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DESIGNING OPTICAL FIBER TO THE HOME (FTTH) NETWORKS BY USING HYBRID TECHNIQUES

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Supervisor Certification

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صدق الله العلي العظيم

[طه: 114]

ABSTRACT

Optical networks can support the huge increasing of demands for high speed connections suitable to the modern customer requirements in a high-reliable and cost-efficient manner. In this thesis, hybrid systems of OCDMA and OTDM have been proposed to increase the number of simultaneous users. In the last decade, Fiber-to-the-Home (FTTH) networks witnessed great public acceptance worldwide. To satisfy future demands, existing FTTH access networks must be modified. To achieve this purpose, a new FTTH architecture based on high bit rate TDM-OCDMA-PON hybrid system increasing the network scalability has been designed and simulated.

In order to increase the number of users, an OCDMA encoder/decoder technique employing two orthogonal polarization states of 2D code has been investigated. Both the polarization and wavelength scheme (P/W) are included in this 2D code. In addition, optical fiber systems (OFS) and free space optics (FSO) scenarios are utilized with some of incoherent spectral amplitude coding OCDMA (SAC-OCDMA) codes. These codes are Multi-Diagonal (MD) and Zero Cross Correlation (ZCC) codes. Whereas, they are selected due to reducing the effect of Multi Access Interference (MAI) which is considered the most important factor of noise and interference in a SAC-OCDMA.

TDM-PON is considered a good solution for a high bit rate and a flexible bandwidth system. In the present thesis, the simulation of a high speed bit-interleaving TDM transmitter has carried out. The proposed scheme of FTTH downstream is based on single Mach–Zehnder modulators (MZM) and single laser diode to carry electrical multiplexed data. In addition, different bit rate of TDM-PON has been simulated in different scenarios. To simulate those systems the Optisystem V.15 software package has been utilized.

The results of the OCDMA system show that the number of the total supported of simultaneous users for the 2D codes is doubled in comparison with 1D codes. Besides, the simulation results show the performance of the MD code is better than ZCC in both OFS and FSO scenarios. Next, the results of TDM-PON system show that the electrical multiplexed TDM transmitter provides better performance than the traditional optical TDM transmitter in different scenarios with different bit rates. Finally, the results of OTDM-OCDMA hybrid FTTH system demonstrate that this system can make a considerable increase in the network scalability by increasing either time slots or OCDMA codes numbers.

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LIST OF ABBREVIATIONS

Symbol	Description
1D	One-Dimensional
2D	Two-Dimensional
a.u	Arbitrary Units
AON	Active Optical Network
APON	Asynchronous Transfer Mode over Passive Optical Network
AS	Active Star
AWG	Arrayed waveguide grating
BER	Bit Error Rate
BIBD	Balanced Incomplete Block Design
Bi-PON	Bit Interleaving PON
BPON	Broadband Passive Optical Network
BW	Bandwidth
CAGR	Compound Annual Growth Rate
CDMA	Code Division Multiple Access
CO	Central Office
CW	Continuous Wave
CWDM	Coarse Wavelength Division Multiplexing
DCF	Dispersion Compensating Fiber
DGD	Differential Group Delay
DLC	Digital Loop Carrier
DM	Material Dispersion
DPSK	Differential Phase Shift Keying
DSLAM	Digital Subscriber Loop Access Multiplexer
DT	Total Dispersion
DW	Waveguide Dispersion
DWDM	Dense Wavelength Division Multiplexing
EDB	Electrical Duobinary
EDFA	Erbium Doped Fiber Amplifier
EMI	Electromagnetic Interference
EPON	Ethernet Passive Optical Network
FBG	Fiber Bragg Gratings
FPLD	Fabry–Perót Laser Diodes
FSAN	Full Service Access Network
FSO	Free Space Optics
FTTB	Fiber-to-the-Building
FTTC	Fiber-to-the-Curb

FTTCab	Fiber-to-the-Cabinet
FTTH	Fiber-to-the-Home
FTTP	Fiber-to-the-Premises
FTTx	Fiber-to-the-x
FWM	Four-Wave Mixing
Gbps	Giga bit per second
GE-PON	Gigabit Ethernet PON
GPON	Gigabit Passive Optical Network
HC	Hybrid-Coded
Hz	Hertz (Cycle per second)
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IPTV	Internet Protocol TV
ISI	Inter-Symbol Interference
ITU-T	International Telecommunication Unit-Telecommunication
Km	Kilometer
KS	Khazani-Syed
Laser	Light Amplification by Stimulated Emission of Radiation
LCP	Local Convergence Point
LED	Light Emission Diode
LoS	Line of Sight
LPF	Low-Pass Filter
MAI	Multiple Access Interference
Mbps	Megabit per second
MD	Multi-Diagonal
MDRZ	Modified Duobinary Return to Zero
MDW	Modified Double Weight
MFH	Modified Frequency Hopping
MMF	Multimode Fiber
MQC	Modified Quadratic Congruence
MUX	Multiplexer
MZM	Mach-Zehnder Modulator
NDF	Negative-Dispersion Fiber
NG-PON	Next Generation-PON
NRZ	Non-Return-to-Zero
OCDMA	Optical Code Division Multiple Access
ODB	Optical Duobinary
ODN	Optical Distribution Network
OFDM	Orthogonal Frequency Division Multiplexing
OFS	Optical Fiber Systems
OLT	Optical Line Terminal
ONT	Optical Network Terminal

ONU	Optical Network Unit
OOK	On-Off-Keyed
OTDM	Optical Time Division Multiplexing
P/W	Polarization/Wavelength
PAM-4	Quaternary Pulse Amplitude Modulation
PAPR	Peak-to-Average Power Ratio
PIIN	Phase Induced Intensity Noise
PMD	Polarization Mode Dispersion
PON	Passive Optical Network
PRBS	Pseudo Random Bit Sequence
PtMP	Point-to-Multi-Point
PtP	Point-to-Point
Q-Factor	Quality Factor
QoS	Quality-of-Service
RD	Random Diagonal
RN	Remote Node
RoF	Radio over Fiber
RTT	Round-Trip Time
RZ	Return to Zero (line encoding)
SAC-OCDMA	Spectral Amplitude coding- OCDMA
SBS	Stimulated Brillouin Scattering
SCMA	Subcarrier Multiple Access
SMF	Single Mode Fiber
SNR	Signal-to-Noise Ratio
SPC-OCDMA	Spectral Phase Code- OCDMA
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
SSMF	Standard Single-Mode Fiber
SWZCC	Single Weight Zero Cross Correlation
TDMA	Time Division Multiple Access
TDM-PON	Time Division Multiplexing - Passive Optical Network
TOF	Tunable Optical Filter
TPC-OCDMA	Temporal Phase Coded OCDMA
TWDM-PON	Time and Wavelength - Passive Optical Network
VoD	Video on Demand
WDM	Wavelength division multiplexing
WH/TS	Wavelength-Hopping Time-Spreading
XG-PON	10 Gigabit Passive Optical Network
XPM	Cross-Phase Modulation
ZCC	Zero-Cross Correlation
ZDW	Zero Dispersion Wavelength
ZMD	Zero Material Dispersion

NOMENCLATURES

Symbol	Definition	Unit
B	Electrical bandwidth	MHz
d_R	receiver aperture diameter	m
e	Electron charge	C
h	Planck's constant	Js
I	photocurrent	mA
K	number of simultaneous homes	---
K_b	Boltzmann's constant	J/K
N	Number of OTDM channel	---
P_i	input optical power	watt
P_o	output optical power	watt
P_{sr}	Broadband effective power	dBm
$\Re$	photodiode responsively	A/W
R_L	Receiver load resistor	Ω
T_n	Receiver noise temperature	K°
v_c	Operating wavelength	nm
Z	temporal positions	---
τ	interpulse width	nsec
	Greek Symbols	
α	Atmospheric Attenuation	dB/km
Δv	Linewidth broadband source	THz
η	Photodetector quantum efficiency	---
θ	Beam Divergence	mrad
λ	Wavelength	μm
λc	in-phase cross correlation	---
σ^2	optical detector noise variance	$(watt/Hz)^2$
σ_{sh}	beat noise	watt/Hz
σ_{th}	thermal noise	watt/Hz

LIST OF PUBLICATIONS

“Performance Analysis of High Speed Bit-Interleaving Time-Division Multiplexing Passive Optical Networks (TDM-PONs)”, Journal of Physics: Conference Series, World Engineering, Science and Technology Conference 2019, “accepted”.

“Evaluation Performance of Two-Dimensional Multi-Diagonal Code Using Polarization and Wavelength of OCDMA System”, International Journal of Engineering & Technology, “accepted”.

CHAPTER ONE

INTRODUCTION

1.1 Background

The huge demand for a larger capacity of network traffics and the expected growth in the near future have led many operators to find out and establish networks based on fiber optical access instead of other technologies. The optical networks system can ensure a good performance for such a system of large number of users.

The worldwide Internet activity was 100 GB per day in 1997, while in 2016 the Internet activity was about 26,600 GB per second. According to Cisco expectation, the anticipated expansion of the Internet activity in 2021 will be 105,800 GB per second, where the expected consumption of the Internet for each household is about 155 GB per month [1].

Smartphones and tablets play an essential role in changing the way of consuming media. With the rise of mobile TV, video-on-demand (VoD) services and high definition gaming … etc. Consequently, user interests have completely changed, where the most important denominator to cancel their interest to cable-based broadcast television services and depend rather on Internet-based media services. Figure 1.1 projects the increment in worldwide IP traffic between 2016-2021 [1].

In recent years, the explosion of the Internet of Things (IoT), smart home and cloud services have changed the lifestyle of the Internet user. Smart home sensors, wearable devices, health monitors, security systems, cars, electronic appliances, speaker systems, vending machines and hundreds of other objects, being connected to the internet every day, which require more analyses and storage.

Therefore, cloud with its computing and data storage can be a solution for those issues, but this means that more capacity and scalable network must be provided [2].

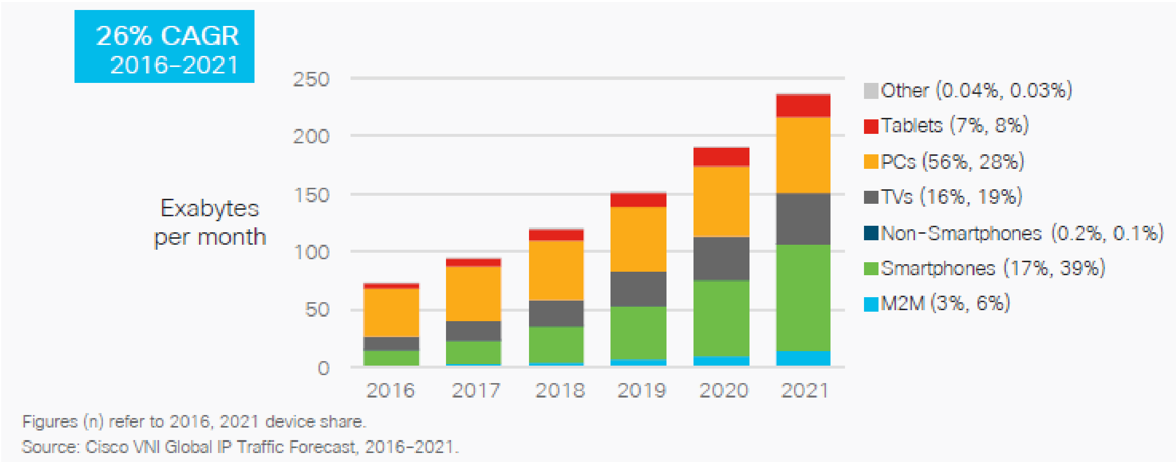


Fig. 1.1: Global internet traffic by device type, where the compound annual growth rate (CAGR) is 26%, 2016-2021, adapted from [1].

1.2 Motivation

A good performance communication system for large number of users and high quality services access become a purpose objective of each operator. End-to-end fiber can undoubtedly meet such service levels. Furthermore, in the end-to-end, fiber will offer the capacity to higher data rate without key changes. Fiber-based access systems are a future-proof novel solution that can easily provide the anticipated increase in data rate for end-clients in addition to several advantages that are offered by optical fiber technology, such as high security, reliability and long distance access [3].

The development of optical networks is essentially based on the maximum utilization of bandwidth of fiber optics using different access techniques. A hybrid model is based on combining two or more multiple access techniques which leads to increasing the number of users in the FTTH networks.

1.3 Problem Statement

The limitations of current mediums, such as digital subscriber line (DSL), drive the researchers to investigate in FTTH network as an alternative solution. Optical code division multiple access (OCDMA) technique has been considered, by many researchers, as a good solution for high bandwidth network. In this thesis hybrid systems of OCDMA and optical time division multiplexing (OTDM) have been proposed to increase the number of simultaneous active homes in the FTTH network. To achieve that, the OCDMA system should be designed with maximum number of codes at high bit rate transmission where more OTDM channel can be used by sharing this bandwidth.

1.4 Thesis Objectives

The main objectives of this work are:

1. Designing and simulating a high performance FTTH network offers an increasing in the number of homes while ensuring sufficient data rate and low bit error rate by using OptiSystem simulation tool v.15.

2. Carrying out the simulated design of OCDMA system based zero cross-correlation SAC-OCDMA and investigate a new method ensuring larger number of OCDMA users.

3. Designing and simulating a high speed bit-interleaving TDM-PONs.
4. Demonstrating several hybrid approaches that combine OCDMA and OTDM.
5. Discussing the effect of increasing the optical link distance on the systems performance.

1.5 Scope of Study

Optical fiber communication techniques have many interesting aspects to study. Figure 1.2 shows the scope of this study model in order to provide the entire picture of research scope with simplify approach. This flow chart describes the relationship of the main topics in optical fiber communication field and the research work focusing in this thesis, where the solid items refer to the main points which have been focused by this thesis.

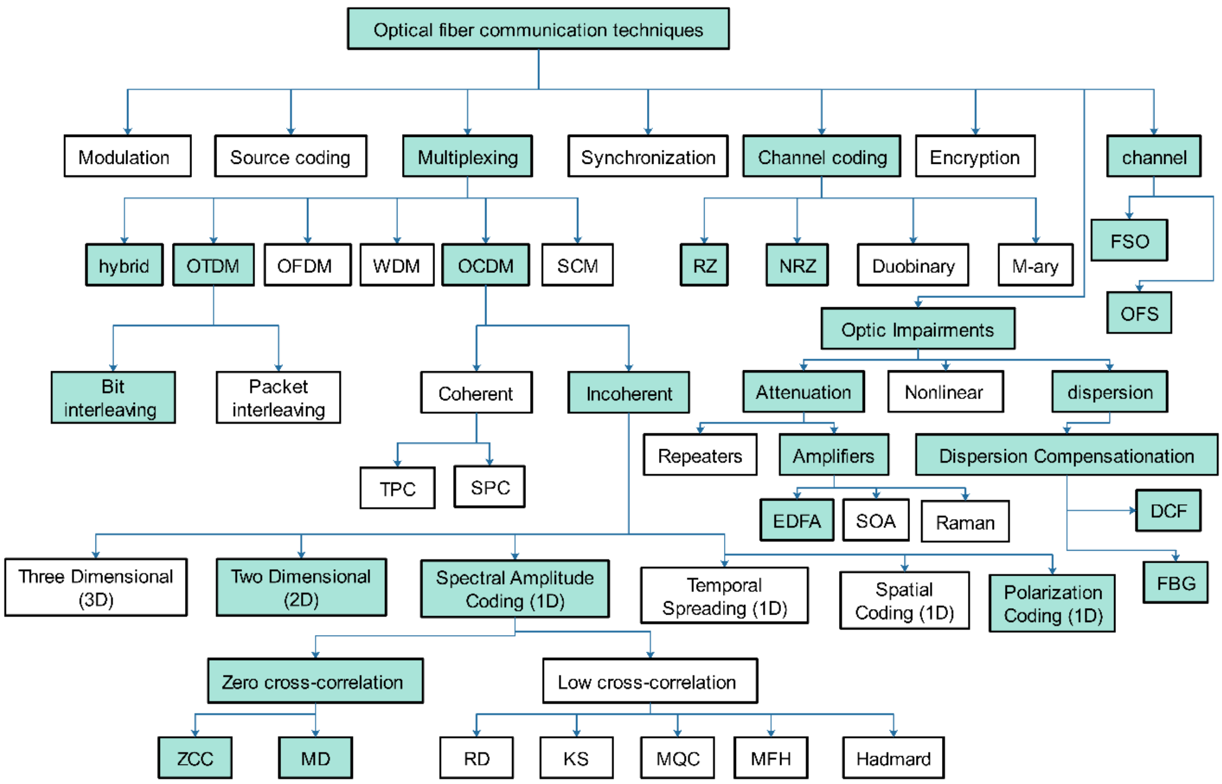


Fig. 1.2: Scope of study

1.6 Brief Method

Figure 1.3 shows the brief method of this work. Where there are three main topics: the OCDMA system, the OTDMA system and the combination system between those two techniques.

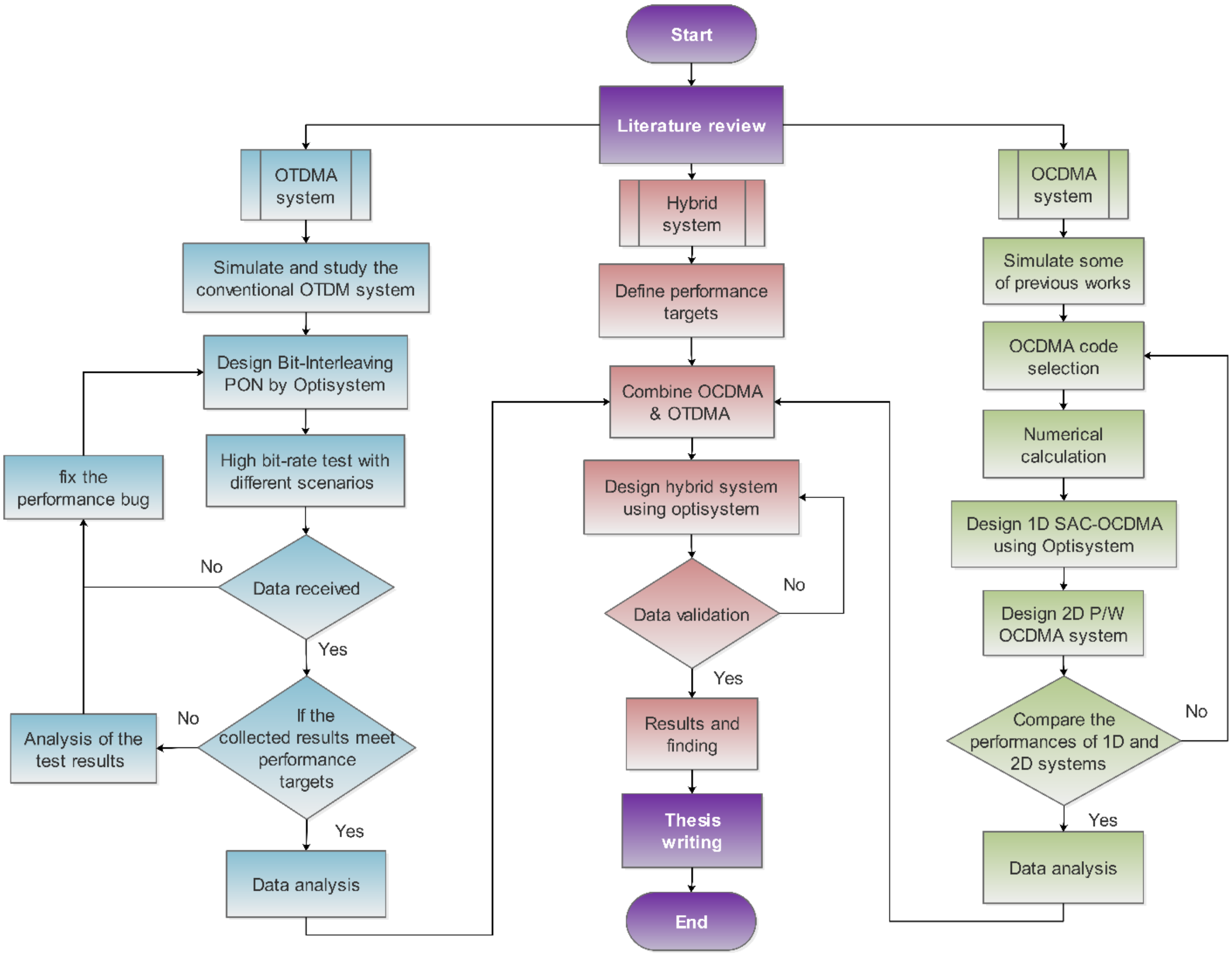


Fig. 1.3: Brief method

1.7 Thesis Contributions

1. A comprehensive study has been carried out on zero cross-correlation SAC-OCDMA 1D and 2D (polarization/wavelength). A 2D-MD OCDMA system design has been proposed and demonstrated.
2. Simulation of a bit-interleaving TDM transmitter has been carried out.
3. A FTTH model based on TDM-OCDMA-PON hybrid system increasing the network scalability has been proposed and demonstrated.

