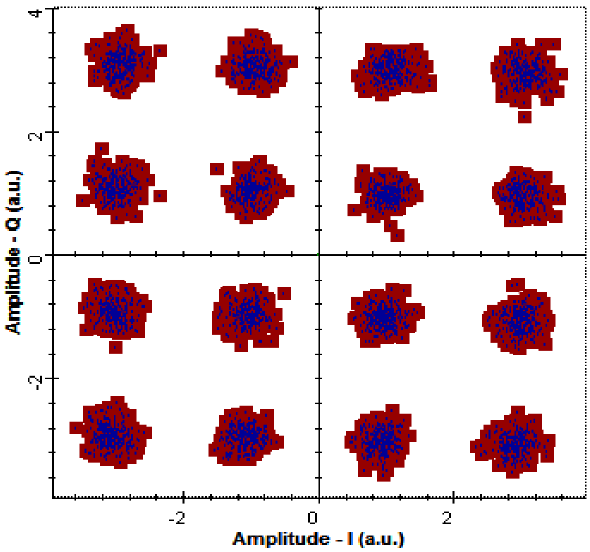
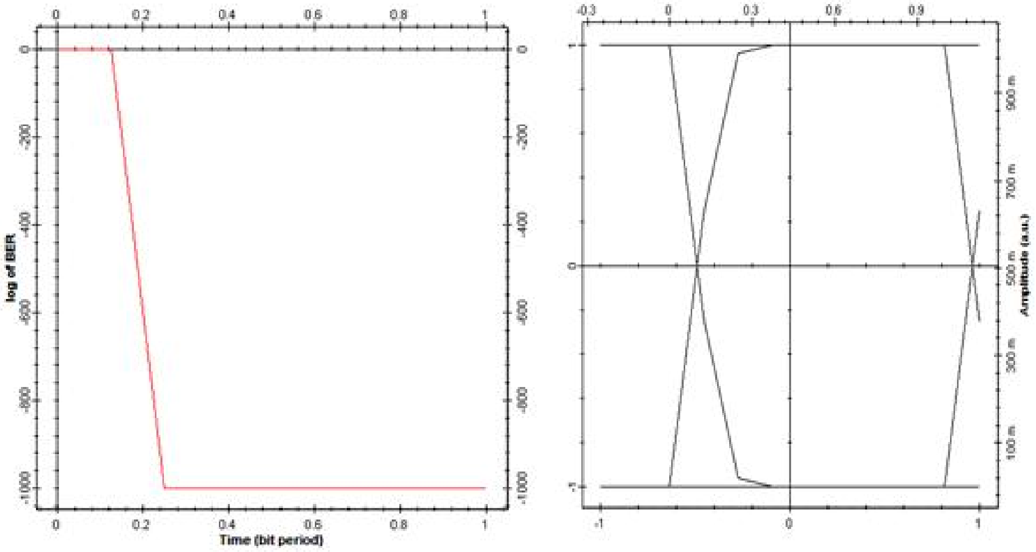


Figure 5.22: Final 16QAM Decoder Constellation Diagram.