1.8 Thesis Organization

Chapter 1 presents the background, motivation of the researches, problem statement, scope of study, thesis objectives, brief method, main contributions and the layout of this thesis.

Chapter 2 is an overview including active and passive optical network topologies, the development of FTTH systems, types of optical based networks, PON standardizations, multiplexing techniques and FTTH access network architecture, including network components, various optical channels, optic impairments, optical amplifiers, dispersion compensation techniques and a literature survey of the related works.

Chapter 3 sheds light on the design and simulation of OCDMA system, TDM-PON system, and new architecture for increasing network scalability using OCDMA-TDM-PON hybrid system.

Chapter 4 provides the results and the discussion of the theoretical and the simulated systems that have been designed.

Chapter 5 concludes this thesis and offers suggestions for future work.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Telecommunications network generally consists of three main subnetworks: backbone/long-haul, metro/regional and access network. Optical fiber link has commenced involving into the telecommunications network in the backbone network where the large capacity is needed. With the phenomenal increase in the demand by the modern subscribers, the optical fiber goes farther toward the access segment of the network. The optical networks provide a number of extremely attractive advantages: enormous bandwidth, data security, electrical isolation, immunity to interference and crosstalk, low transmission loss, system reliability and potential low cost of the links [4].

Optical networks, like other communication systems, have different topologies. Star, ring, linear bus, and mesh are the most common topologies used for optical communication. Star configuration connect all nodes to a single point at the center of the network. Similar to other communication systems, ring topology connect nodes together point-to-point sequentially forming a close single path. As linear bus configuration, all nodes linked to a single backhaul cable via optical couplers. Finally, mesh architecture terminal devices are connected directly with each other by direct links. Figure 2.1 illustrates the four topologies [5].

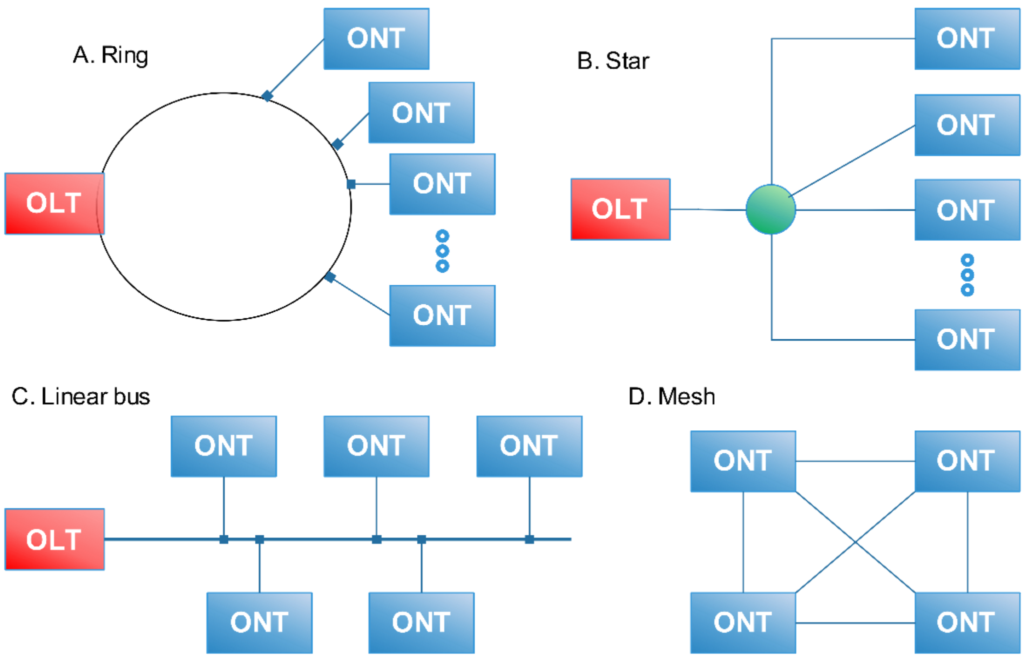


Fig. 2.1: Optical network topologies: A. Ring, B. Star, C. linear bus, and D. mesh. OLT: Optical Line Terminal. ONT: Optical Network Terminal

2.2 Development of Fiber-to-the-Home (FTTH) Systems

The first try of Fiber-to-the-Home (FTTH) (168 customers) network was established in 1977-Higashi-Ikoma, Japan by transferring video for a specific purpose [6]. During the 1980s, FTTH was developed for various trials and spread out crosswise over Europe like Milton-Keynes in England, Biarritz, France, Bigfon in Berlin, and North America, Japan and other places [7]–[13].

Many factors prevented the spread of this technology at that time. In fact, the cost was a key factor, which made the changing of the copper network that already exists by a more complex one like FTTH is a difficult decision, where the cost per subscriber is about $600 up to thousands of dollars depending on the distance [3]. The high cost is often due to the price of the fiber. The topology used required that each subscriber to be connected via single cable in a point-to-point (PtP) network, plus two transceivers, as in Fig. 2.2.

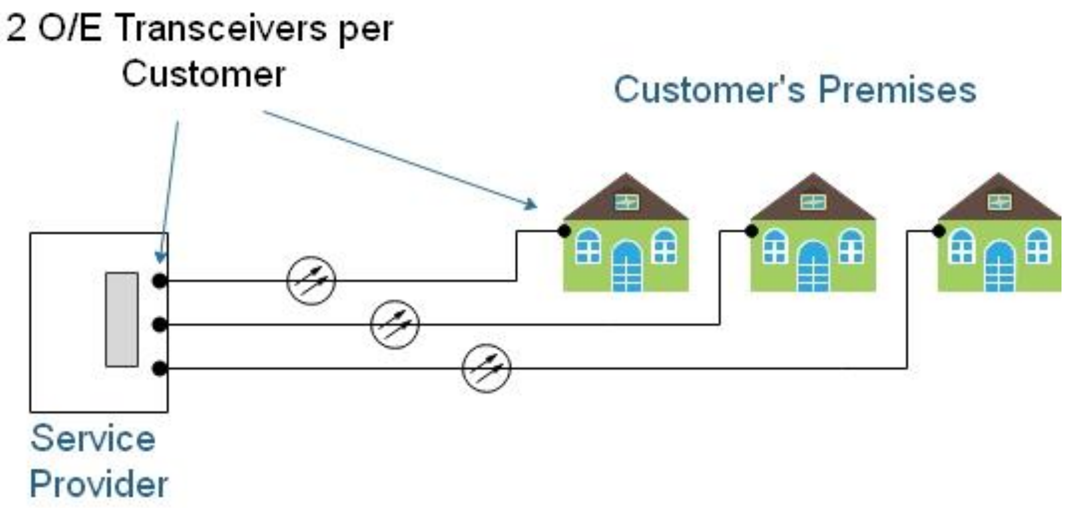


Fig. 2.2: point-to-point (PtP) network

At the beginning of the cost reduction journey, point-to-multipoint (PtMP) system was a great step, Fig. 2.3, as first use to Fiber-to-the-Curb (FTTC) or Fiber-to-the-Cabinet (FTTCab) PON solutions. The concept is to achieve a hybrid network with an optical back-haul access to provide a considerable capacity that is able to feed many network units, e.g. a radio base station or a Digital Subscriber Loop Access Multiplexer (DSLAM). FTTC was used first in the mid-1980s to enhance a Digital Loop Carrier (DLC) system replacing the metallic feeder cable by fiber from the telephone central office (CO) to the remote cabinets by multiplexing number of electrical signals in a single fiber. Demultiplexer was placed in the remote cabinets, then it delivered service to the client over twisted pair copper cables (with up to 96 subscriber lines) [14]. After that, the FTTC was moved closer to the customer making more cost reduction until the spreading of optical multiplexing techniques which played an essential role in FTTH system cost reduction.

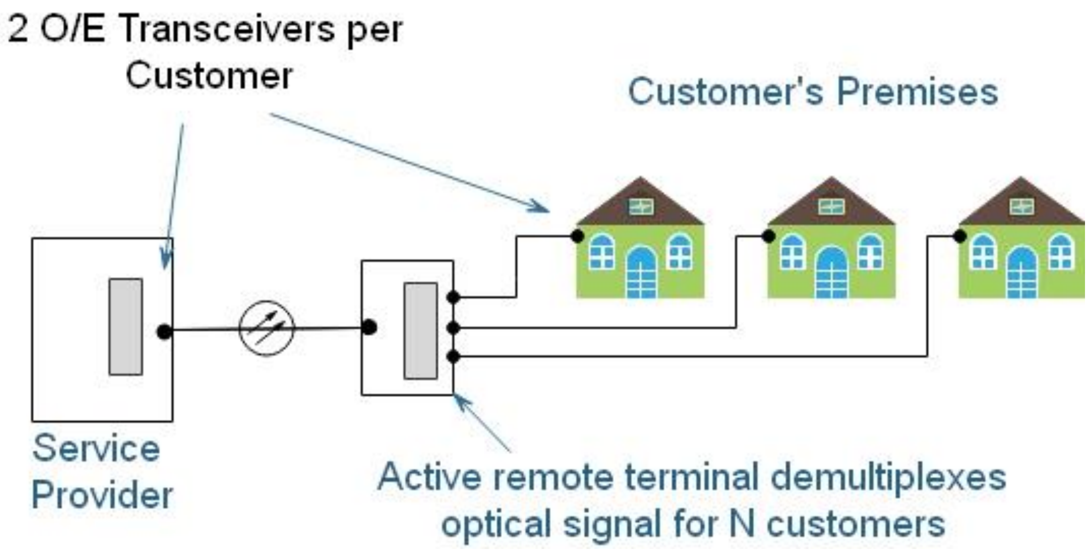


Fig. 2.3: Point-to-multipoint (PtMP) network

Fiber-to-the-Home/Building (FTTH/B), also called Fiber-to-the-Premises (FTTP), is the direct connection between a Local Convergence Point (LCP) and individual premises (such as residence houses, apartment buildings, businesses and service buildings) using optical fiber to provide future-proof ultra-high-speed access. FTTH is currently considered the most widespread communication technique, particularly in Asia and the Pacific area where about 77% of the overall networks is FTTP [15]. Fiber-to-the-Home (FTTH), Fiber-to-the-Building (FTTB), Fiber-to-the-Curb (FTTC), Fiber-to-the-Node (FTTN), and other different structures are gathered under name Fiber-to-the-x (FTTx). Figure 2.4 illustrates some types of FTTx.

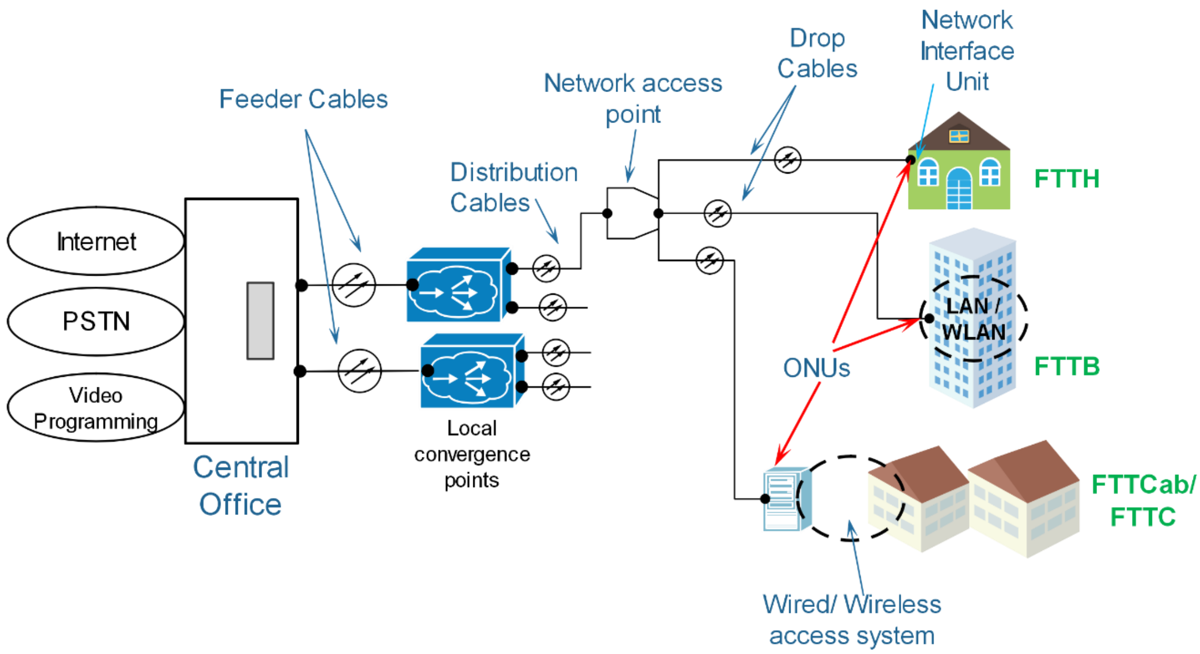


Fig. 2.4: FTTx fiber access alternatives with cable types and some terms are used to describe locations of the equipment.

2.3 Types of Optical Based Networks

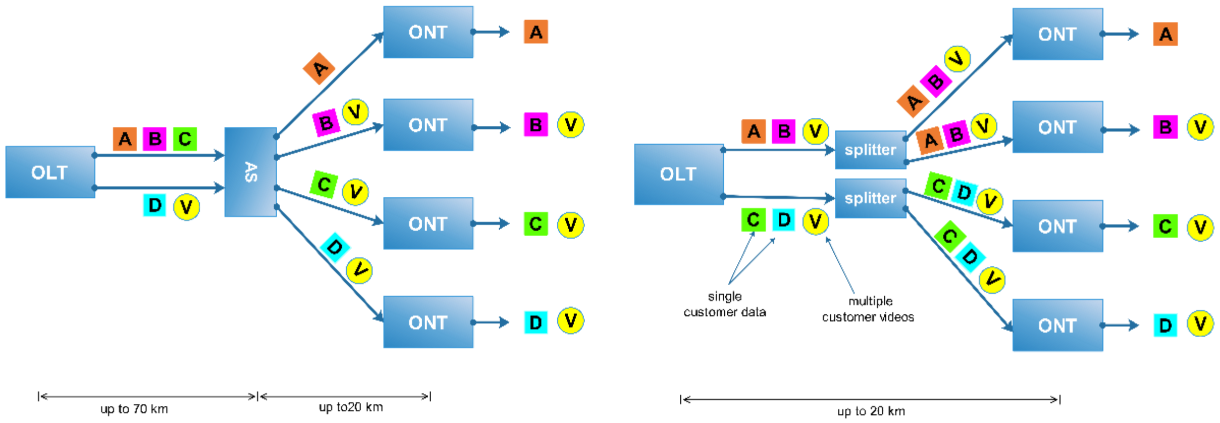
There are two main types of the optical networks: active optical network (AON) and passive optical network (PON).

2.3.1 Active optical network (AON)

AON, which also called active Ethernet, is the most deployed solution of FTTx networks in Europe and was standardized in 2005 [16]. There are two different infrastructures of AON: active star (AS) and PtP. The topology of the AS is point-to-multipoint, where active remote nodes (RNs) is utilized to connect the CO with various premises by a single fiber, as in Fig. 2.5A.

2.3.2 Passive optical network (PON)

Passive optical networks have no active device. It has the same layout of AS with replacing the active switch that needs electrical power by a passive optical multiport device (splitting/combining optical signals). The link between optical line terminal (OLT) and optical network unit (ONU) perform all transmission in PON. OLT is located at CO, while ONU resides at the end-user location. The main PON's feature is the all-optical distribution network (ODN), which is based on an optical splitter. This device is considered a sort of passive device with no need to any power supply or electronic device. Nowadays, the increment of PON that is used for commercial purposes concentrates on TDM-PON, WDM-PON and hybrid between both techniques [17].



(A) (B)

Fig. 2.5: A- Active Optical Network (AON), B- Passive Optical Network (PON)

There are several advantages to the wide use of PON over AON (both PtP and AS) [3]:

1. Costs are shared by K of ONUs that utilized the same fiber-feeder.
2. The cost of the power consumption of an AS is eliminated.
3. No need to outside-premises electrical power and high-energy standby batteries, where PON depends on completely passive nature.
4. Outside optoelectronic and electronic devices are not required, where the tough environmental.

5. The optical connection avoids electromagnetic interference (EMI) and the incompatibilities that may occur with copper conductors, as well as the noise from power converters.
6. The branch point is not bandwidth-dependent like AS; this permit future upgrades with minimal cost.

The combiner in PON (PtMP passive star topology) merges the data stream optically. Collision may occur when a traffic multiplexing is done by passive optical power combiner. To avoid that collision, a multiple access technique should be added to develop PONs [18].

2.4 PON Standardization

A large production volume can be achieved by sharing a common design accessible from multiple suppliers. It meet with the requirements of several large network providers and cost reductions. Seven major European and Japanese telecom providers met in 1995 with ten international manufacturers for this approach [3]. Later, the International Telecommunication Union - Telecommunications (ITU-T) cooperates with the Full Service Access Network (FSAN) Group to compose FSAN/ITU-T standards [19].

In the same manner, IEEE remarks that most of the data on the Internet is originating from an Ethernet source. Indeed, supporting Ethernet traffic in access networks is reasonable. Therefore, a first-mile group meeting was commenced in November 2000, and then Ethernet IEEE 802.3 standardization committee initiated a goal of drafting Ethernet standards for fiber-based access networks [20].

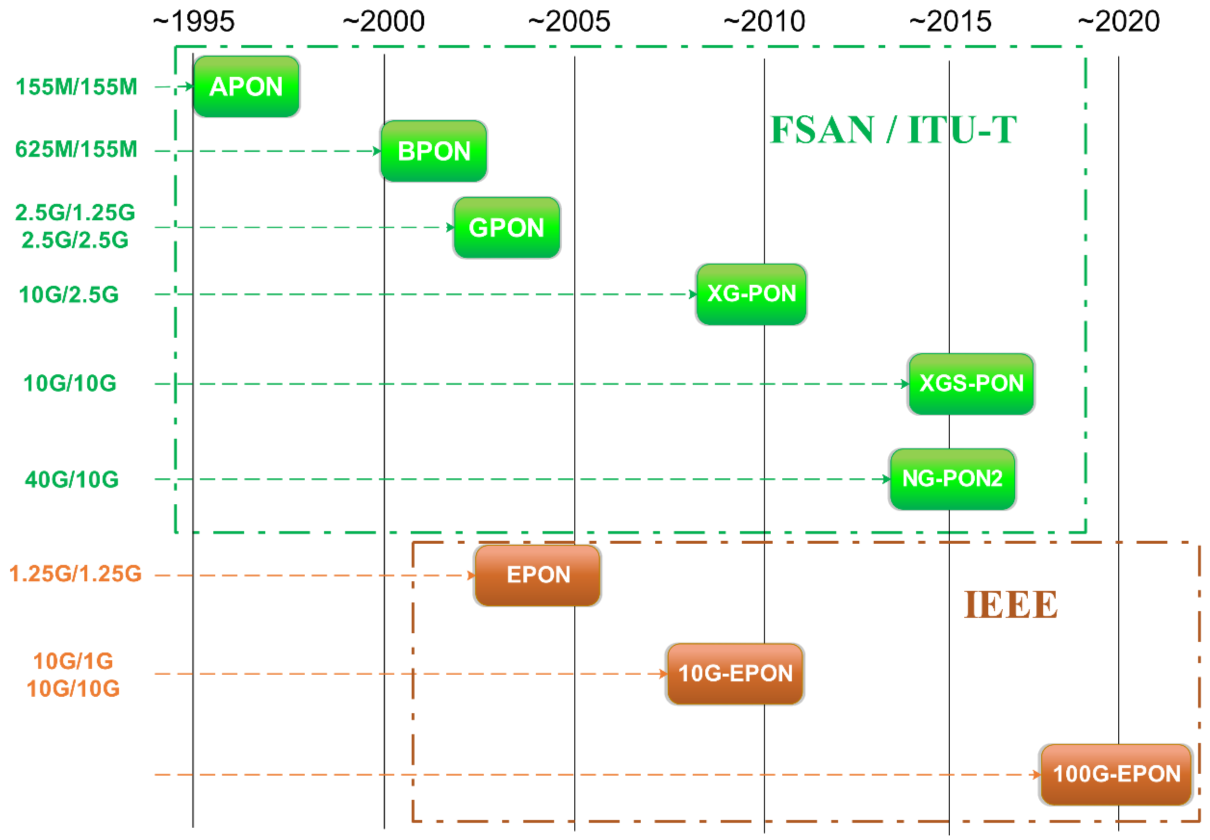


Fig. 2.6: PON evolution

Time division multiplexing (TDM) has been used for downstream and time division multiple access (TDMA) for upstream by both two bodies standard of PONs.

2.5 Multiple Access Techniques in PONs

In order to share a single fiber feeder by all ONUs, that terminate the branching fibers and send traffic upstream from individual ONU toward the OLT with a collision-free transmission, an appropriate multiple access technique(s) is(are) required. Three major multiple access categories have been developed for FTTH networks: time division multiple access (TDMA), wavelength division multiple access (WDMA) and optical code division multiple access (OCDMA).

2.5.1 TDM-PONs

Two methods are used for TDM-PON: the first involves packet interleaving while the second one involves bit interleaving.

2.5.1.1 Packet interleaving (Packet-by-Packet transmission)

The packet interleaving TDM-PON, where the number of bits are grouped together and targeted to a particular ONU, has been used for downstream by both two bodies standard (IEEE and FSAN/ITU-T) of PONs. In packet-by-packet transmission, data is sent to various users by a single downstream optical carrier in assigned slots form, as shown in Fig. 2.7. While the upstream packets of TDM system are sent from an ONU in an individual time slot at the combiner which requires careful synchronization at the ONUs, as shown in Fig. 2.8. To ensure collision-free transmission, the data of each ONU should be sent at the right time instantly. From a practiced point of view, there is a different relative distance between the ONUs and the OLT. Hence, the use of ranging protocols are essential. Round-trip time (RTT) can be used to sense this distance. In the OLT, a burst mode receiver is required which can handle different levels of the amplitude of the received packets (this amplitude fluctuation is due to the path loss experienced difference). Initially, with time division multiple access PONs (TDMA-PONs), as the ONUs are sharing the capacity of OLT, this capacity of each ONU decreases with an increase in the ONUs number. However, modern TDMA-PONs can adjust each optical network terminal (ONT) bandwidth dynamically depending on the demand of the customer.

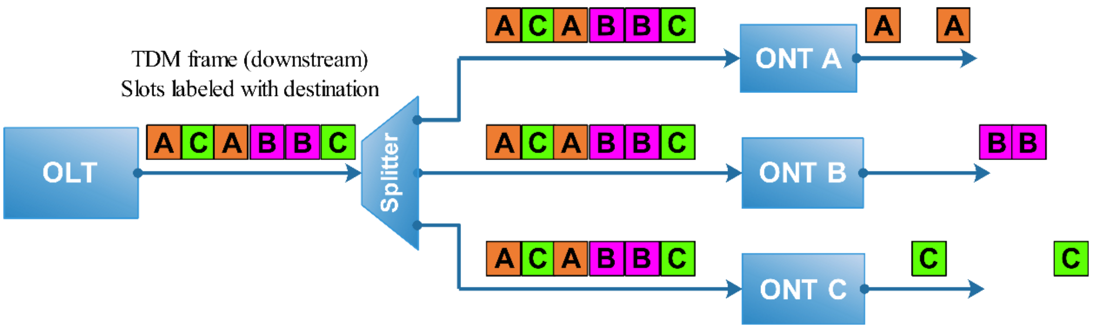


Fig. 2.7: Network Architecture of TDM-PON (downstream).

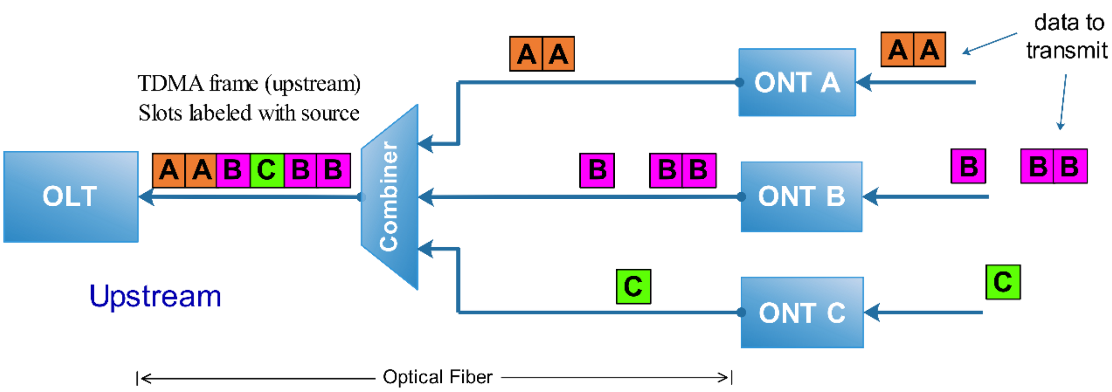


Fig. 2.8: Data Transmitting over TDMA-PON (upstream).

2.5.1.2 Bit interleaving (Bit -by- Bit transmission)

In the bit interleaving PON (Bi-PON) all information bits are reorganized in a form of bit-interleaved style according to the targeted ONUs in a regular structure frame, where each ONU can extract its own information easily in a simple periodic style. Bi-PON reduces the number of functional blocks which are necessary to operate at full line transmit. Hence, lower dynamic power consumption will be required in a Bi-PON ONU [21].

An optical power source, as illustrated in Fig. 2.9, generates the periodic pulse train of Bi-PON, and by using a splitter to split this pulse stream to K of pulses, then the encoded data signals will modulate over those light pulses by external modulator. Optical delay of iτ will delay each pulse train. If framing pulses are used, at that point, the interpulse width is $\tau = T/(n + 1)$ since n + 1 pulses should be transmitted in each bit period.

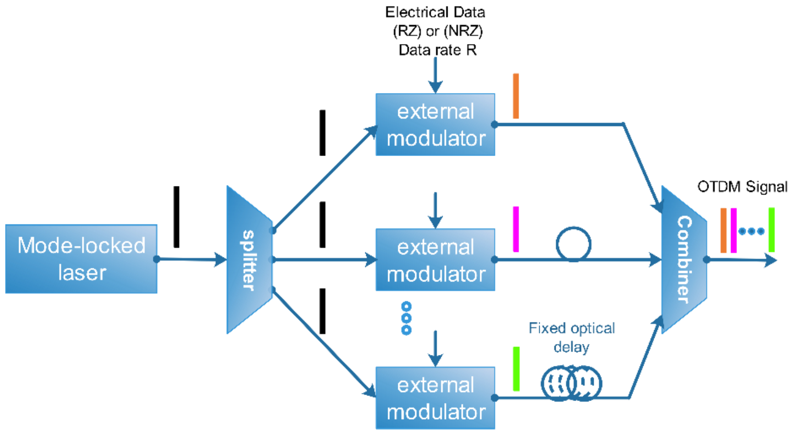


Fig. 2.9: Bit-Interleaved TDM-PON

2.5.2 WDMA or WDM-PONs

In the WDMA system, a dedicated wavelength is used for each ONU. Time synchronization is not needed. The power splitter/combiner in the WDM-PONs is usually replaced by array waveguide grating (AWG), which is wavelength selective filter (used to distribute correctly the routed wavelengths with symmetric bandwidth to each ONU and the CO) which existing a virtual point-to-point fiber transmission links (the users do not share bandwidth between them). Each one of those wavelength channels can be used for upstream and downstream simultaneously. The AWG power loss is much lower, so less power budget and the split ratio are required. For a dedicated wavelength of any ONU a specific laser diode is required. Thus this adds more cost and complexity [17].

WDM has two types: conventional/coarse wavelength-division multiplexing (CWDM) and dense wavelength-division multiplexing (DWDM). CWDM uses wider wavelength spacing, thus leading to fewer supported channels. Contrary to CWDM the DWDM system keeps the wavelengths tightly packed and usually is used for long haul transmission.

2.5.3 OCDMA PON

OCDMA is one of the approaches of NG-PON2 technology. In OCDMA, a unique orthogonal optical code word is assigned to each ONUs in order to distinguish this ONU from the others. There are two main types of optical CDMA techniques: coherent and incoherent. The coherent OCDMA codes use phase modulation, while the incoherent OCDMA codes are unipolar encoding systems that use amplitude modulation. With both techniques (during the high-speed OCDMA transceiver operations) the imperfectly orthogonal signature codes may occur. This may cause some crosstalk between users who share the common channel. This crosstalk is a kind of the multiple access interference (MAI). The noise of the source and MAI is considered the main source of bit errors. The reduction of the MAI is one of big challenges in order to make OCDMA more practical solution for FTTH systems.

2.5.3.1 Coherent OCDMA

The coding methods of the coherent OCDMA can be classified into two main categories: temporal phase coded OCDMA (TPC-OCDMA) and spectral phase coded OCDMA (SPC-OCDMA) [22]. The encoding of TPC-OCDMA systems is applied in the temporal domain. The source of these methods is a Z replication of short pulses (Z = temporal positions number in a bit period). Each copy is delayed by time space to lie on time grid by an equally spaced, and each of those copies is subjected to changing in the phase depending on the code sequence assigned for each user. While the encoding of SPC-OCDMA systems is applied in the spectral domain. A multi-wavelength source has been used for those systems with a unique phase code per user of each spectral component of those wavelengths.

2.5.3.2 Incoherent OCDMA

The incoherent OCDMA coding methods use the simpler, more standard techniques of intensity modulation with direct detection while coherent schemes are based on the modulation and detection of optical phase. The most common techniques of incoherent OCDMA for encoding/decoding are based on either spectral-amplitude, spatial, temporal spreading, two-dimensional (2D) or three-dimensional (3D) coding [23].

Spectral-amplitude coding OCDMA (SAC-OCDMA) is typically implemented by spectral decomposition of a broadband laser before the modulation step. SAC-OCDMA system may use cheap white light sources which can be affected by Phase Induced Intensity Noise (PIIN). This noise dramatically limits the SAC-OCDMA system performance [24].

2.5.4 Hybrid PON

Hybrid PON multiplexing integrates different PON techniques (two or more) to get powerful PONs. Also, the combination of two technologies WDM and TDM introduces TWDM PON into the access network. This allows for high bandwidth. Other common examples of hybrid PON are WDM being combined with OCDMA or SCM. A hybrid PON system may comprise either or both optical or electrical domain multiplexing [4].

2.6 FTTH Access Network Architecture

This section briefly describes the general FTTH access network architecture, as shown in Fig. 2.10. The main purpose of any FTTH system is to reduce the length of distribution and drop optical fiber cables at the expense of the outside cable plant which minimize the overall cost of a FTTH network.

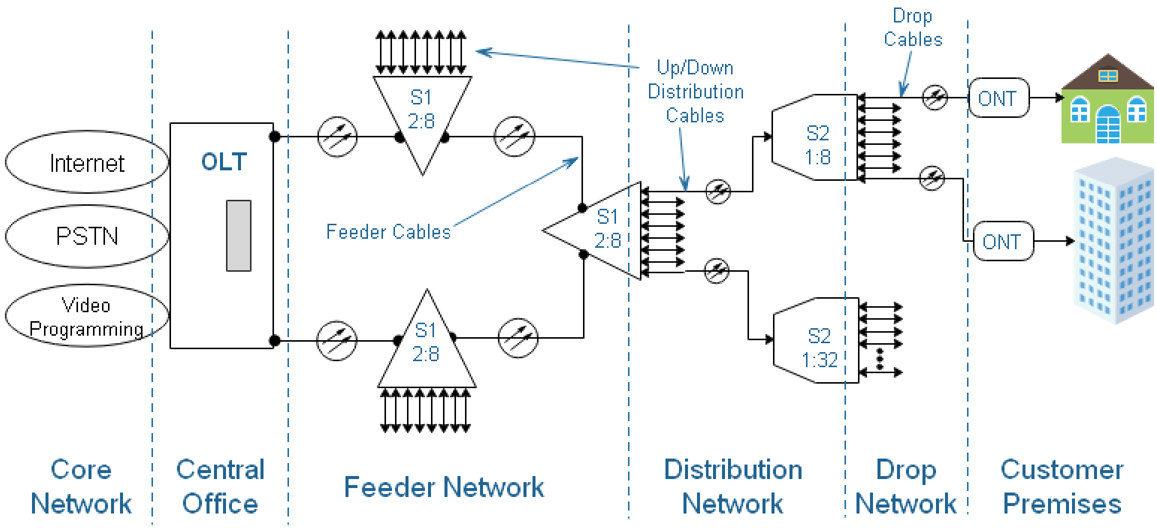


Fig. 2.10: FTTH access network architecture. S is power Splitter/combiner.

2.6.1 Optical Line Terminal (OLT)

The OLT is the endpoint device which is usually placed in the Local Exchange in a PON. The primary functions of OLT are bandwidth allocation, buffer control and traffic scheduling [25].

2.6.2 Optical Splitters and Combiners

Unpowered optical splitters are used in FTTH network to divide the power of the signals that are carried by single optical fiber into a given number of customer's homes or premises. However, the split ratio of those splitters depends on the offered service per home or business, where more split ratio leads to cost reduction and less QoS. The power splitter during the splitting operation usually attenuates the signal but without changing of its structure and properties. Low insertion loss and high reliability are needed in any optical splitter as well as the operating on wide wavelength range.

On the contrary of the splitters, the power combiners are used to combine the signals before transmitting them via single fiber (combine the optical power of two or more waveguides onto a single waveguide), then those signals are distributed for ONUs at the receiver side.

2.6.3 Optical Fiber Systems (OFS)

The fiber link may consist of an optical power combiner, fiber cable, and power splitter. Unlike the copper, the optical fiber is a dielectric transmission media that transfers the light, which carries information. The widespread use of optical fiber is due to its advantages: faster speed with less attenuation, greater bandwidth, impervious to EMI, thin and reliable in corrosive environments.

Optical fibers consist of core, cladding, fiber coating, and buffer jacket, as shown in Fig. 2.11. Basically, the optical fiber has two main types: single-mode fiber (SMF) and multimode fiber (MMF). They can have either a step or graded index profile. Each an optical mode is corresponding to only one of those possible multiple ways that is used to propagate a wave through the optical fiber. SMFs have smaller core diameters in compares to MMF and this is to allow single-mode propagation, to avoid losses of the evanescent field the cladding diameter must be larger than core diameter by at least 10 times. For MMF this relatively larger diameter provides a valuable advantage where the injection of light into the optical fiber is less losses of the coupling, which makes using a large-area and cheap light source possible, e.g. light-emitting diode (LED). However, the MMF has a noticeable disadvantage called intermodal dispersion. Because of different angles of incidence at the boundary of core-cladding each mode has propagate at different velocity. Hence, at the receiver side different light rays of same source will arrive at different times. Thus the pulse will broaden in the time domain. Intermodal dispersion limits the maximum reach distance and the bit rate; this is because of the intermodal dispersion is directly proportional to the distance of propagation. Therefore, in FTTH networks the MMF is not preferable to use. On the other hand, the SMF is widely utilized in FTTH which has no intermodal dispersion.

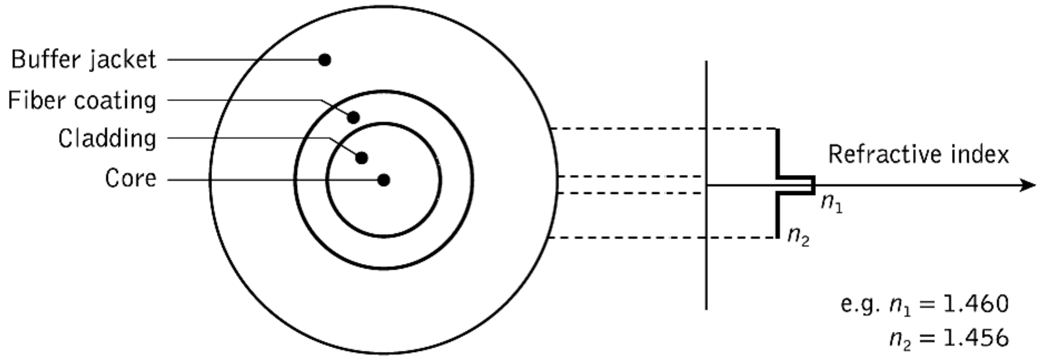


Fig. 2.11: Typical structure for a standard single-mode fiber with step index profile [4]

2.6.4 Free-Space Optics (FSO)

FSO is another optical communication technology, it is also called Free-space optical communication. It utilizes light propagating in free space and transmits the data wirelessly over free space (air, outer space, or vacuum) instead of using optical fiber cable. However FSO system provides good advantages, like the initiation cost, deployment time and low maintenance cost, making it a good alternative solution for the last mile connection where using an optical fiber cable is difficult.

In the FSO there is no dispersion occurs while large attenuation relative with the atmospheric conditions like haze, rain, and clear air which are dramatically affect the power received as in the equation 2.1. More losses can also increase the attenuation of FSO channel due to mispointing, scintillation and other perturbations. They can be defined as additional losses [26].

$$P_{Received} = P_{Transmitted} \frac{d_R^2}{(d_T + \theta R)^2} 10^{-\alpha R/10} \qquad (2.1)$$

Where d_R is the receiver aperture diameter, d_T transmitter aperture diameter, θ beam divergence (mrad), α atmospheric attenuation (dB/km) and R is the range of the distance in km.

2.6.5 Optic Impairments

Many impairments can reduce the quality of the system where they react with the propagated signal. Attenuation, dispersion and nonlinearity are the most significant impairments in the optical networks. At relatively high-speed system, the dispersion compensation becomes more important where distance between symbols become closer.

2.6.5.1 Attenuation

Attenuation in both OFS and FSO leads to minimize the power of the light signal according to the distance travelled by this signal. The attenuation is a significant factor because the receiver sensitivity needs specific amount of signal power with the aim of correctly detection of the transmitted signal. So it is important to determine the maximum distance of the propagation signal for given receiver sensitivity and transmitter power. There are several mechanisms that are considered the cause of the attenuation like absorption, scattering and geometric effects. Attenuation is usually characterized in decibels per length (dB/km) as follows [4]:

$$\alpha_{dB} = \frac{10\ \log_{10} \frac{p_i}{p_o}}{l} \qquad (2.2)$$

Where α_{dB} is the signal attenuation, *Pi* is the input (transmitted) optical power into a fiber, *Po* is the output (received) optical power from the fiber and *l* is the fiber length.

2.6.5.2 Dispersion

In single-mode fibers, the pulse broadening almost results from chromatic dispersion. The reason of the chromatic dispersion mechanism is due to using of non-monochromatic optical source (finite spectral Linewidth), where there is no optical source can emits only a single wavelength but a band of frequencies. Thus different propagation delay occurs between different spectral components that caused by different velocities of the pulses travelling and hence signal distortion will be occur [4]. Pulse broadening can harm the performance of a system in two ways. First, intersymbol interference (ISI) may be created because the adjacent pulses overlap with each other. Second, when the optical pulse broadens, the energy of this pulse will reduce. Thus, the SNR will reduce also at the decision circuit. Hence, more power is required at the receiver to maintain the system performance.

The chromatic dispersion is a combination of two dispersion parameters: material dispersion mechanism and waveguide dispersion mechanism. In the optical fiber the refractive index is a function of wavelength, therefore different group delay will happen for each spectral component. It leads to pulse broadening. This is called material dispersion. While the waveguide dispersion is the variation in group velocity that results from fiber parameters (like the difference between core/cladding refractive indices and core radius). Figure 2.12 shows the combination of dispersions as functions of wavelength for a conventional single-mode fiber. It can be noted that the zero material dispersion (ZMD) point is found at a wavelength of 1.276 μm. While the effect of waveguide dispersion shifts the overall dispersion to makes the minimum dispersion occurs at wavelength (λ_0) of 1.32 µm [4].