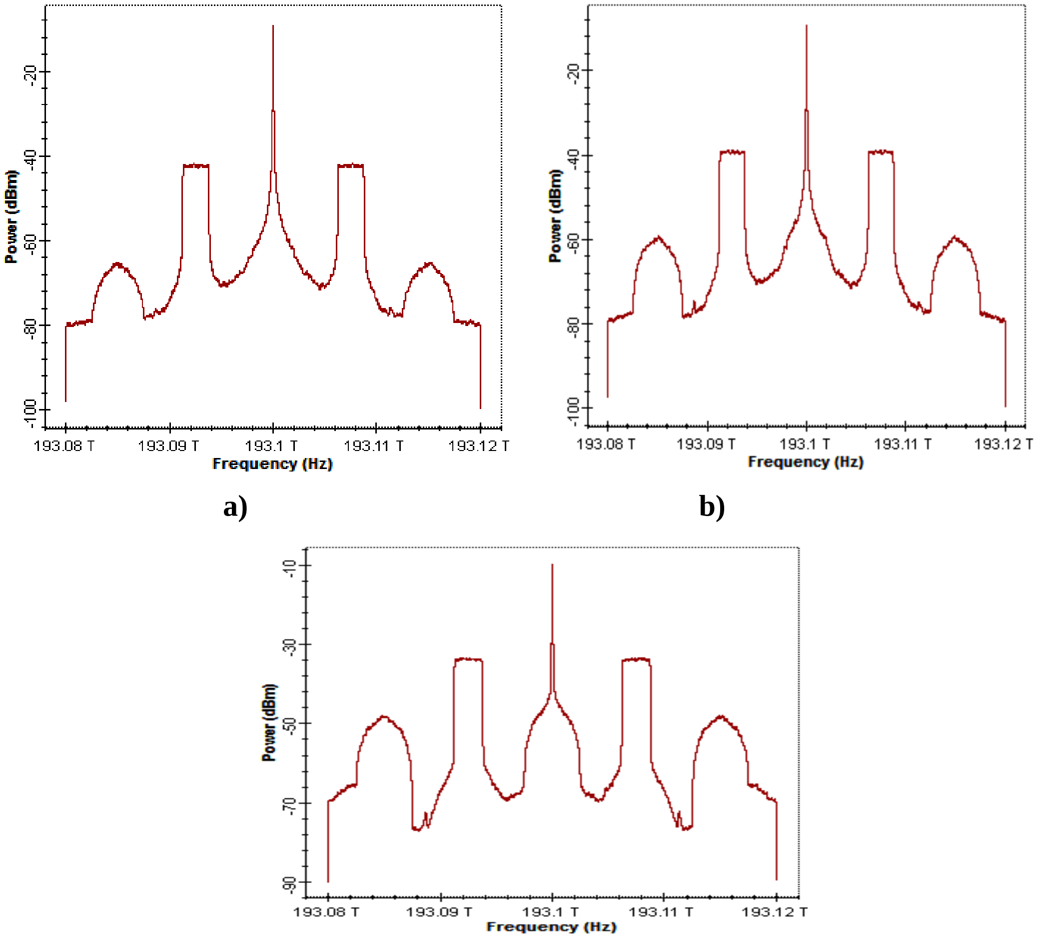
a) **b)**

Figure 5.23: BER Analysis a) Min BER, b) BER Pattern.

From Figure 5.23a above the best value of BER of zero value is achieved, the high open eye diagram as shown in Figure 5.23b also is achieved. All of these best results are achieved because of use the BPF that eliminate the side noise of the received OFDM signal as shown in Figure 5.21.

5.5.3 The Simulation Results for 128, 256 and 1024 Subcarriers

The result for 16QAM 128, 256 and 1024 subcarriers system, which is in electrical, frequency are shown in the figures below from Figure 5.24 to Figure 5.28, these results show the signal after MZM modulator in frequency domain, output constellation diagram and the Min BER.



a) **b)**

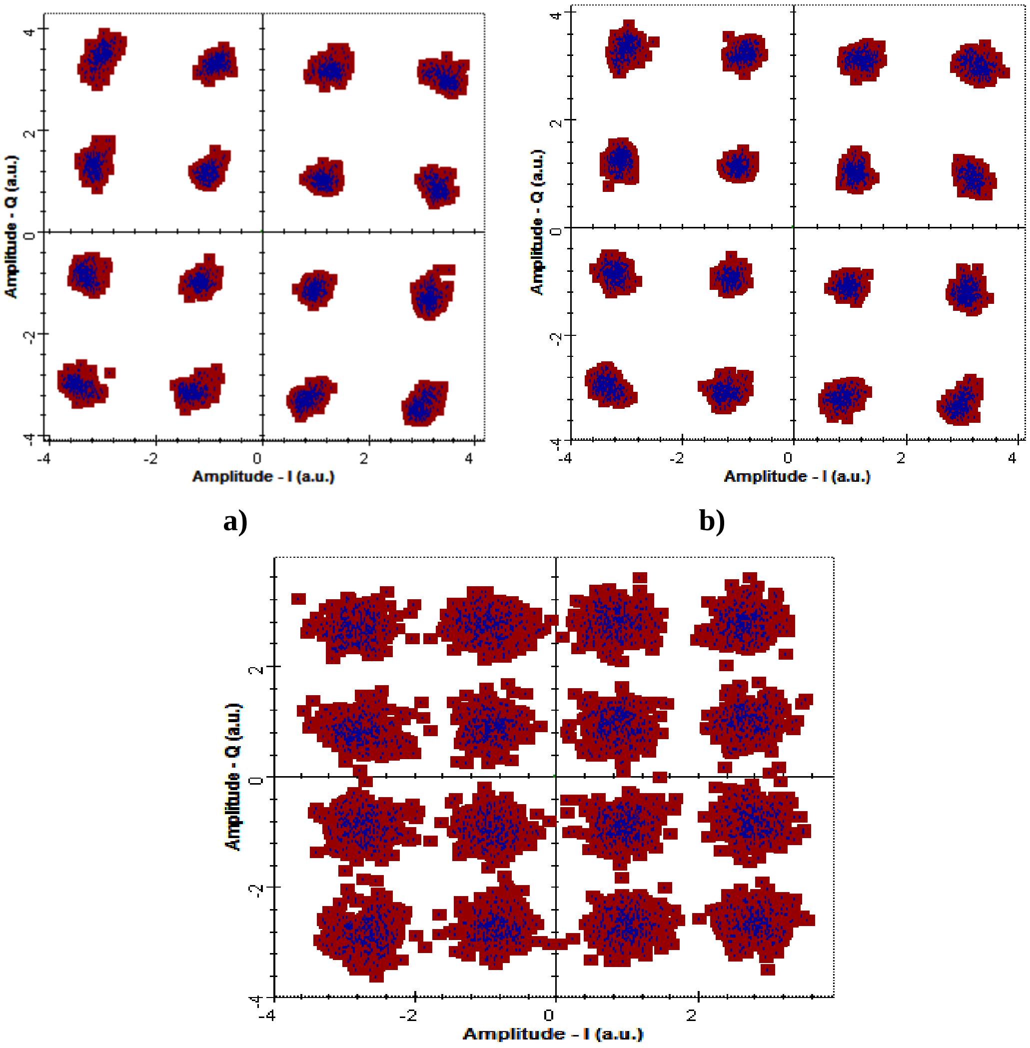
c)

Figure 5.24: Modulated optical signal for 16QAM 128, 256, 1024 subcarriers

a) 128 subcarriers, b) 256 subcarriers, c) 1024 subcarriers

In Figure 5.25 the final or result constellation diagram at receiver side is shown for all forms of QAM which are discussed above, the best constellation diagram is for 16QAM 128 subcarrier and 256 subcarrier.