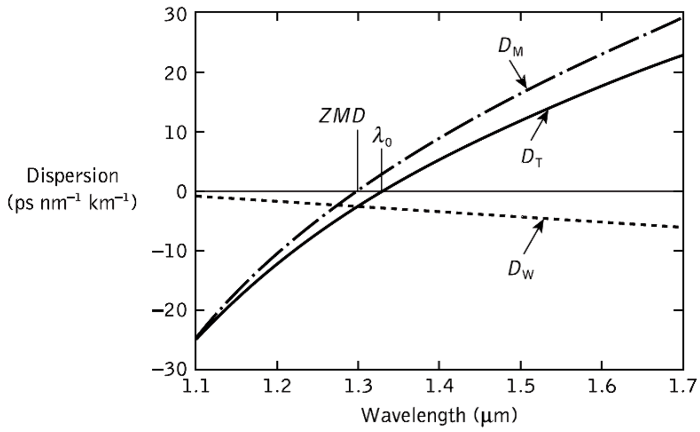


Fig. 2.12: Combination of dispersions as functions of wavelength for a conventional single-mode fiber. The material dispersion (DM), the waveguide dispersion (DW) and the total dispersion (DT) [4].

2.6.5.3 Nonlinearity

Nonlinear effects in fiber optic may possibly have a significant impact on the performance of high-speed optical communications systems. There are two main categories of those effects. First, nonlinear effect that is caused by the interaction of lightwaves with phonons (light pass over thermal molecular vibrations to produces a phonon) in the fiber. The first category parameters are stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). The second nonlinear effect is called Kerr effects. It is caused by the intensity-dependent refractive index of the optical signal. The refractive index results from the applied optical field that is disturbing the medium molecules to produce a polarization oscillating which will radiate and produce an overall perturbed field. The most important Kerr effects in this category are cross-phase modulation (XPM), self-phase modulation (SPM), and four-wave mixing (FWM) [4],[27]. But Kerr effects have been not covered in this work because of the master study limitation.

2.6.6 Optical amplifiers

Instead of using optoelectronic repeaters which have electronic circuitry for pulse reshaping, slicing and retiming, optical amplifiers are placed along a fiber link at a distances to prove a linear amplification of the transmitted signal. Widespread use in the recent years of the optical amplifiers is due to their simplicity as they can be used for any type of modulation at any transmission speed. The effects of signal dispersion may be small in the systems of single-mode fiber, so the major limitation on such a distance is the attenuation. The systems with this features may not need to full regeneration of the signal at each repeater. Thus the optical amplifier is sufficient for such system. Hence over optical amplifiers have emerged as promising network elements not just for the use as linear repeaters but as optical gain blocks, wavelength converters, optical receiver preamplifiers and, when used in a nonlinear mode, as optical gates, pulse shapers and routing switches [4].

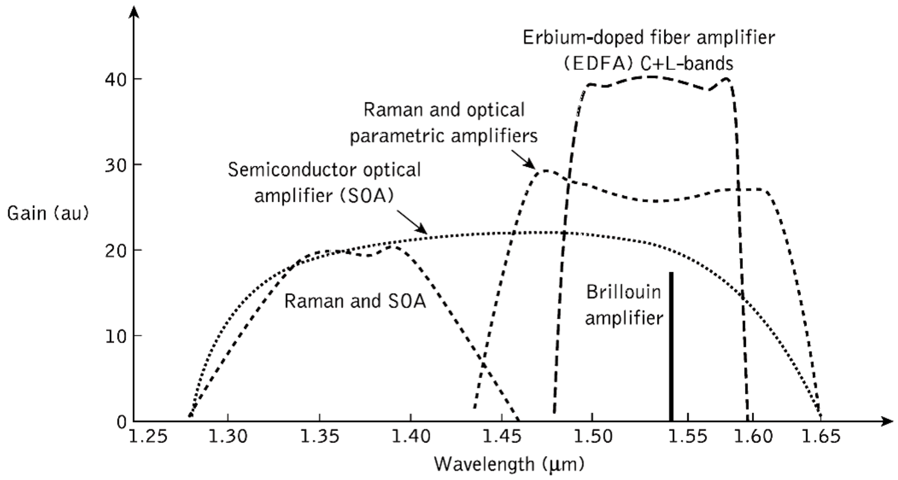


Fig. 2.13: Gain versus bandwidth of different optical amplifiers [4].

As shown in Fig. 2.13, the semiconductor optical amplifier (SOA), the Raman fiber amplifier and the erbium-doped fiber amplifier (EDFA) all provide wide spectral bandwidths. Generally, the typical gain profiles of those amplifiers are based around the wavelength regions of 1.3 and 1.5 μm.

2.6.7 Dispersion Compensation Techniques

Dispersion compensation is a critical point in the high capacity and time compressed systems. Narrow time slot between the ONU's pulses makes the TDM-PON very sensitive to the dispersion effect. Hence, two dispersion compensation techniques will be discussed where those techniques are implemented in such a system to enhance its tolerance and performance. The first one is based on alternating fiber that has negative dispersion value of the first used one, named dispersion-compensation fiber (DCF) or negative-dispersion fiber (NDF). The second technique uses Fiber Bragg Gratings (FBG) filter to inverse the dispersion [4].

2.6.7.1 Dispersion compensation using single mode DCF

The dispersion compensation using negative-dispersion fiber is known as dispersion compensating fiber (DCF). Figure 2.14 illustrates the chromatic dispersion characteristic where a null accumulated dispersion is achieved by inserting a suitable length of single-mode DCF with the standard single-mode fiber (SSMF). The DCF length is much less than SSMF length because of the often large absolute negative dispersion of DCF. Hence, zero overall dispersion will be acquired at the wavelength of 1.55 μm on the transmission channel [4].

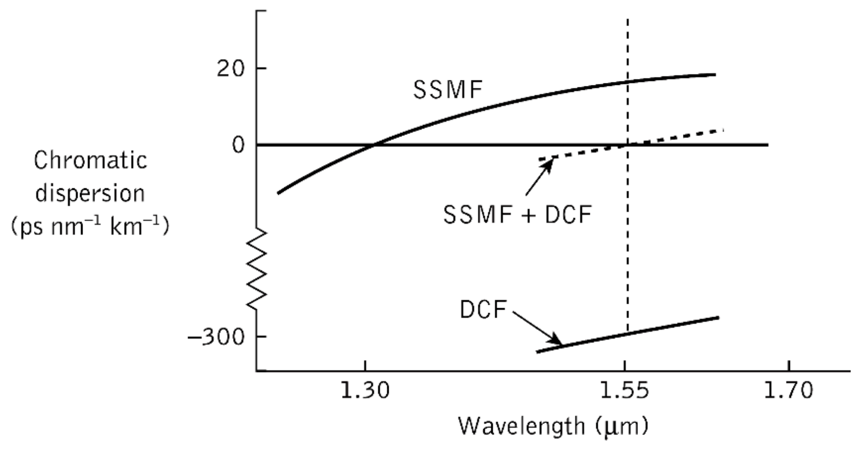


Fig. 2.14: Dispersion compensation by DCF [4]

There are three possible algorithms for dispersion compensation schemes using DCF: pre-compensation algorithm where the DCF is placed before the SSMF; the second algorithm is post-compensation where SSMF is placed before the DCF; and the last one is the mixed compensation algorithm where the DCF placed in both before and after the SSMF. By comparison, the mixed compensation method gives the best performances [28].

2.6.7.2 Dispersion compensation using Fiber Bragg Gratings (FBG)

The use of the fiber Bragg gratings have seen significant growth in modern optical communications systems. The operation of the FBG is depending on facilitating reflections of different wavelengths, where a portion of the power signal will be reflected back at each interface between the Bragg regions. The principle FBG operation is shown in Fig. 2.15. The total reflection can increase to about 100% reflection of a wavelength with specific dispersion and passing all others if the spaces between those regions are arranged in such a way to make the partial reflections be constructively in phase [4]. Cost effective passive optical component with low insertion losses the FBG has been used as a dispersion compensation in the fiber optical transmission systems.

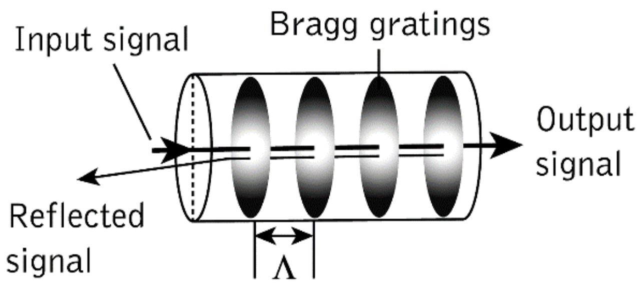


Fig. 2.15: Optical fiber core schematic diagram with consisting of four fiber Bragg gratings [4]

2.6.8 Polarization impairments compensation

The single-mode fiber allows the propagation of two nearly degenerate modes with orthogonal polarizations. Generally, the cylindrical optical fibers do not maintain the state of the polarization for a long distance. Hence, it is important to maintain the polarization states of the input light over significant distances. Some single mode fibers have been designed for this purpose. The maintenance of the polarization state is described in terms of a fiber birefringence. In the ideal optically circularly symmetric core optical fiber both polarization modes propagate with identical velocities. But with manufactured optical fiber there is some birefringence appeared due to differences in the core geometry resulting from the variations in the internal and external stresses, and fiber bending. The fiber birefringence phenomenon will produce a difference in the effective refractive indices for these two orthogonally polarized modes, and hence different phase velocities will occur and it causes polarization mode dispersion (PMD). The PMD produces a pulse broadening which can be considered as a limiting factor for optical fiber communications especially at high transmission rates. Therefore, using polarization-maintaining (PM) fibers will permit light to pass through while retaining its state of polarization [4].

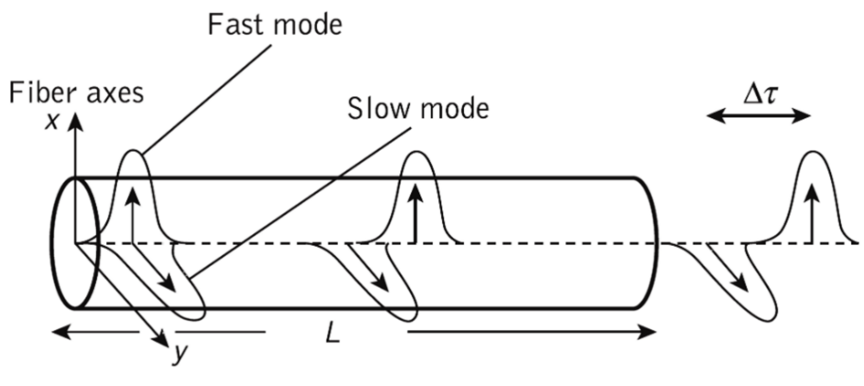


Fig. 2.16: Polarization mode dispersion effect in a short fiber length with a pulse being launched with equal power on the two birefringent axes, x and y, becoming two pulses at the output separated by the differential group delay [4].

2.6.9 Optical Network Terminal ONT

ONT or ONU is placed at customer's premises. In PONs, the ONTs connect to the OLT by an optical fiber and without any active element within the access link. Each ONT has a transceiver act as a physical connection between this customer and the central office.

2.7 Literature Survey

Many researchers have worked on OCDMA, OTDM and hybrid techniques to improve their performance, cost, BER, MAI cancellation … etc. In studies below, the most related works to this work will be reviewed.

2.7.1 OCDMA System

In SAC-OCDMA technique, bandwidth content of a signal is coded by selective blocking which transfers it according to a code signature. SAC-OCDMA method is suitable for an access environment in which cost is considered as one of the important factors [29].

A. Garadi has presented a novel 2D encoder technique of SAC-OCDMA system based on two orthogonal polarization states (vertical and horizontal) in order to increase the number of simultaneous users. The authors have used Zero-Cross Correlation (ZCC) code with only single weight. The theoretical results of this article show that the 2D ZCC OCDMA of the proposed system can multiplex the double number of users in comparison to the 1D ZCC OCDMA system [30].

Phase-Induced Intensity Noise (PIIN) cancellation using a novel receiving architecture for spectral/spatial SAC-OCDMA system has been studied by A. Bouarfa et al, where the PIIN is a drawback. There is a limitation to increase users number in a 1D SAC-OCDMA system. Therefore, to overcome this limitation A. Bouarfa et al presented a new design of 2D wavelength/spatial system with using of single weight multi-diagonal (MD) in 2017. This architecture possesses the same features of 1D-MD code, which leads to entire cancellation of the MAI. Unlike traditional receivers that used in previous studies, where the suggested structure makes reducing in the system architecture not only eliminates PIIN. The results have shown that the user's number achieved by the proposed system is the user number of the 1D system multiply by the couplers' number. In addition, the new proposed system has presented good performances at the high data rate [31].

Simulation of a SAC-OCDMA 10 User ×15 Gbps System Using MD Code has been presented by Morteza Motealleh and Mohsen Maesoumi. They discuss section MD code structure technique and the way to create its matrix. The results show that for 10 users the effect of beat noise and thermal noise is 10-22 watt/Hz and error rate is of 10^{-9}. In additional, the researchers find that the system designed has the best transfer rate of 15 Gb/s for each user which achieve along a 30-km long fiber [32].

To control the effect of the noises and MAI A. Cherifi et. al. have developed a novel design of a 2D wavelength/spatial code named 2D Single Weight Zero Cross Correlation (2D-SWZCC) utilized a single weight code which has zero cross correlation and higher number of users. The simulation results show that the 2D-SWZCC code technique has good performance with comparison to the other systems based on 2D-MD, 2D-PD, 2D-DCS, 2D-FCC/MDW, 2D-Extended-EDW, and 1D-SWZCC codes [33].

2.7.2 OTDM System

The most common PON standards are employing a TDM technique. In a communication system, higher data rate transmission is always a goal for the researcher. R. Kaur and Anjali have proposed a TDM-PON system providing flexible bandwidth and higher bit rate with two types of modulation format. Modified duobinary return to zero (MDRZ) and return to zero (RZ) are carried out. The comparison results of Q-factor value between these technologies show that TDM-PON system with MDRZ without using repeater has more transmission distance than the system with RZ technology, where the transmission distance of an acceptable bit error rate (BER) is only up to 300 km in the RZ TDM-PON [34].

D. Veen and V. Houtsma experimentally reported a 25 and 50 Gbps TDM-PON with different modulation formats in 2016 [35]. A bi-directional 25G/50G TDM-PON system was experimentally tested by the same researchers (D. Veen and V. Houtsma) in 2017. They have used a single carrier 25 Gbps for the upstream and 50 Gbps for the downstream using a commercial 25G APD receiver with duobinary, where a simple 3x3 fiber splitter has been used for the coherent detection scheme of a NRZ On-Off-Keyed (OOK) signal [36].

2.7.3 Hybrid System

The most popular hybrid system is the TWDM. Initially TWDM is operated by various TDM through a fixed WDM networks (multi-wavelength sharing TDM-PON). Lots of researches have been carried out to achieve any probable development of TWDM PONs (such as system capacity improvement, power budget saving, loss reduction, and ONU cost). Some of these researches have proposed different TWDM architectures with experimental demonstration. Linin demonstrated the first successful system configuration of TWDM-PON compatible with TDM-PON in 2012 [37]. Then in 2012, Zheng Xuan proposed a low complex and a compatible TWDM PON with low cost ONUs, which used a single feeder fiber, a 1× n splitter in each ONU and single tunable optical filter (TOF) that work to select the downstream wavelength for any optical unit [38]. TWDM system with 8 wavelengths stacked to provide 80/10 Gbps

Downstream/Upstream capacity was investigated in 2012 by Lilin [39]. The recent prototype TWDM-PON system was tested by Yuanqiu using low-cost tunable ONUs. The result showed the feasibility and technology maturity and proved promising ways to realize a low-cost tunable ONUs [40]. In 2013, a first full-system 40 Gbps successful TWDM-PON prototype with 40/10 Gbps downstream/ upstream bandwidth had been demonstrated. It was the first high split ratio (1:512) architecture and offered power budget of 38 dB with full coexistence to the commercially GPON and XG-PON systems [41].

Several other approaches are used to scale up the subscriber number; some of them depend on all-optical networks by using a combination of two optical multiplexing techniques. One of those scalability-improving technologies is OCDMA/OFDMA. In reference [42], the authors have incorporated those two techniques with advanced subcarrier hopping by two-dimensional hybrid code (2D-HC) to increase the number of subscribers. Another combination has been used to carry different data types by both OCDMA and WDM in one system [43], [44]. Hybrid subcarrier multiplexing (SCM) combined with SAC-OCDMA technology is investigated for enhancing the networks of radio over fiber (RoF) [45].

T. B. Osadola, S. K. Idris and I. Glesk have proposed and demonstrated a novel hybrid architecture for increasing the number of network users of an incoherent OCDMA system by way of overlaying M-user OCDMA over N-channel OTDMA approach. This enables OCDMA code reusing that lead different OCDMA groups to communicate simultaneously in separate OTDMA channels. The results of the experimental test show that over 17km of fiber optic link the connectivity of the hybrid system successfully done with achieving less than 10^{-9} of BER [46].

In 2017, I. Glesk, T. B. Osadola, and W. C. Kwong proposed a novel approach to improve the scalability of the hybrid OCDMA–OTDMA system that they previously had demonstrated in 2012 [46]. To increase the number of users, the authors proposed adding a new dimension to the original OCDMA-OTDMA system by utilizing 2D OCDMA system (number of wavelength and number of chips positions) to encode the modulated light signal of the users before being transmitted simultaneously by N-channel of OTDM. This article has used the 2D wavelength-hopping time-spreading (2D-WH/TS) OCDMA code that depends on multi-wavelength picosecond pulses which is designed to occupy P wavelength bands. In dead, each one of those bands can support of M-Users OCDMA systems [47]. Table 2.1 listed the researcher works with their references that has been used in the literature survey.

Table 2.1: The summarization of literature survey

no	Author	year	PON	Multiplexing					OCDMA code	Encoding /coding	Data bit rate (bps)
				OCDM	OTDM	SCM	WDM	OFDM			
1	A. Garadi	2018		✓					2D-ZCC	NRZ	622 M
2	A. Bouarfa	2017		✓					2D-MD	NRZ	1 G
3	M. Motealleh	2014		✓					MD	NRZ	15 G
4	A. Cherifi	2019		✓					2D-SWZCC	NRZ	1 G
5	R. Kaur	2017			✓					RZ, MDRZ	40 G
6	D. van Veen	2016	✓		✓					NRZ, PAM-4, EDB, ODB	25, 40 G
7	V. Houtsma	2018	✓		✓					NRZ, PAM-4, EDB	25, 50,100 G
8	Lilin Yi	2012	✓		✓		✓			NRZ	10/1.25 G
9	Y. Luo *et al.*	2013	NG-2		✓		✓				40/10 G
10	Zhengxuan Li	2012	✓		✓		✓			NRZ	10/1.25 G
11	Lilin Yi	2012	✓		✓		✓			NRZ	80/10 G
12	Hichem Mrabet	2018	✓	✓				✓	2D-HC	16-QAM	40 G
13	M. Islam	2016		✓			✓		MDW	DPSK	2.5 G
14	Thanaa Hussein Abd	2012		✓		✓			MD	NRZ	622 M
15	Tolulope B. Osadola	2012	✓	✓	✓				2D-WH/TS		622 M
16	I. Glesk	2017	✓	✓	✓				2D-WH/TS		2.4 G

SYSTEM DESIGN

3.1 Introduction

In this chapter, different FTTH networks will been designed based on incoherent SAC-OCDMA (1D-MD, 2D-MD, 1D-ZCC and 2D-ZCC codes), high speed bit-interleaving TDM-PON and hybrid system combining OCDMA/OTDM techniques with two main scenarios of optical link: Optical Fiber Systems (OFS) and Free Space Optics (FSO). Matlab software will been used for mathematical results, and OptiSystem simulation software V.15 will been used to design and simulate those systems.