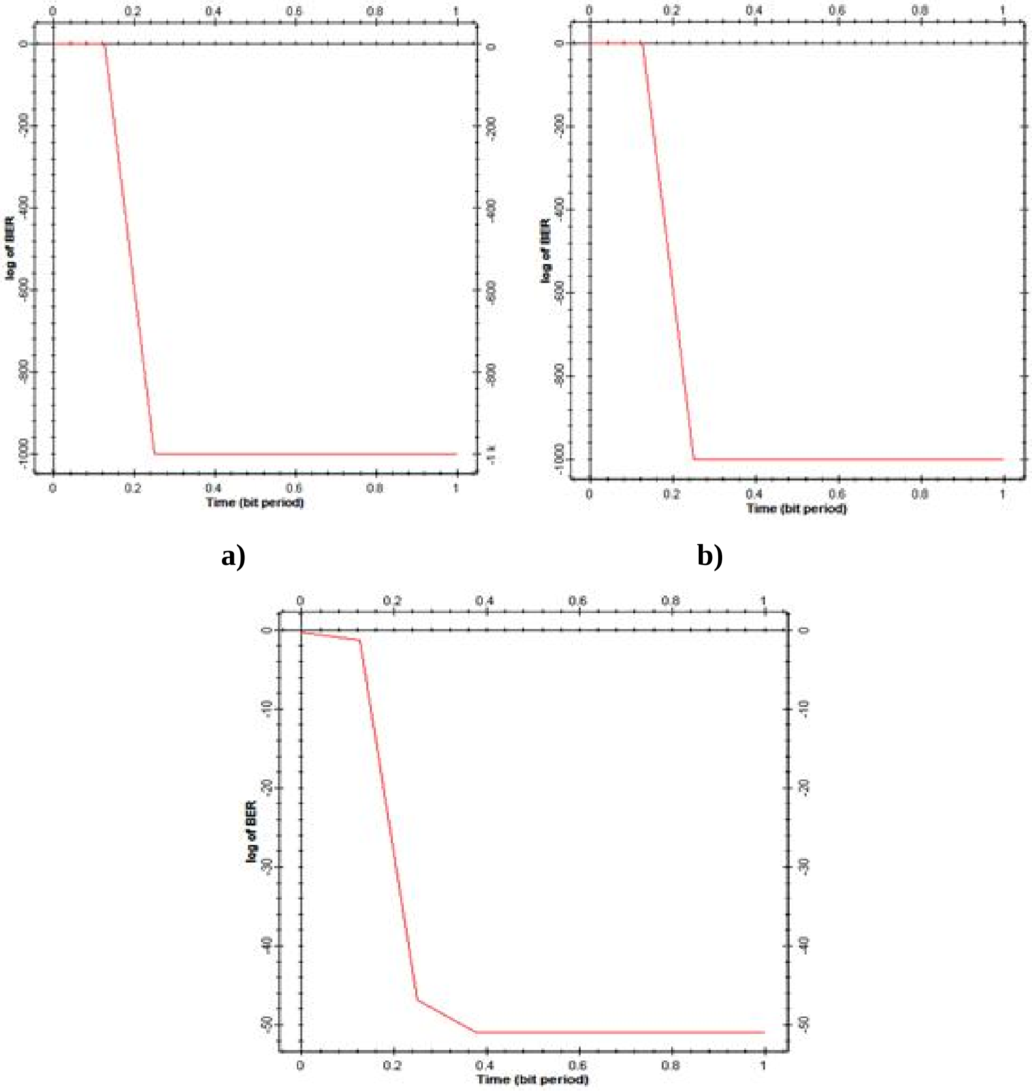
However 16QAM 1024 subcarrier has worse result this result will be shown clearly in Figure 5.26c as a result of Min BER of value 1.09×10^{-51}, this result because of the data close to each other and then the percentage of error increased, but this result is very suitable because the best result of Min BER at minimum of 10^{-12} [2].



a) **b)**

c)

Figure 5.25: Final constellation diagram for 16QAM 128, 256, 1024 subcarriers a) 128 subcarriers, b) 256 subcarriers, c) 1024 subcarriers



a) **b)**

c)

Figure 5.26: Min BER for 16QAM 128, 256, 1024 subcarriers a) 128 subcarriers, b) 256 subcarriers, c) 1024 subcarriers

5.6 64QAM-OFDM RoF System Simulation Results

In 64QAM-OFDM RoF system the bit generator will generate a sequence of 0 and 1 of NRZ form signal with 16384 bits, then those bits encoded with 64QAM decoder, which will use 6 bit per symbol with 512 subcarriers. All of the figures below from Figure 5.27 to Figure 5.33 describe the results of simulations.