3.2 OCDMA System Design and Code Selection

Optical CDMA (OCDMA) technique is the solution for future access of optical networks. OCDMA technique allows multiple simultaneous clients to share the same frequency and time interval. There are many types of coherent and incoherent OCDMA. The incoherent SAC-OCDMA codes are simpler and lower cost and hence those codes are more popular. Usually, this category of coding have either zero-cross-correlation property or low cross correlation.

There are many articles that have discussed a comparison of those categories with various codes [48][49][50], e.g. Fig. 3.1 illustrates the analytical computation for many SAC-OCDMA codes.

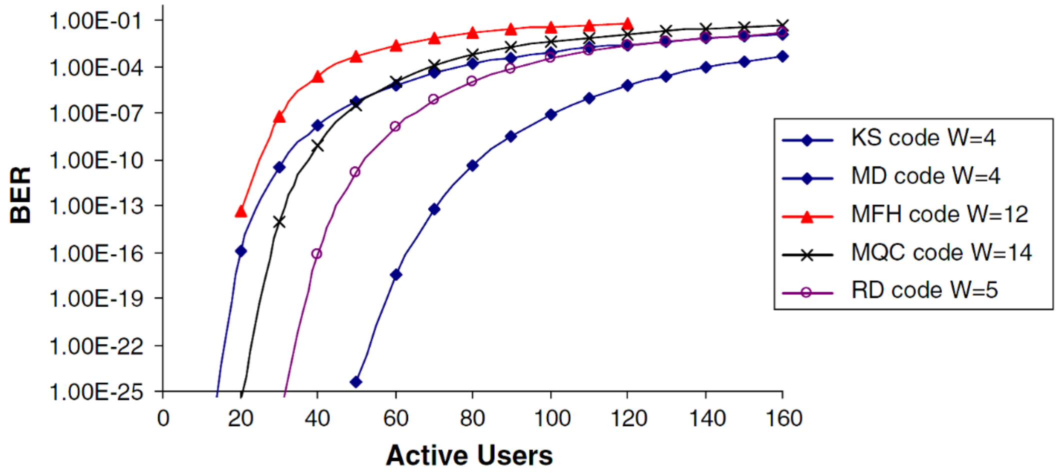


Fig. 3.1: Number of active users against the BER for various codes employing the technique of SAC-OCDMA: Khazani-Syed (KS), modified frequency hopping (MFH), modified quadratic congruence (MQC), random diagonal (RD), and multi-diagonal (MD) codes [50].

As it is clear in Fig. 3.1 that MD code provides better performance and larger number of users. The interest of this work will be toward the zero cross-correlation incoherent SAC-OCDMA codes.

3.2.1 1D zero cross-correlation SAC-OCDMA design

The cross-correlation of any two different code sequences is given by [29]:

$$C = \sum_{i=1}^{L} X_i \, Y_i \tag{3.1}$$

Where C is the in-phase cross correlation, L is the code length, $X = (x_1, x_2, \ldots, x_L)$ and $Y = (y_1, y_2, \ldots, y_L)$ are the two code sequences. The most important parameters are the weight W (number of ones in each row) and λ_c, where they are directly affect the Signal-to-Noise Ratio (SNR) of the overall system. The SNR (average signal power to noise power, $SNR = I^2/\sigma^2$ where I is mean of optic current and σ^2 is the variance of the optical detector) and the bit error rate (BER) are important equations to calculate the system performance of the 1D codes [51]. Gaussian approximation is used to calculate BER, where σ^2_{th} is the variance of thermal noise and σ^2_{sh} is the variance of shot noise:

$$\sigma^2 = \sigma_{sh}^2 + \sigma_{th}^2 = 2eBI + \frac{4K_bT_nB}{R_L} \tag{3.2}$$

Where B is electrical bandwidth, T_n is absolute receiver noise temperature, K_b is Boltzmann's constant, R_L is receiver load resistance and e is electron load, respectively.

To the photocurrent I. First, let $C_k(i)$ and $C_l(i)$ are numbers of k_{th} sequence of matrix of a code for the encoders and decoders, where direct detection technique is used for a code properties and they are expressed as [4]:

$$\sum_{i=1}^{L} C_k(i)C_l(i) = \begin{cases} W, & \text{for } k = 1 \\ 0, & \text{Otherwise} \end{cases} \tag{3.3}$$

And the power density of the received optic signal is given as follows:

$$G(v) = \frac{P_{sr}}{\Delta v} \sum_{k=1}^{K} d_k \sum_{i=1}^{L} C_k(i)C_l(i)\, \Pi(i) \tag{3.4}$$

(Where K is the number of users, d_k is data bit of k_{th} user, P_{sr} is the effective received power of broadband source, Δv is the optical source bandwidth and $\Pi(i)$ given as [32]:

$$\Pi(i) = u\left[v - v_0 - \frac{\Delta v}{2L}(-L + 2i)\right] - u\left[v - v_0 - \frac{\Delta v}{2L}(-L + 2i + 2)\right] \tag{3.5}$$

Where $$u(v) = \begin{cases} 1 & v \geq 0 \\ 0 & v < 0 \end{cases}$$

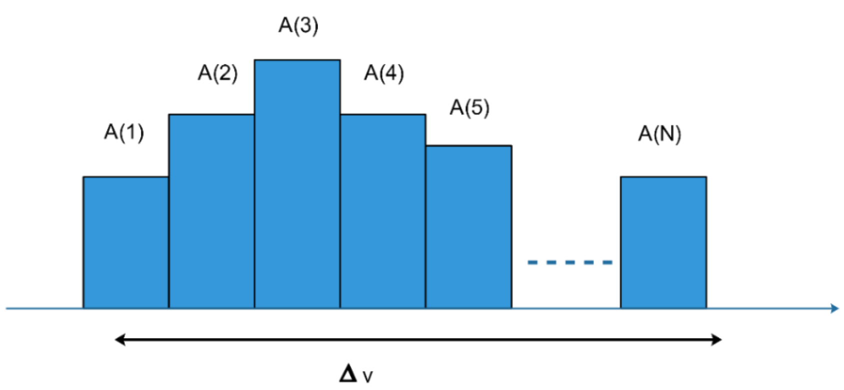


Fig. 3.2: The power spectral density of the received optic signal

To calculate *G(v)* integral, w will consider an example of the power spectral density (PSD) first, as it is shown in Fig. 3.2, where *A*(*i*) is spectrum signal amplitude with width of Δ*v*/*L*:

$$\int_0^\infty G(v)dv = \int_0^\infty \left[\frac{P_{sr}}{\Delta v} \sum_{k=1}^{K} d_k \sum_{i=1}^{L} C_k(i)C_l(i)\, \Pi(i)\right] dv \tag{3.6}$$

$$\int_0^\infty G(v)dv = \frac{P_{sr}}{\Delta v}\int_0^\infty \left[\sum_{k=1}^{K} d_k \,.W.\frac{\Delta v}{L}\right] dv \tag{3.7}$$

When all users send a bit simultaneously $\sum_{k=1}^{K} d_k = d_1 + d_2 + \cdots + d_K = W$, so

$$\int_0^\infty G(v)dv = \frac{P_{sr}W^2}{L} \tag{3.8}$$

The photocurrent *I* is given as

$$I = \Re \int_0^\infty G(v)dv \tag{3.9}$$

Where $\Re$ is the photodiode responsively, which can be given by $\Re = \eta e/hv_c$, and η is the quantum efficiency, v_c is the optical pulse central frequency of the original broad-band and *h* is Planck's constant [33]. Equation 3.9 can be rewritten as:

$$I = \Re \int_0^\infty G(v)dv = \frac{\Re\, P_{sr}W^2}{L} \tag{3.10}$$

Substitute equation 3.10 into equation 3.2:

$$\sigma^2 = \frac{2eB\, \Re\, P_{sr}W^2}{L} + \frac{4K_bT_nB}{R_L} \tag{3.11}$$

The equation 3.11 can be written as follows if the transmitting probability of 0.5 is taken into account for each bit 1 at any time per user:

$$\sigma^2 = \frac{eB\, \Re\, P_{sr}W^2}{L} + \frac{4K_bT_nB}{R_L} \tag{3.12}$$

Hence, SNR and BER of the direct detection technique can be expressed as:

$$SNR = \frac{I^2}{\sigma^2} = \frac{\left(\frac{\Re P_{sr}W^2}{L}\right)^2}{\frac{eB\Re\, P_{sr}W^2}{L} + \frac{4K_bT_nB}{R_L}} \tag{3.13}$$

$$BER = \frac{1}{2}\, erfc\left(\sqrt{\frac{SNR}{8}}\right) \tag{3.14}$$

Where *erfc* is the function of complementary error.

3.2.1.1 Multi-diagonal (MD) code

The MD code is characterized by the (L, W, λ_c) parameters to construct a diagonal matrix of size ($K \times L$). Assume I_K the identity matrix ($K \times K$):

$$I_1 = [1],\ I_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \ldots,\ I_K = \begin{bmatrix} 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & 0 & \ddots & 0 \\ \vdots & 0 & \ddots & 0 & \vdots \\ 0 & \ddots & 0 & 1 & 0 \\ 0 & 0 & \cdots & 0 & 1 \end{bmatrix} \tag{3.15}$$

So, by using cross-correlation equation 3.1 between any two rows of I_K a value of zero can be achieved.

The MD matrix has been constructed from the sequences repetition of a diagonal matrix, where w represented number of repetition. For example, an MD matrix with five users and weight is three, since K=5 and W=3 the length of the MD code is given by $L = K \times W$, [52], where L here is 15 and the codeword is:

$$\mathrm{MD}_{code} = \begin{bmatrix} 1&0&0&0&0&0&0&0&0&1&1&0&0&0&0 \\ 0&1&0&0&0&0&0&0&1&0&0&1&0&0&0 \\ 0&0&1&0&0&0&0&1&0&0&0&0&1&0&0 \\ 0&0&0&1&0&0&1&0&0&0&0&0&0&1&0 \\ 0&0&0&0&1&1&0&0&0&0&0&0&0&0&1 \end{bmatrix}_{5\times15} \tag{3.16}$$

$$codewords = \begin{cases} user1 & \Rightarrow \quad \lambda_1, \lambda_{10}, \lambda_{11} \\ user2 & \Rightarrow \quad \lambda_2, \lambda_9, \lambda_{12} \\ user3 & \Rightarrow \quad \lambda_3, \lambda_8, \lambda_{13} \\ user4 & \Rightarrow \quad \lambda_4, \lambda_7, \lambda_{14} \\ user5 & \Rightarrow \quad \lambda_5, \lambda_6, \lambda_{15} \end{cases} \tag{3.17}$$

3.2.1.2 Zero cross-correlation (ZCC) code

The ZCC code has been designed to solve the MAI problem and terminate the effect of the PIIN which are considered the major causes of the SNR limitation. Hence, leading to much better BER performance. The balanced incomplete block design (BIBD) algorithm is used to construct 1D ZCC [30]. It is essential to note that the determination of users number K is based on the following equation [53]:

$$(K) + (W - 1) \times K \leq L \tag{3.18}$$

$$K \leq \frac{L}{W} \tag{3.19}$$

Moreover, the position of the each "1" is specified by:

$$P_{\mathrm{m}} = \varepsilon^{(i+jK)} modC \tag{3.20}$$

$$0 \leq i \leq (K - 1), \;\; 0 \leq j \leq (W - 1) \tag{3.21}$$

Where C is the prime number and ε is the primitive root of C.

As example, for L=12, W=3, and K=4 the code is:

$$ZCC_{code} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{3.22}$$

3.2.2 2D zero cross-correlation OCDMA design

According to what it has mentioned before and in order to apply 1D-OCDMA's there are some disadvantages in those codes, such as limited allowed number of users and large bandwidth consumption. Therefore, two dimensional optical code multiplexing encoding and decoding OCDMA systems (2D-OCDMA) have been investigated to solve these limitations by spreading the code into two different domains (polarization and spectral). In order to generate 2D-OCDMA, the existing 1D coding technique will be utilized in a scheme of combined polarization and wavelength (P/W). In 2D coding structure, each user is specified by a different wavelength and different orthogonal polarization angle. Therefore, the number of users will be double if two orthogonal polarization states have been used with the same spectral signature, as shown in the equation 3.23. In this work, to generate two polarization axes at 0° and 90° a polarization beam splitter will be used after the optical source as shown in Fig. 3.3.

$$K_{2D} = 2 \times K_{1D} \tag{3.23}$$

Since, wavelengths will be used twice ($\lambda^{\parallel}$ and $\lambda^{\perp}$) the power spectral density will be doubled; therefore, equation 3.6 can be rewritten as:

$$G(v) = \left[\frac{P_{sr}}{\Delta v} \sum_{k=1}^{K} d_k \ \sum_{i=1}^{L} C_k(i) C_I(i) . \Pi(i)\right] . (\cos\theta + \sin\theta) \tag{3.24}$$

Moreover, it can be expressed that the integral of the power spectral density as:

$$\int_0^\infty G(v)dv = \frac{P_{sr}}{\Delta v} \int_0^\infty \left[\sum_{k=1}^{K} d_k \sum_{i=1}^{L} C_k(i) C_I(i) . \frac{\Delta v}{L} \right] . (\cos\theta + \sin\theta) dv \tag{3.25}$$

$$\int_0^\infty G(v)dv = \left[\frac{P_{sr}}{L} \sum_{k=1}^{K} d_k \sum_{i=1}^{L} C_k(i) C_I(i) \right] . (\cos\theta + \sin\theta) \tag{3.26}$$

$$\int_0^\infty G(v)dv = \left[\frac{P_{sr}}{L} \sum_{k=1}^{K} d_k . W \right] . (\cos\theta + \sin\theta) \tag{3.27}$$

Therefore, when all users send a bit simultaneously the summation $\sum_{k=1}^{K} d_k = d_1 + d_2 + d_3 + \cdots + d_K = W$, the power spectral density integration will be:

$$\int_0^\infty G(v)dv = \frac{P_{sr} W^2}{L} . (\cos\theta + \sin\theta) \tag{3.28}$$

Then, by substituting the equation 3.28 into the equation 3.9 of photocurrent for each polarization states:

$$I = \frac{\eta e}{h v_c} \int_0^\infty G(v)dv = \frac{\eta e}{h v_c} . \frac{P_{sr} W^2}{L} \qquad if \ \ \theta = 0° \ or \ \theta = 90° \tag{3.29}$$

Hence, by using equations 3.2 & 3.29 the SNR and BER relations of the direct detection technique of 2D system can be determined as [30]:

$$SNR = \frac{I^2}{\sigma^2} = \frac{\left(\frac{\eta e}{h v_C} . \frac{P_{sr} W^2}{L}\right)^2}{2 . \frac{\eta e^2}{h v_C} . \frac{P_{sr}}{L} . B + \frac{4 K_b T_n B}{R_L}} \tag{3.30}$$

$$BER_{2D} = \frac{1}{2}\, erfc\left(\sqrt{\frac{\left(\frac{\eta e}{hv_C}.\frac{P_{sr}W^2}{L}\right)^2}{8.\left(2.\frac{\eta e^2}{hv_C}.\frac{P_{sr}Bw^2}{L}+\frac{4K_bT_nB}{R_L}\right)}}\right) \tag{3.31}$$

3.2.3 OCDMA systems description

The proposed design of three or four residence buildings with different code techniques (1D-2D MD and 1D-2D ZCC) by using OFS and FSO are described in this section as shown in Figures 3.3 to 3.5. A wavelength division multiplexer (WDM) has been used to encode the light as amplitude-spectrally according to a certain code. The data of each user, which generated by pseudo random bit sequence (PRBS) and using non-return to zero (NRZ) pulse generator, is optically modulated by optical external modulator (Mach–Zehnder modulator) on a light into code sequence at the transmitter end. The Mach–Zehnder, which is based on an interferometeric principle acts as an intensity modulator. The light source that is utilized in the proposed system is a white light source, which has broad optical bandwidth. Finally, user’s modulated code sequences are combined together and transmitted through the channel. At the receiving side, the optical signal passes through a splitter into a Fiber Bragg Grating (FBG) filter that acts as decoder, where direct detection is used for MD and ZCC codes as shown in Figures 3.3 to 3.5. To detect output signal, PIN photodetector has been used to convert the optical signal to an electrical signal. Finally, the electrical signal passes through a low-pass filter (LPF) to retrieve the original information.

For 2D (P/W) encoder, the difference to the 1D encoder is that a polarization splitter is used to split the light signal into two signals and rotate one of them by polarization angle of 90˚. Hence two angles of polarization of the light signal will be created as in Fig. 3.3. In the receiving side, a PMD compensator has been used as a polarization compensator then a power splitter and two polarization linear filters have been utilized to separate the two polarization states.

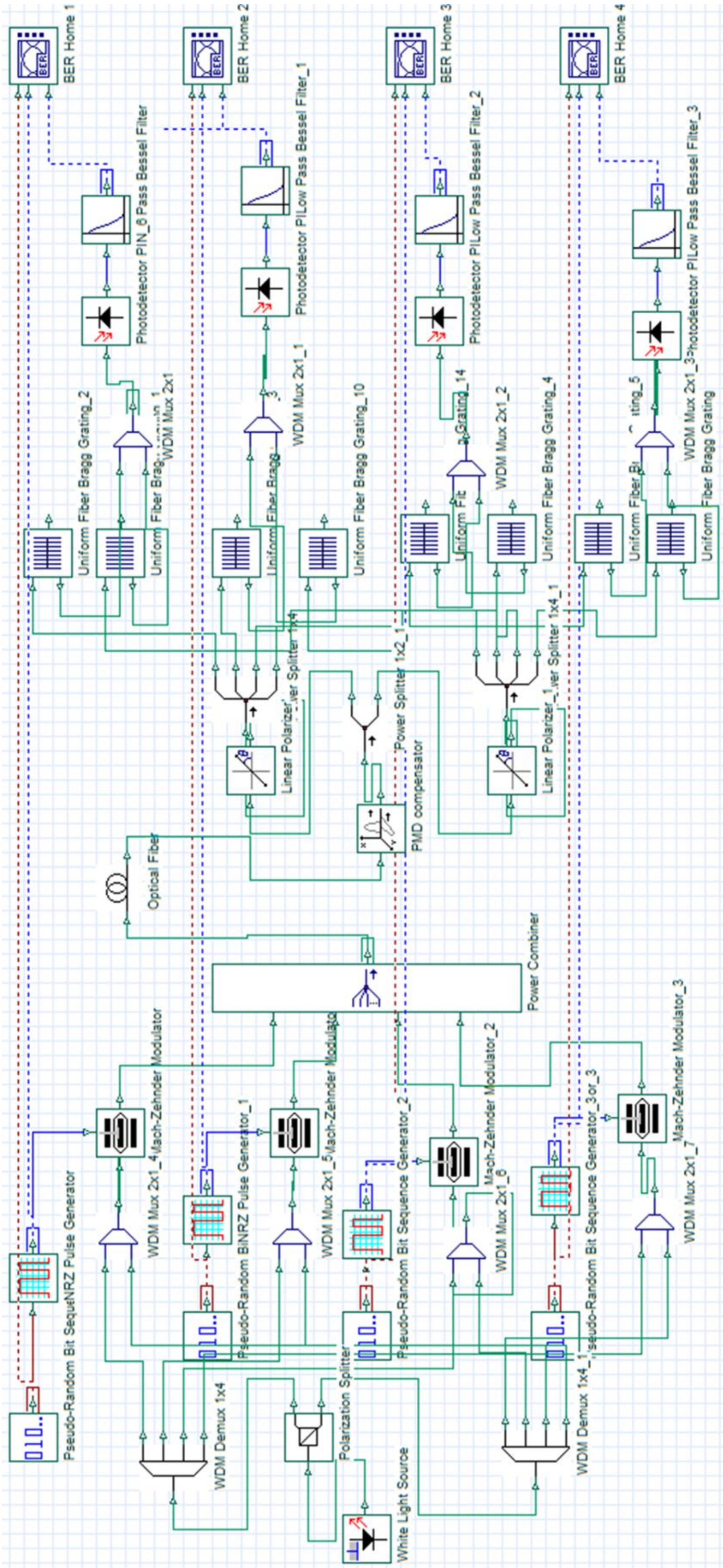


Fig. 3.3: Schematic block diagram of the 2D-MD/ZCC (P/W) codes with SMF, K=4 and W=2