5.6.1 The Transmitter Model Simulation Results

The result for the transmitter part which is in electrical, frequency and optical domain was shown in the figures below from Figure 5.27 to Figure 5.30, these results show the constellation diagram for 64QAM encoder output, time and frequency domain OFDM signal, the laser signal, the signal after MZM modulator.

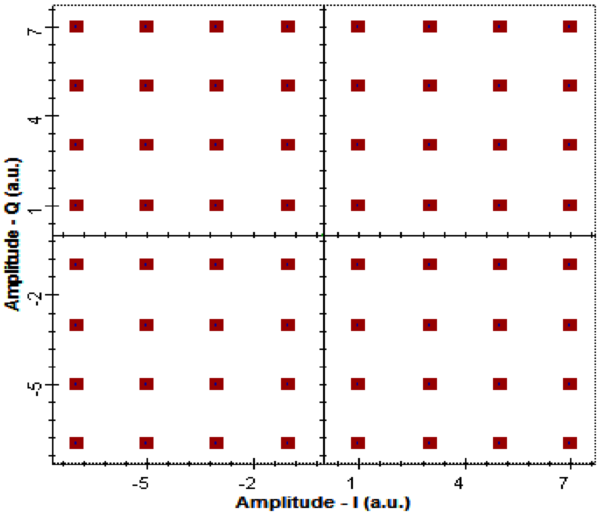
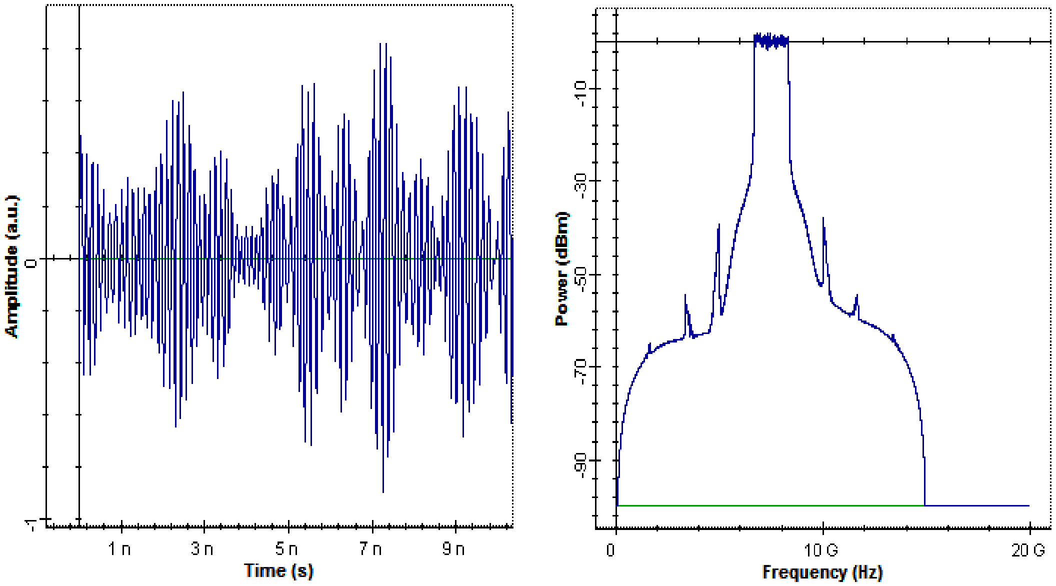


Figure 5.27: 64QAM Encoder Constellation Diagram.



a) **b)**

Figure 5.28: OFDM Signal. a) Time Domain, b) Frequency Domain.