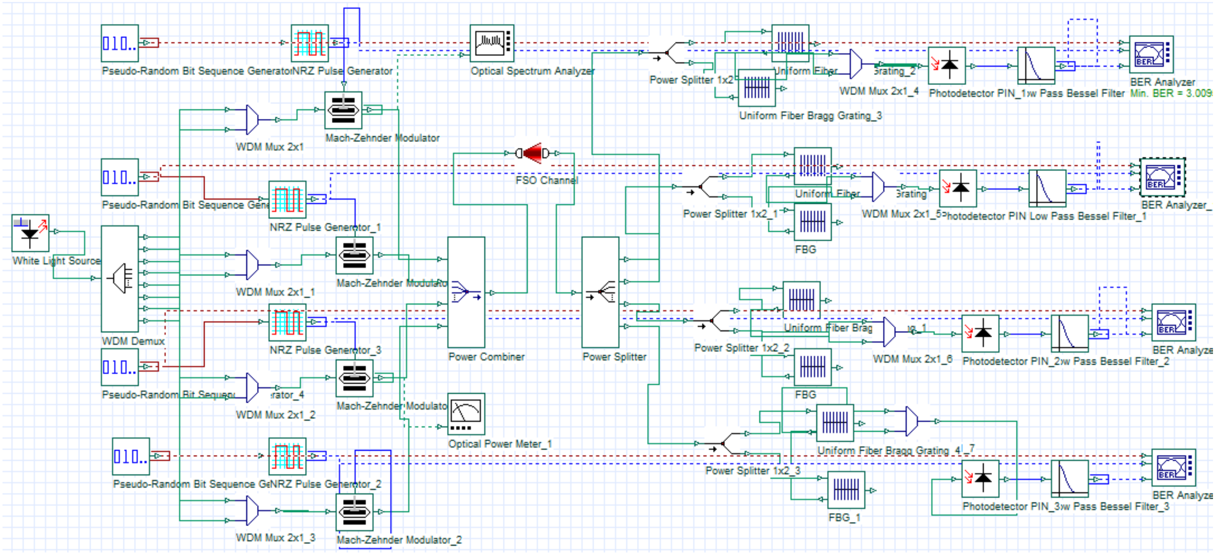


Fig. 3.4: FSO system with 1D-MD/ZCC codes, K=4 and W=2

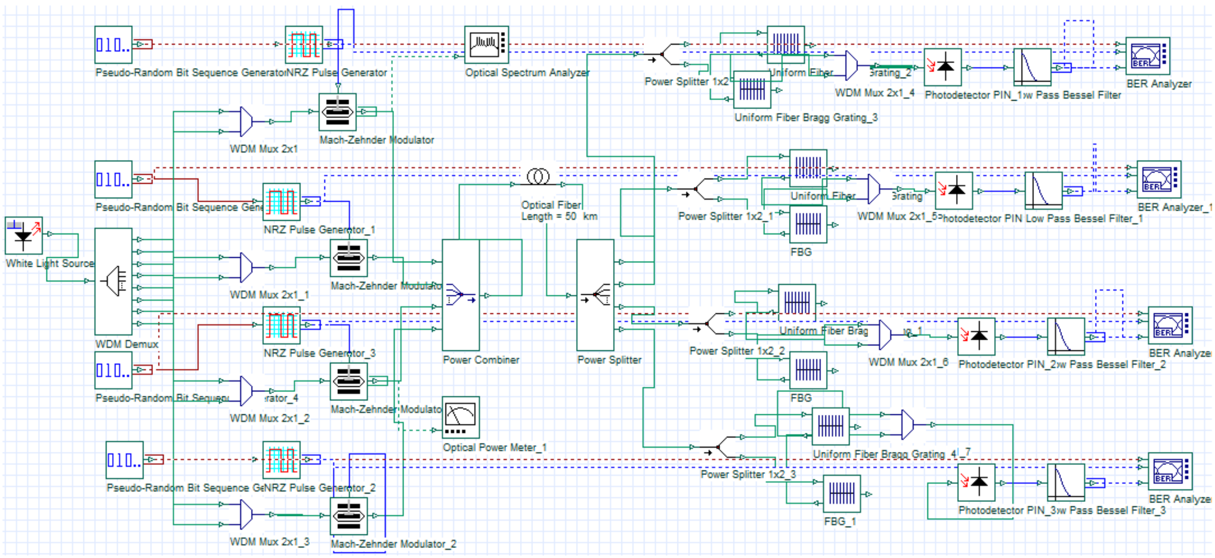


Fig. 3.5: block diagram of the 1D-MD/ZCC codes with SMF, K=4 and W=2

In this work, two scenarios have been utilized for the channel. The first one is single mode fiber as an appropriate transmission media for FTTH networks where low attenuation and dispersion is required. Different lengths of a SSMF (ITU-T G652) have been used with dispersion of 16.75 ps/nm/km, dispersion slope 0.075

ps/nm^2/km, polarization mode dispersion (PMD) of 0.5 $ps/\sqrt{km}$, attenuation coefficient of 0.2 dB/km and non-linearity refractive 2.6e-20 m^2/W [4].

The second scenario of the transmission media is the FSO. This system is considered a good solution for such a last mile connection which using an optical fiber cable is difficult, where in FSO a light travels through the atmosphere instead of fiber. Thus, FSO system has other advantages like the initiation cost, deployment time and low maintenance cost.

FSO system has some constraints such as Line of Sight (LoS) and attenuation. The atmospheric conditions like fog, rain, haze, hot and dry cause the attenuation, absorption and scattering [54], [55].

3.3 TDM-PON System Design

The proposed designs of four ONUs TDM-PON will be evaluated for different bit rates and optical media lengths. Two methods have been used in the OLT of the system for downstream (the OLT is a transmitter). The first one, as shown in Fig. 3.6, consist of a laser diode (wavelength of 1552nm, line width 100 KHz and 5 dBm power), power splitter to divide the optical signal, four external modulators, and four optical delays with time delay of (i / K*bit rate) where i = 0, 1,…, K-1 to make each destination data able to be transmitted at a specific time slot. The second system consists of an electrical time division multiplexer which proposed to enhance the transmitted power (downstream) and reduce the optical components, connectors and optical fibers inside the OLT, where four electrical delays have used with a combiner. Then a single modulator and single unshared light source will modulate the multiplexed signal, as shown in Fig. 3.7. Both TDM-PON systems consist of a PRBS generator and a return to zero (RZ) pulse generator used to generate the data of each user.

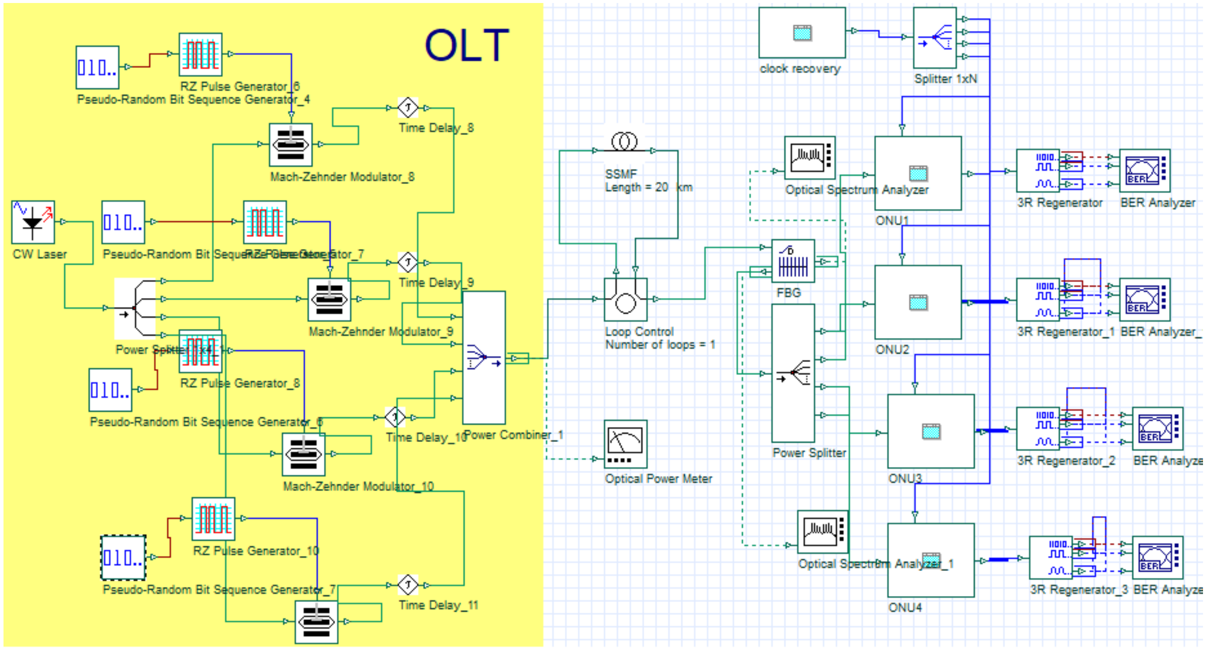


Fig. 3.6: The schematic block diagram of TDM-PON with four MZM, the transmission media is SSMF and FBG filter to compensate the dispersion.

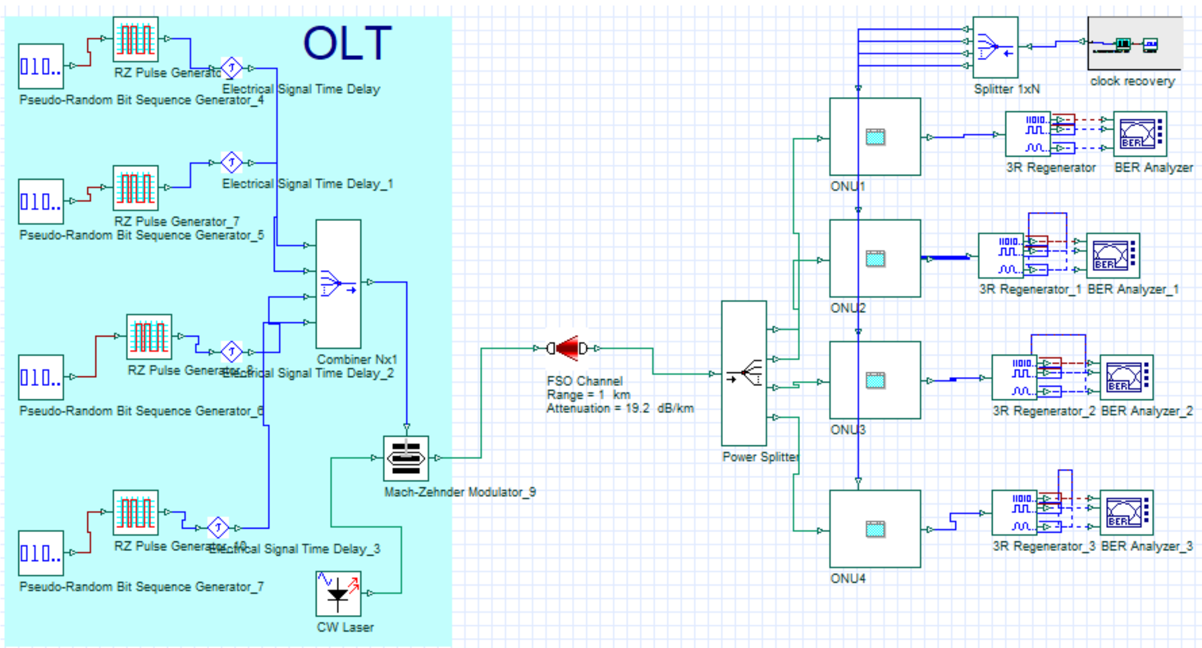


Fig. 3.7: The schematic block diagram of TDM-PON with one MZM, the transmission media is FSO.

At the receiving side, the optical signal that has passed through a specific channel goes to an optical power splitter to be divided for many copies; each one of those signal copies has entered into an ONU subsystem detector to extract the original information. In the de-multiplexing operation, a time delay and clock-recovery should be used to receive the custom signal for this user, as in Fig. 3.8. Subsequently, by PIN diode photodetector (dark current 5 nA, responsivity of 1 A/W and thermal noise 1.8e-024 W/Hz) the optical signal will be converted to an electrical signal with the help of a low pass filter (LPF) of cut-off frequency 0.75*Bit rate [56].

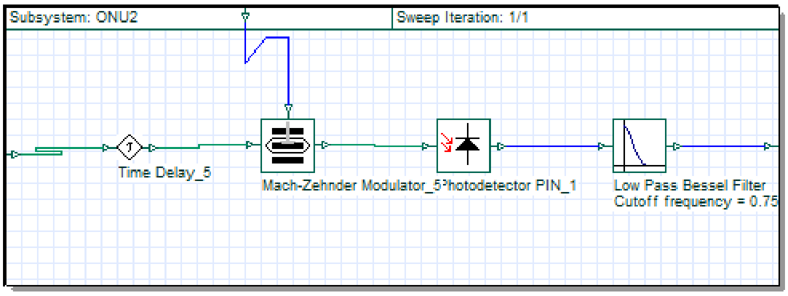


Fig. 3.8: The schematic block diagram of ONU subsystem.

Finally, a 3R-Regenerator is used to generate the original bit sequence of the data. The modulated electrical signal of the RZ pulse generator is used for BER analysis, to measure Q-factor value and BER. The Q-factor can evaluate the qualitative-performance of a receiver. It can be calculated by:

$$Q = \frac{i_H - \gamma_{opt}}{\sigma_{iH}} = \frac{\gamma_{opt} - i_L}{\sigma_{iL}} \tag{3.32}$$

$$Q = \frac{i_H - i_L}{\sigma_{iH} + \sigma_{iL}} \tag{3.33}$$

$$BER = erfc(Q) \tag{3.34}$$

Where γ_{opt} optimal value of the decision level, i_H and i_L are the current corresponding to the optical power level on the photodetector for both log.1 and log. 0 levels.

In this section, to evaluate the proposed TDM-PON system performance, three scenarios have been used for the channel. The first scenario is an SSMF of the attenuation coefficient of 0.2 dB/km, dispersion 16.75 ps/nm/km, non-linearity refractive 2.6e-20 m2/W and dispersion slope 0.075 ps/nm2/km with using FBG filter as a dispersion compensator and without using an amplifier, as in Fig. 3.6.

The second scenario is the FSO as in Fig. 3.7, where there is no dispersion and large attenuation relative with the atmospheric conditions like haze, rain, hot and dry which are dramatically affect the power received as shown in the equation 2.1. More losses can also increase the attenuation of FSO channel due to mispointing, scintillation and other perturbations. That can be defined as additional losses [26].

The third scenario of the optical transmission media is long optical fiber distance which consists of a sequence of SSMF/DCF/SSMF with appropriate lengths that ensure almost zero chromatic dispersion, as in Fig. 3.9. To reach a long distance optical power amplifiers must be used to compensate the power dissipated by the fiber. In this work, EDFAs of 4 dB noise figure and 22 dB gain have been used. The DCF of attenuation coefficient of 0.5 dB/km and dispersion (D_{DCF}) of -170 ps/nm/km have been used in this work. The total compensation of the dispersion (D_T) should be equal to zero for a certain length of the DCF (L_{DCF}). To compute this length, the following expression can be used [57].

$$D_T = D_{SMF}L_{SMF} + D_{DCF}L_{DCF} = 0 \tag{3.35}$$

$$L_{DCF} = -\frac{D_{SMF}L_{SMF}}{D_{DCF}} \tag{3.36}$$

Where L_{SMF} and D_{SMF} are the length and the dispersion of the SMF respectively.

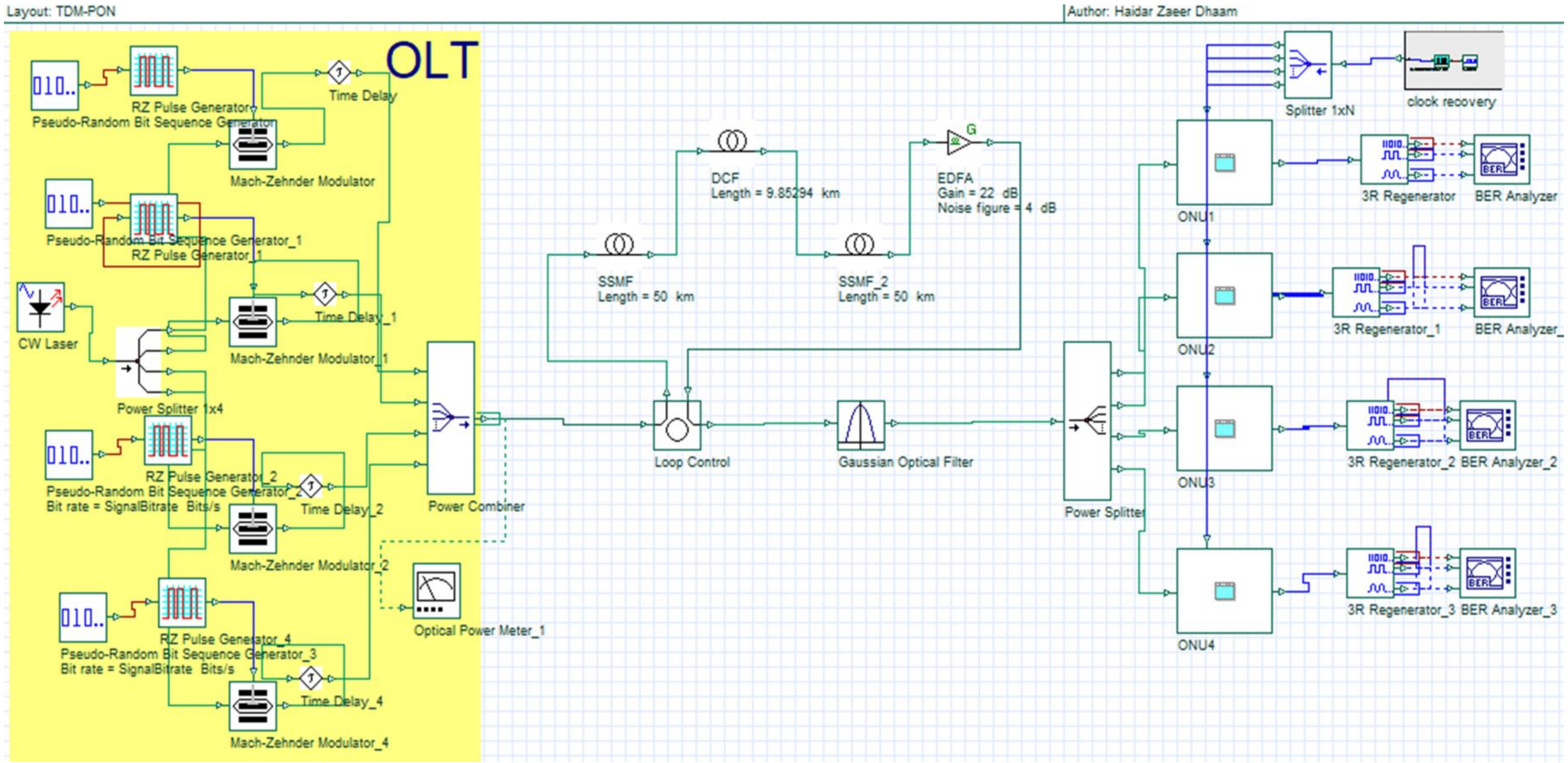


Fig. 3.9: The schematic block diagram of long reach TDM-PON over 329.55 Km, dispersion compensation based on

3.4 Hybrid System Design

In this section, two hybrid systems have been proposed to enhance the scalability and increase the number of simultaneous homes. The first is OCDMA over OTDMA. This system can be used in the FTTH network efficiently in both downstream and upstream. The second system is TDM-PON over OCDMA. This hybrid system can be used for downstream of FTTH network.

3.4.1 OCDMA over OTDM

The proposed architecture which is based on OCDMA over OTDM can enhance the scalability and increase the number of simultaneous homes. Figure 3.10 shows the design of a highly scalable hybrid system based on OCDMA over OTDM. Each OCDMA group of M-homes, and after coding process, will be grouped together by optical power combiner, and multiplexed with other groups by an optical time division multiplexer to implement N channels (time slots) of OTDM network. Each channel will carry out a particular OCDMA group, as illustrated in Fig. 3.11. Each OTDM transmitter is able to transmit data by a fixed period (t_{Ch}). This approach allows reusing of the same OCDMA codes by other groups in different time slots and allows N groups of M-homes of OCDMA to transmit data over OTDM system by reusing the same OCDMA hardware in all groups. The scalability of this hybrid system depends on the reuse factor (the number of the OTDM channel (N) where larger N leads to more users and less bandwidth per user). Comparing with only OCDMA system, the proposed hybrid system provides an increasing in the total number of FTTH's premises by N times. The maximum simultaneous homes (K) of this hybrid OCDMA-OTDM system can be expressed as:

$$K = M \times N \tag{3.37}$$

At the receiving side, to extract the information of a particular user, the time division de-multiplexed extract the channel that includes the signal of this user then it passes through decoding process of the OCDMA system.

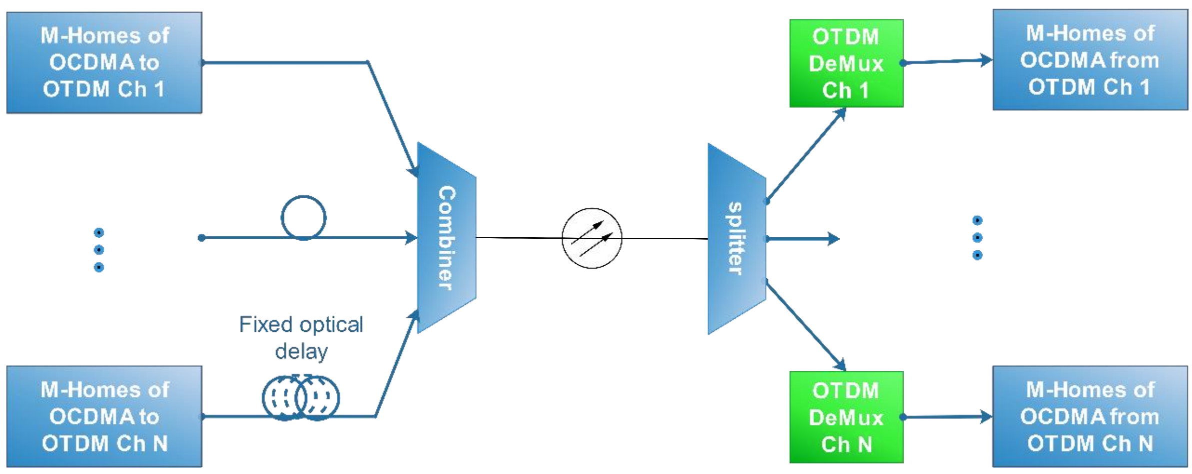


Fig. 3.10: OCDMA over OTDM hybrid system.

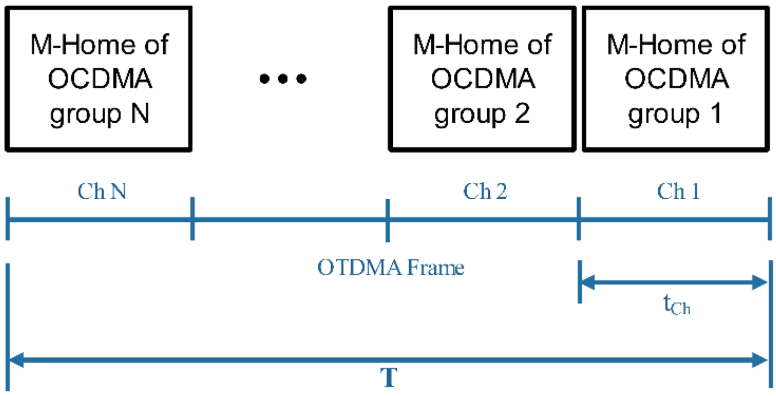


Fig. 3.11: M-Home of OCDMA groups into N-channel of OTDMA frame.

Figure 3.12 is the simulation design of the OCDMA over OTDM system with four OCDMA groups and four OTDM channels, each OCDMA group consists of six users coded by 2D-MD (P/W) (sections 3.2.2 and 3.2.3) with W=3. This is clear in the transmitter and receiver subsystems as in Figures 3.13 and 3.14.

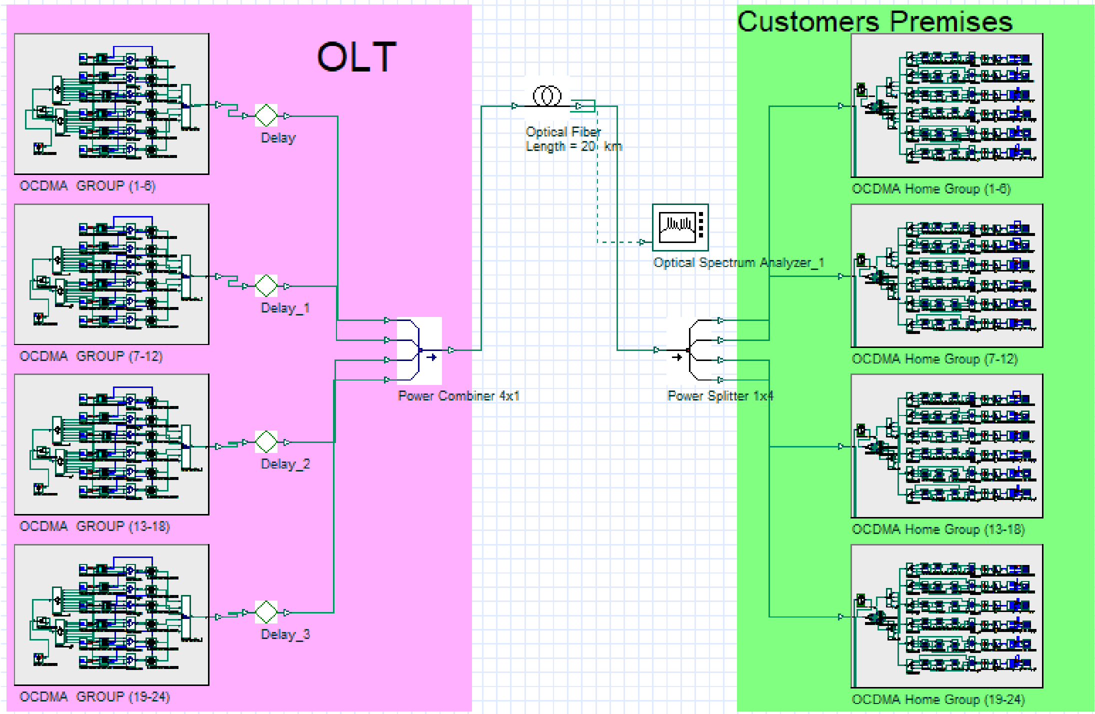


Fig. 3.12: The schematic block diagram of OCDMA over OTDM hybrid system of 4 OCDMA groups and 4 OTDM channels.

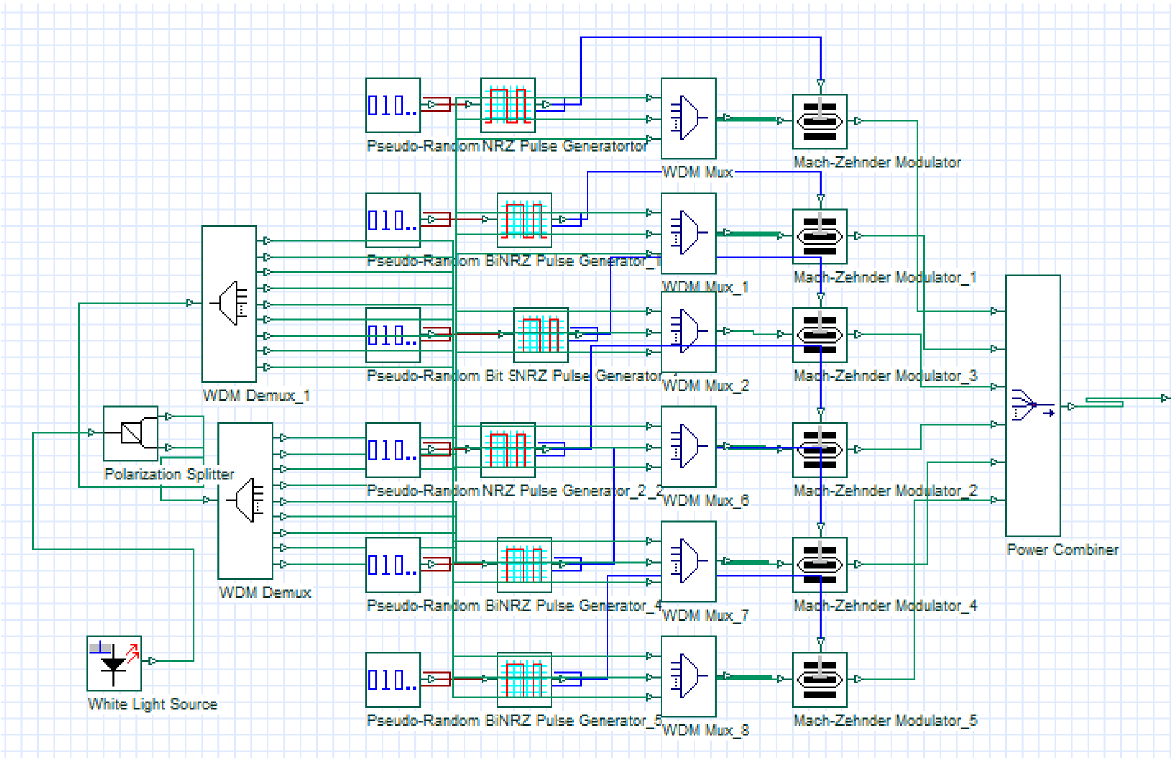


Fig. 3.13: An OCDMA group transmitter subsystem of 6 users encoded by triple weight 2D-MD (P/W) encoder.

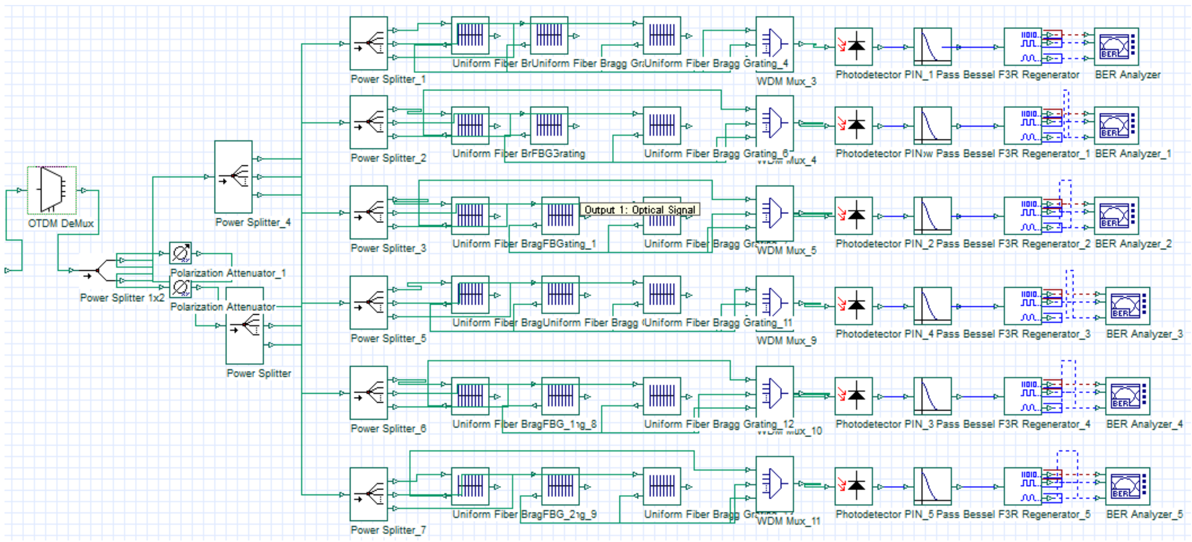


Fig. 3.14: An OCDMA group receiver subsystem of 6 users decoded by triple weight 2D-MD (P/W) decoder.

3.4.2 OTDM over OCDMA

The proposed 10G-TDM-OCDMA-PON hybrid system is based upon TDM bit-interleaving PON (section 3.3) and 2D-MD (P/W) code for OCDMA stage (sections 3.4.2 and 3.4.3). An FTTH downstream network of 16 homes and 4 channels of high-speed TDM is simulated as illustrated in Figures 3.11 and 3.12. In the OLT, the time division multiplexer of N channel has N number of user where each slot time would be assigned for a specific ONU, the same multiplexer will be used with all TDM groups, and the only difference between them is the OCDMA encoder, where each TDM group has a different OCDMA code by use varies wavelength and polarization. The TDM signal will modulate over the encoded light wave by the MZM, then the modulated signals are grouped together by a power combiner. In the receiving side, the power splitter and polarization attenuator have been utilized to separate the polarization resides signal. FBGs are used as dispersion compensators and OCDMA decoders to pass through only the light signal that is assigned to a certain OTDMA group. A power splitter has used to split the light signal for all homes then an optical time division de-multiplexer is placed inside each ONU to recover the sent information to this ONU.

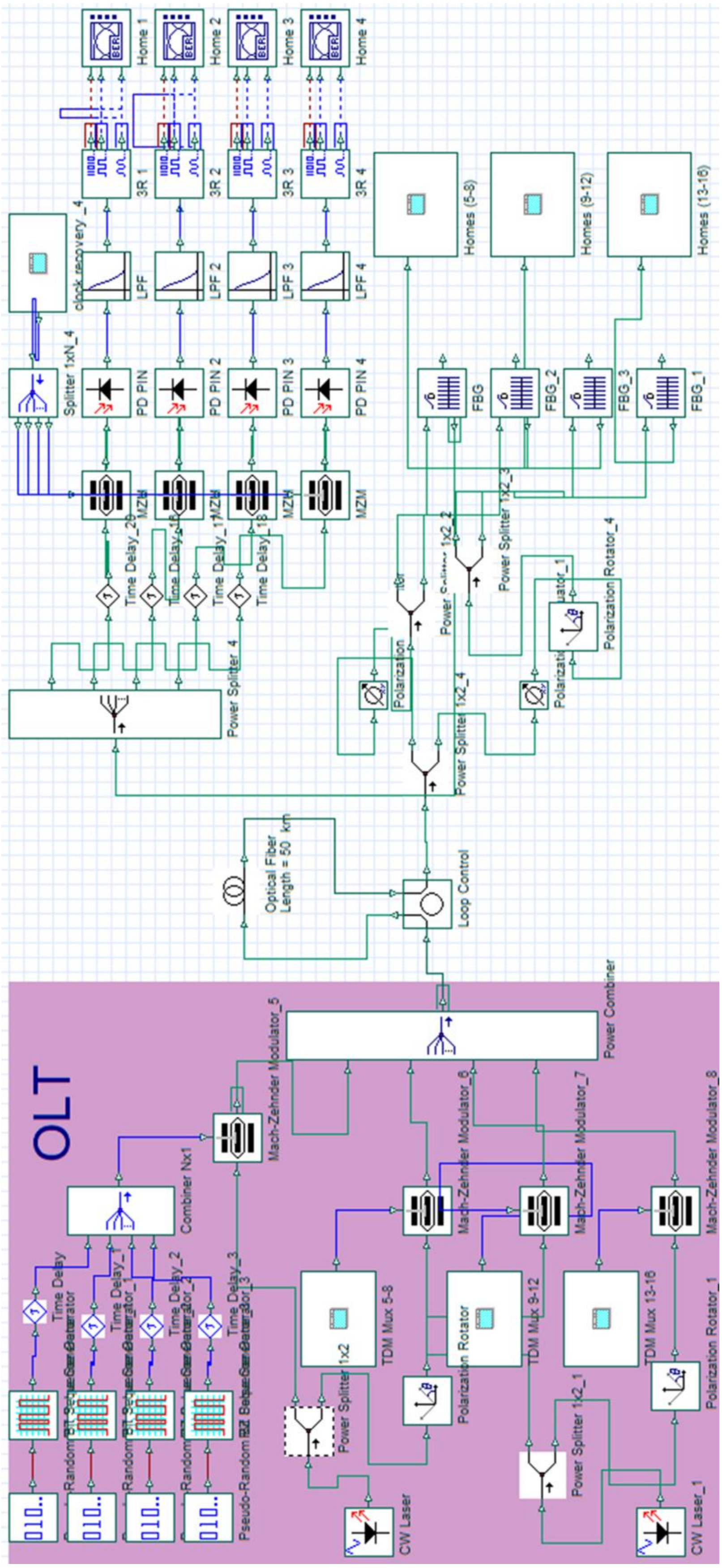


Fig. 3.15: 10G-TDM-OCDMA-PON hybrid system with 16 home coded by single weight 2D-MD (P/W) OCDMA and 4 channel of TDM

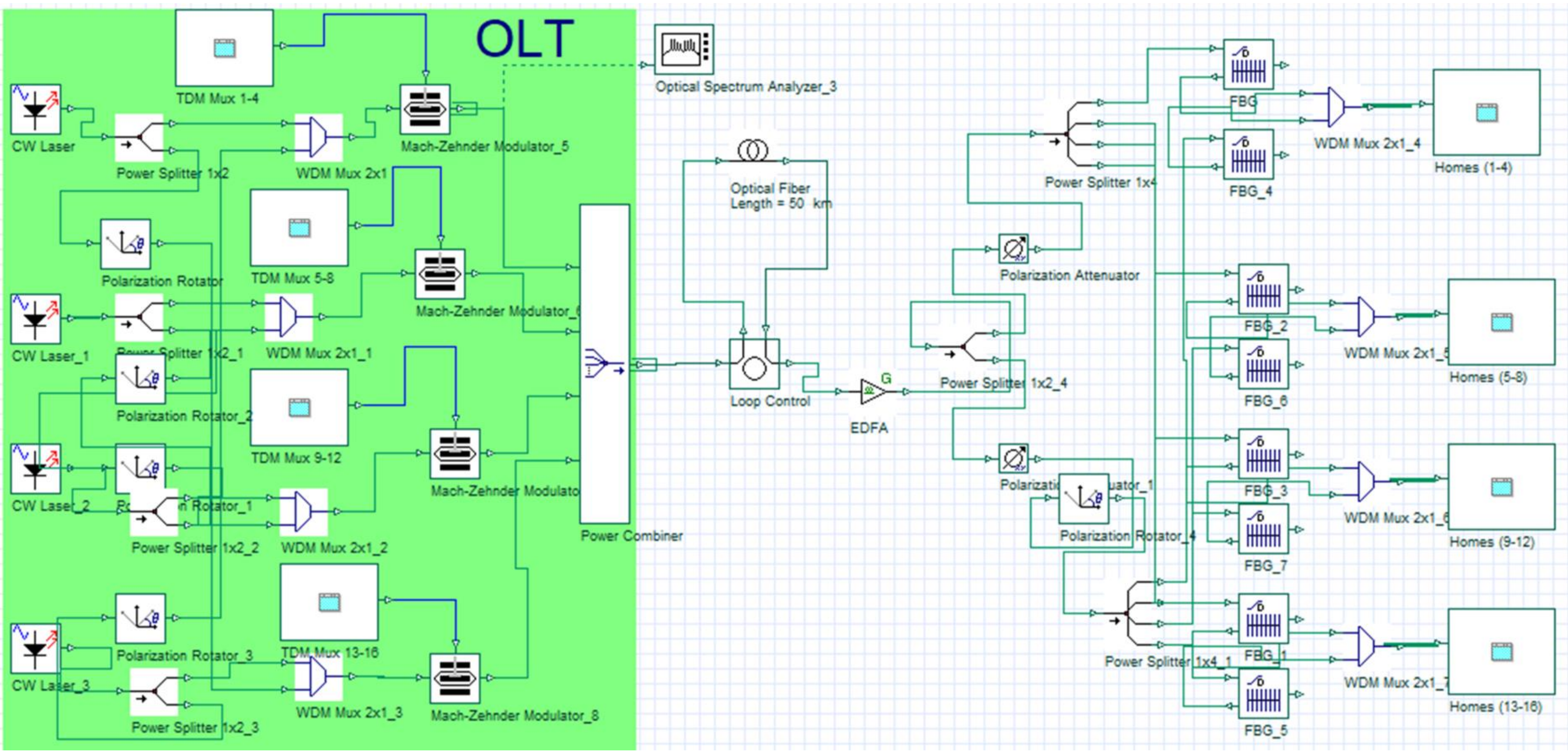


Fig. 3.16: 10G-TDM-OCDMA-PON hybrid system with 16 home coded by double weight 2D-MD (P/W) OCDMA and 4 channel of TDM

3.4.3 Bidirectional FTTH System Design

Figure 3.17 shows the proposed design of hybrid 10G-TDM-OCDMA-PON FTTH network based on (2D P/W and 1D) MD code that has been chosen as a best optical code for a network that has more scalability. Bidirectional symmetric PON of sixteen customers' homes has been simulated with 10 Gbps data rate for both downstream and upstream. Each OCDMA group of four homes with the same color has the same code and each home within a certain group has different time slot (channel). The proposed system consists of five main parts: OLT, feeder network, distribution network, drop network and costumers' homes. The OLT has 2D-MD OCDMA encoder (based on two CW Lasers, 2 polarization rotators and 2 power splitters), four subsystems (transceivers of OCDMA groups), four FBG filters (work as direct decoders and dispersion compensators), four power splitters (1x4) and two power combiners (4x1). The feeder network has two optical fibers for both downstream and upstream and loop controls to control the number of the optical fiber loops. The distribution network contains the optical distribution cables and the distribution passive node (local convergence point) of main multiplexer (4x1) and demultiplexer (1x4). The drop network includes the drop node (network access point) and the optical drop cables that connect the drop node with the costumers' homes.