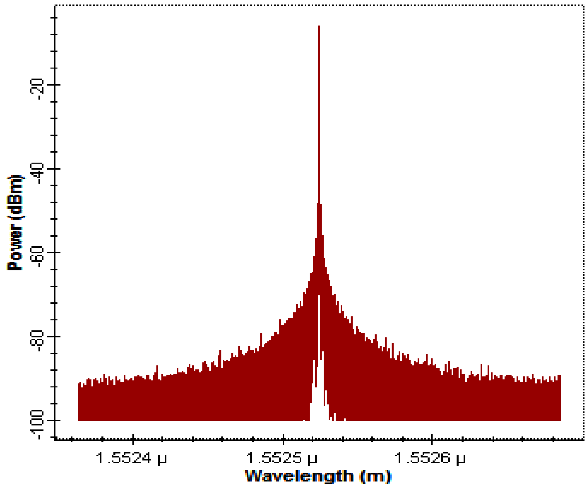
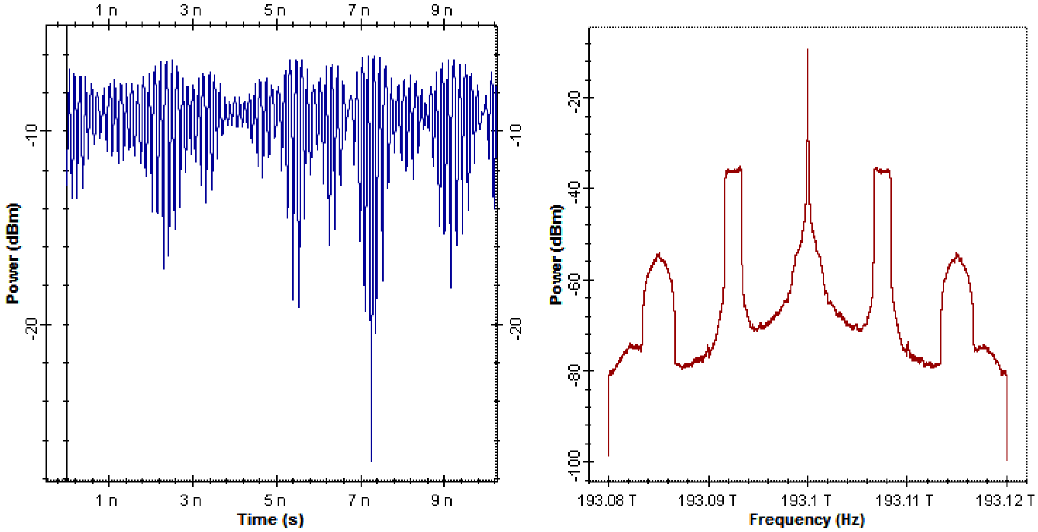


Figure 5.29: Laser Signal with central frequency 193.1 THz.



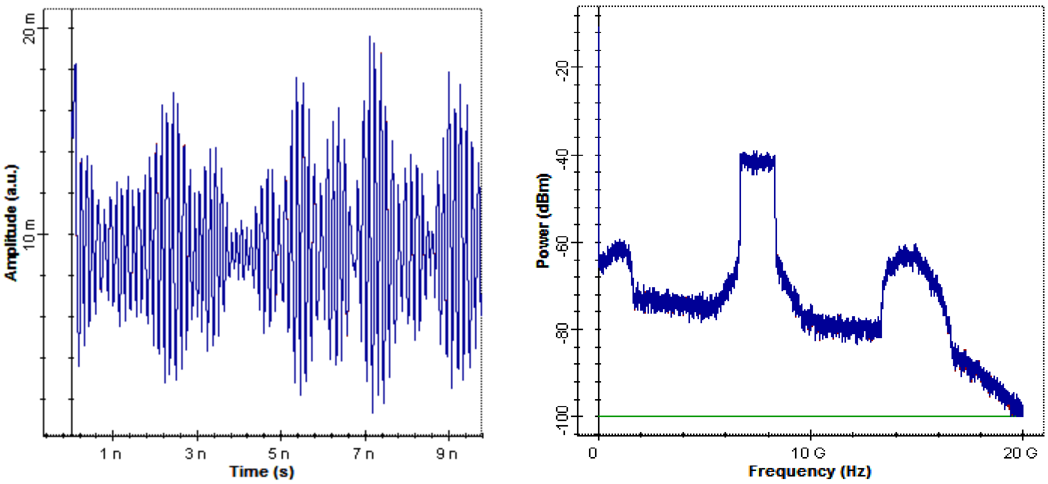
a) **b)**

Figure 5.30: Modulated optical Signal. a) Time Domain, b) Frequency Domain.

5.6.2 The Receiver Model Simulation Results

The result for the receiver part which is in electrical, frequency and optical domain was shown the figures below Figure 5.31 and Figure 5.33, these results show the received signal, output constellation diagram and Min BER.

In Figure 5.33 the 64QAM 512 subcarrier a result of Min BER of value 60.43×10^{-27} and this result is very suitable because the best result of Min BER at minimum of 10^{-12} [2]. In 64QAM, the increasing of Min BER when the number of subcarrier increases because the bandwidth congested with data which will be close to each other and then the percentage of error increased.



a) **b)**

Figure 5.31: Received signal after PD. a) Time Domain, b) Frequency Domain.

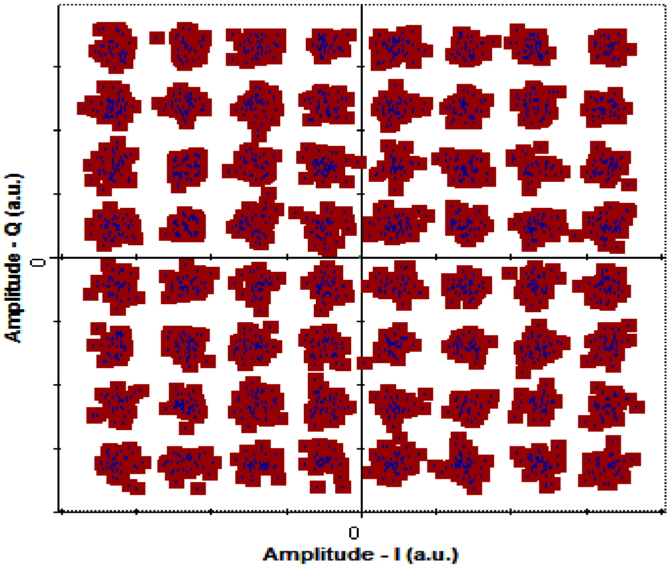


Figure 5.32: Final 64QAM Decoder Constellation Diagram.

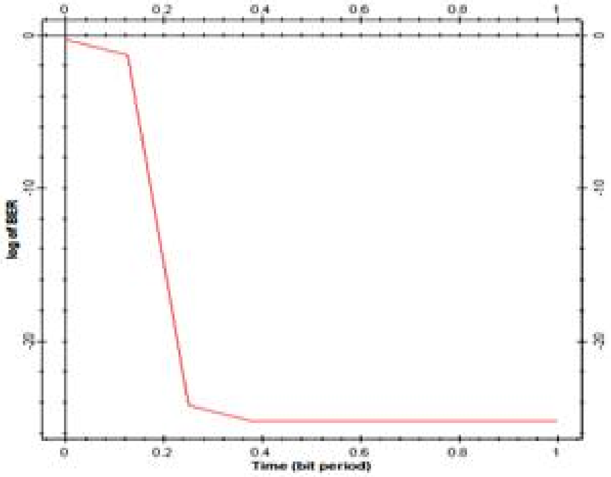


Figure 5.33: Min BER for 64QAM.

5.7 Summary

In this chapter an OptiSystem software and its applications and analysis tools is described, a brief description and explanation of the basic theory about QAM technique to generate the OFDM symbols are presented and discussed, the OFDM-RoF system model is described and all parts of it such as transmitter, receiver and optical link is explained and discussed, the 4QAM OFDM, 16QAM OFDM with 128, 256, 512 and 1024 subcarriers, 64QAM are explained with brief descriptions. 64QAM OFDM simulation results are shown.

In this chapter the best value for Min BER is zero is verified in all QAM system which are explained in previous sections, but in the 16QAM with 1024 subcarriers and 64QAM 512 subcarrier a result of Min BER of value are 1.09×10^{-51} and 60.43×10^{-27} respectively. The increase of Min BER in 16QAM and 64QAM because when the number of subcarrier increases the data will be close to each other and then the percentage of error will increase, and this result is very suitable because the best result of Min BER is a minimum of 10^{-12}.

References

[1] http://www.optiwave.com/products/system_overview.html

[2] Agrawal, G. P. (2012). Fiber-optic communication systems (Vol. 222). Wiley.

6

Conclusion and Future Work

6.1 Conclusion

RoF is a very effective technology for integrating wireless and optical access. It combines the two media; fiber optics and radio, and is a way to easily distribute radio frequency as a broadband or baseband signal over fiber. It utilizes analog fiber optic links to transmit and distribute radio signals between a central CS and numerous BSs. In this sense RoF is a promising technology for future high-capacity and broadband multimedia wireless services.

In this Master Thesis, a revision of basic concepts regarding radio over fiber (RoF) and orthogonal frequency division multiplex (OFDM) have been carried out using the OptiSystem software as a tool to develop system simulations. The goal of this study has been the adaptation of these concepts into the special characteristics offered by optical systems.

With the combination of the advantages from OFDM and RoF, the system can be used for both short distance as well as long haul transmission at very high data rate. This improves the system flexibility and provides a very large coverage area of telecommunication networks without increasing the cost and complexity of the system very much. Also recently, it has been proved by many researchers that OFDM is better compared to the conventional single carrier modulation for long haul optical transmission.

In this thesis the optical OFDM RoF system were modeled for many applications, in this project it used frequency carrier 7.5 GHz. The data rate of the system is 10 Gbps with modulation type 4QAM, 16QAM and 64QAM with different number of subcarriers. The length of the fiber for transmission link are 100 Km. this model is designed and simulated to achieve the best value of BER. The best value of Min BER is zero is achieved and it is verified in all QAM system, but in the 16QAM with 1024 subcarriers and 64QAM 512 subcarrier a result of Min BER of value are 1.09×10^{-51} and 60.43×10^{-27} respectively.

These results caused by the number of subcarrier increases with increases of order of QAM mapping the bandwidth will congest with data which will be close to each other and then the percentage of error will increase. Although that increases of Min BER, the result is very suitable because the best result of Min BER is a minimum of 10^{-12}.

The software OptiSystem has been used as the tool to contrast all the acquired knowledge on optical OFDM in a simulation scenario. Six demonstration simulations offered in this thesis have been tested in order to understand the role of each parameter within the system and the effects resulting from changing their value.

6.2 Future Work

The main results of this Thesis have been very efficient and user-friendly scenarios for the analysis of optical OFDM systems using direct detection (DD) techniques. Similar studies that consider more advanced optical OFDM systems, based on optical IQ modulation and coherent detection, are found of interest for future works.

A MatLab code implementing the OFDM coder and decoder functions will program in OptiSystem to execute the modulating and demodulating functions for the OFDM signal in the optical OFDM system.

The system could have an improvement by occupying the WDM (Wavelength Division Multiplexing) technique, so it would be OFDM-WDM modulation for RoF. This kind of system could provide more bandwidth efficient and manage traffic communication better.

The OFDM RoF system could have an improvement by using coded OFDM system and used coded modulation such as Trellis and Block coded modulation which is a technique to combine the channel coding and modulation for multi-level modulation.