The subsystem of OCDMA transceiver (in the OLT side) consists of the transmitter/receiver that connects toward/from four homes using the same code and four TDM channels, as demonstrated in Fig. 3.18. On the top of this figure, there is an OTDM receiver of four signals, and under it there is a TDM transmitter that has been built to transmit the data toward four homes where the encoded optical signal is considered an input to this subsystem before the modulation process. The TDM system have been described in section 3.3. Since the OCDMA encoder is not involved here, the subsystem can be repeated M times depending on the number of the OCDMA codes; hence, this repetition of the hardware can reduce the cost of the OLT.

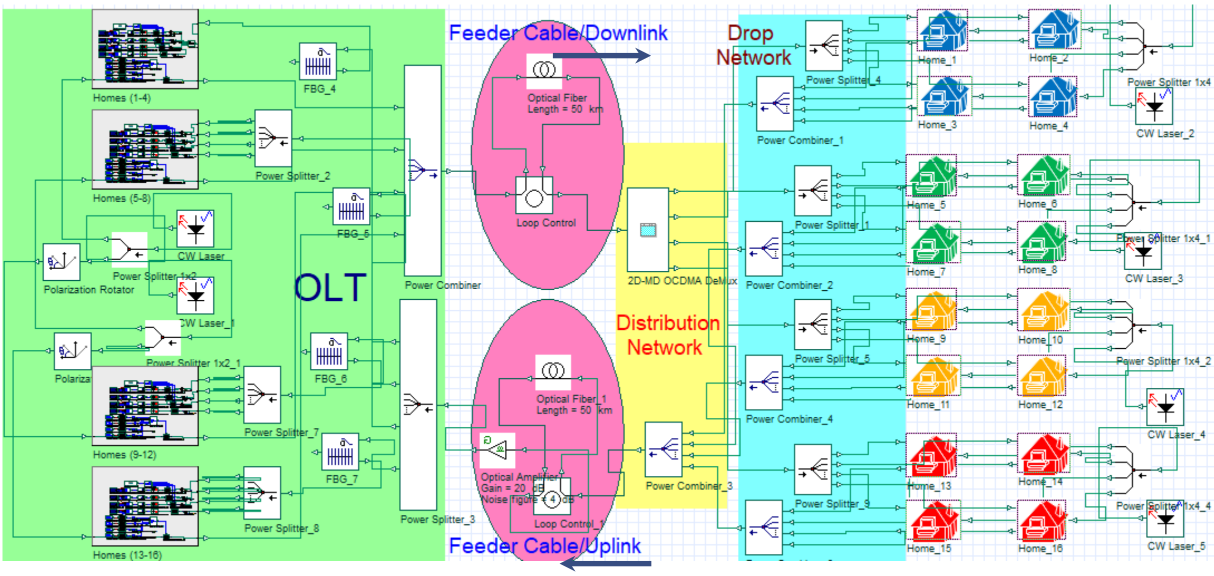


Fig. 3.17 : Bidirectional FTTH network based on hybrid system of 10G-TDM-OCDMA-PON with M=4, N=4 and the total simultaneous homes K=16.

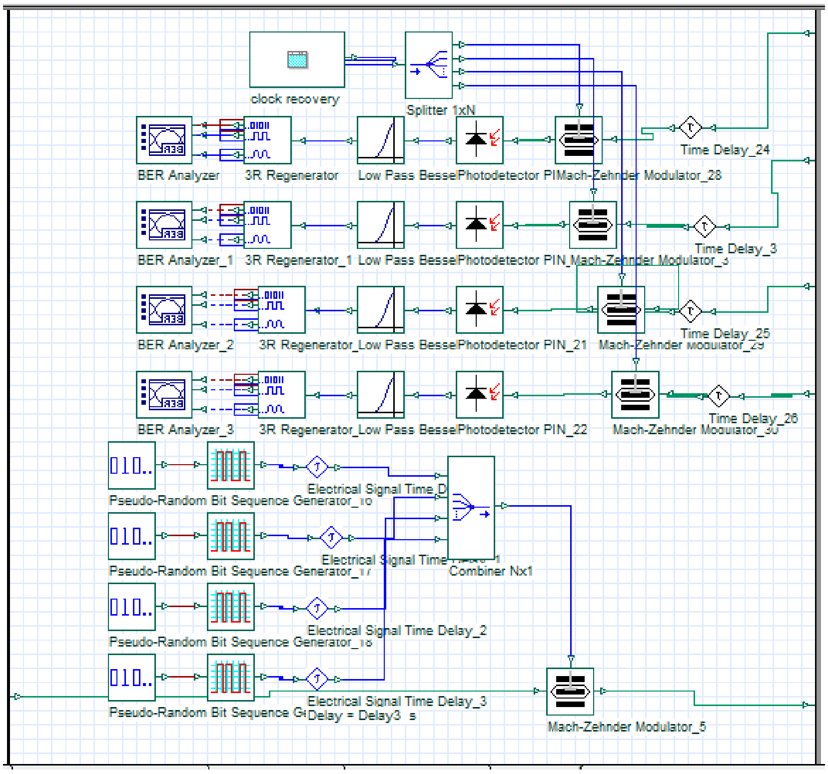


Fig. 3.18: The Subsystem Schematic Diagram of the TDM/OTDM Transceiver of Homes (1-4).

Figure 3.19 illustrates the components of the 2D-MD OCDMA (P/W) demultiplexer, which consists of three power splitters (1x2), two polarization attenuators, a polarization rotator, and four FBGs. This demultiplexer is described in section 3.2.3.

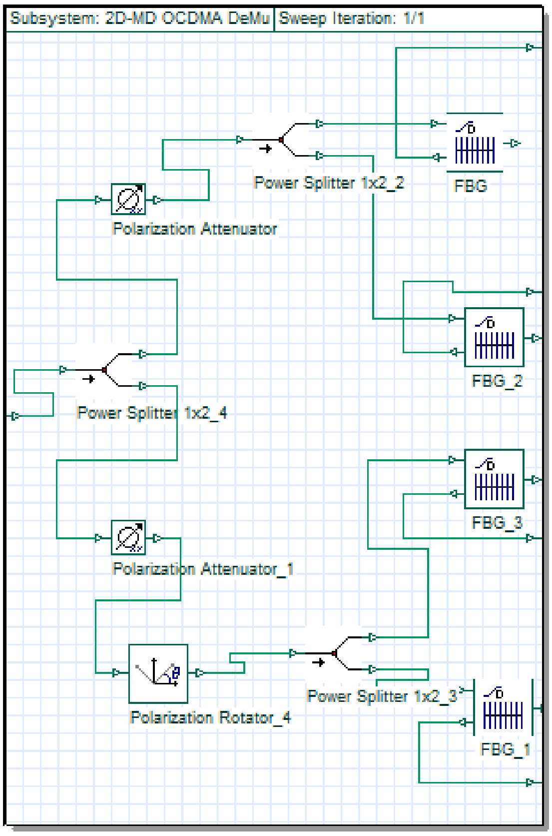


Fig. 3.19: The Schematic Diagram of 2D-MD OCDMA (P/W) Demultiplexer Subsystem.

Bit interleaving OTDM/OTDMA have been used to receiving and sending data from and toward the OLT. The idea of the subsystem's work is described in section 3.3. The port on the right side is the input of an encoded optical signal that has been encoded before using 1D single weight MD code, as in Fig. 3.20. The ONU of each home in the proposed system has a certain time slot on both downstream and upstream.

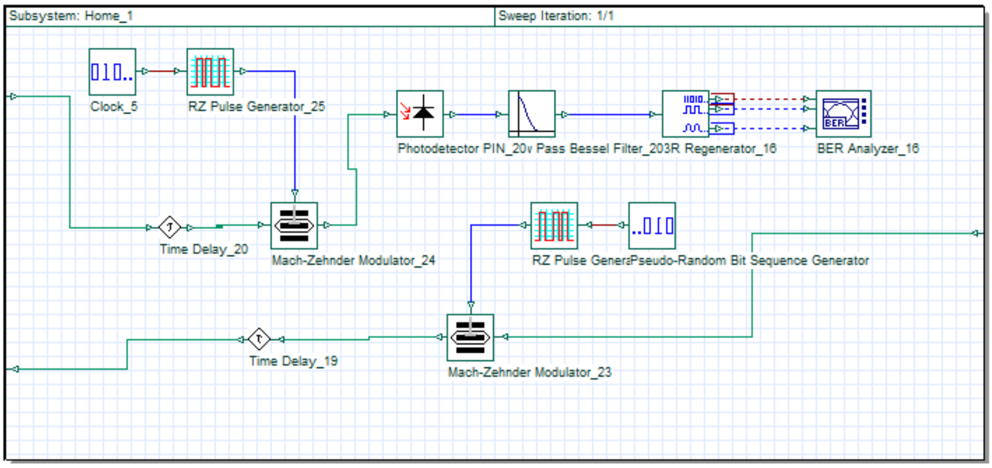


Fig. 3.20: The Subsystem Schematic Diagram of an OTDM Transceiver of a Customer's Home.

RESULTS AND DISCUSSIONS

4.1 Introduction

In the chapter three the OCDMA, TDM-PON and hybrid systems have been designed for FTTH network. The results of the designed systems will be presented in this chapter. The systems design and results were simulated by using Optisystem software v.15. The results show that the hybrid system has provided a high performance. FTTH network offers an increase in the number of homes while ensuring sufficient data rate and acceptable bit error rate.

4.2 Performance Analysis of OCDMA System

According to equations 3.13, 3.14 and 3.31, the BER of 1D&2D of the MD and ZCC codes have been achieved mathematically under conditions of 622 Mbps, power spectral density (Psr = −10 dBm), weight (W = 4), and the number of active users, K, up to 200. The parameters of equations 3.13, 3.14 and 3.31 that are used to find out the numerical calculation are listed in Table 1. The BER versus number of users are shown in Fig. 4.1 which clarifies that (for the maximum acceptable value of BER 10^{-9} [30]) the number of the total supported of users for the 2D codes is doubled in compression with 1D codes. Meanwhile, the MD codes show the same performance compared to the ZCC codes. This behaviour because the only difference between those codes is the arrangement of the ones where both codes give better performance with comparison to other types of SAC-OCDMA codes [58], as illustrated in Fig. 3.1.

Table 4.1: Typical Analysis Parameters.

Symbol	Parameter	Value
v_c	Operating wavelength	1550 nm
Δv	Linewidth broadband source	3.75 THz
P_{sr}	Broadband effective power	−10 dBm
B	Electrical bandwidth	311 MHz
T_n	Receiver noise temperature	300 K
η	Photodetector quantum efficiency	0.6
R_L	Receiver load resistor	1030 Ω
h	Planck's constant	6.66×10^{-34} Js
e	Electron charge	1.6×10^{-19} C
K_b	Boltzmann's constant	1.38×10^{-23} J/K

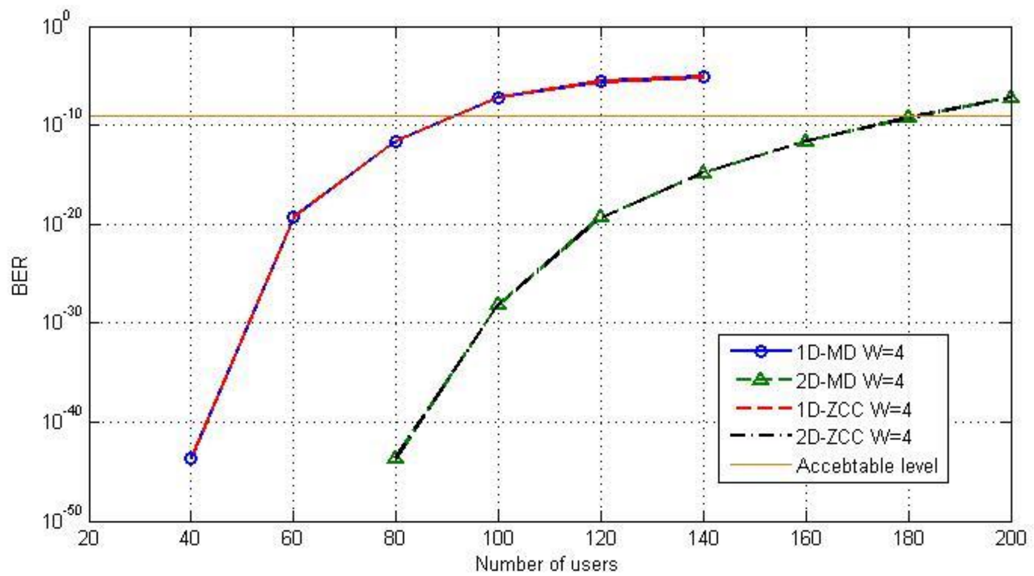


Fig. 4.1: Comparison BER performance versus number of users for 1D-2D MD and 1D-2D ZCC codes

Figure 4.2 shows that the higher number of weight the better performance of the system as this can be seen with 1D-MD W=1 compared to 1D-MD W=4. On the other hand, it must be taken into account that this increment of the weight will make the encoder and decoder more complex.

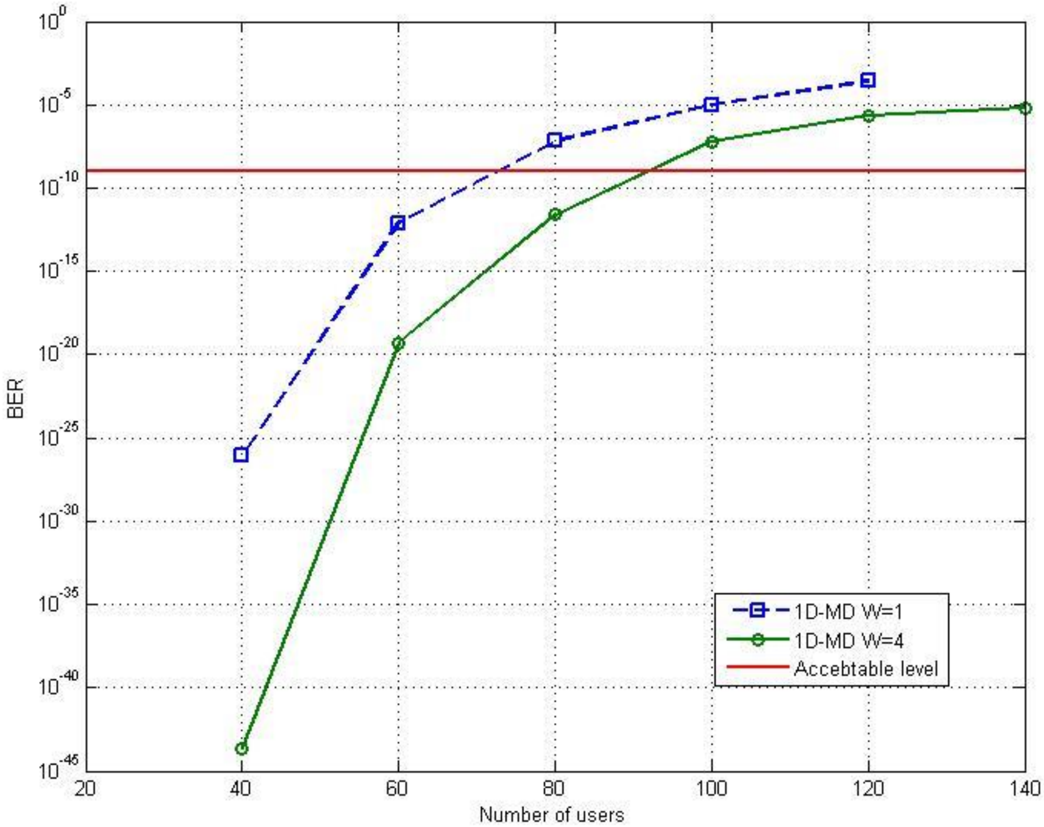
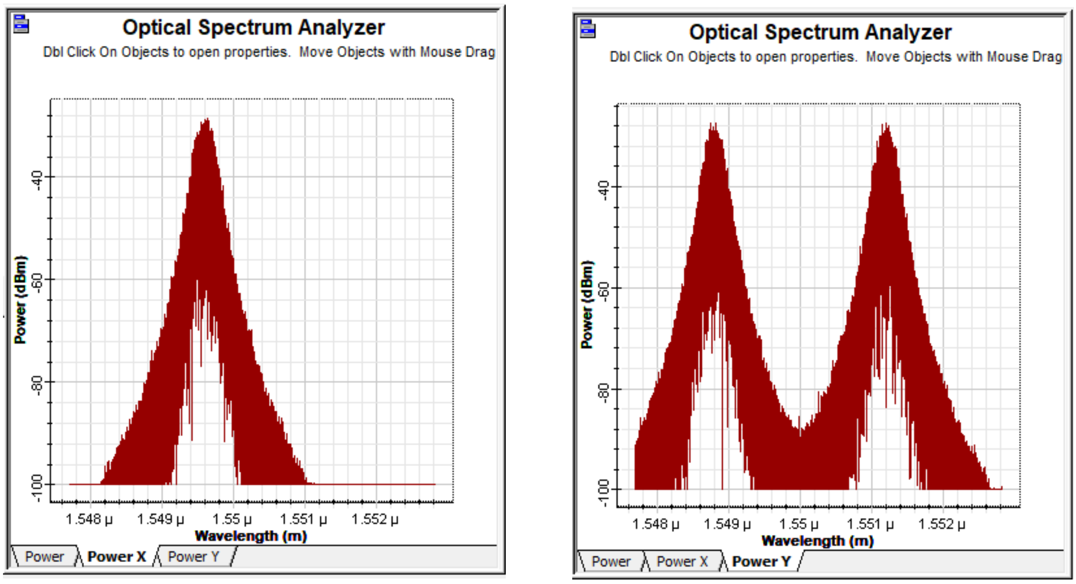


Fig. 4.2: Comparison BER performance versus number of users for 1D-MD codes with weight equal to one and four

Figure 4.3 demonstrates a sample of the optical spectrum of 2D code (polarization/wavelength) with weight equal to three. The difference between (a) and (b) is 90° of polarization. The weight is divided into two angles of polarization (X and Y) where this allows the reusing of those wavelengths another once by other codes.



(a) (b)

Fig. 4.3: Optical spectrum of a 2D (polarization/wavelength) code with W=3.

Figure 4.4 demonstrates the optical spectrum of an OCDMA based on 1D-MD code with weight of three. Figure 4.4a shows the optical spectrum of the white light source that generates broad optical bandwidth. Figures 4.4b to 4.4d show the encoded light signals of three users by 1D-MD code where the weight is three (user1: 1548, 1549.5, 1551 nm, user2: 1548.5, 1550, 1551.5 nm and user3: 1549, 1550.5, 1552 nm). Figure 4.4e shows the spectrum of the combined signal of those three users at the receiver after 20 km of SSMF length, and Fig. 4.4f shows the spectrum of the first user signal at the receiver after the OCDMA direct decoder where the wavelengths of 1548, 1549.5, and 1551 other services like G-PON and video services, by considered many candidate systems such as WDM PONs, TDM PONs and hybrids system of those two technologies have been recovered.

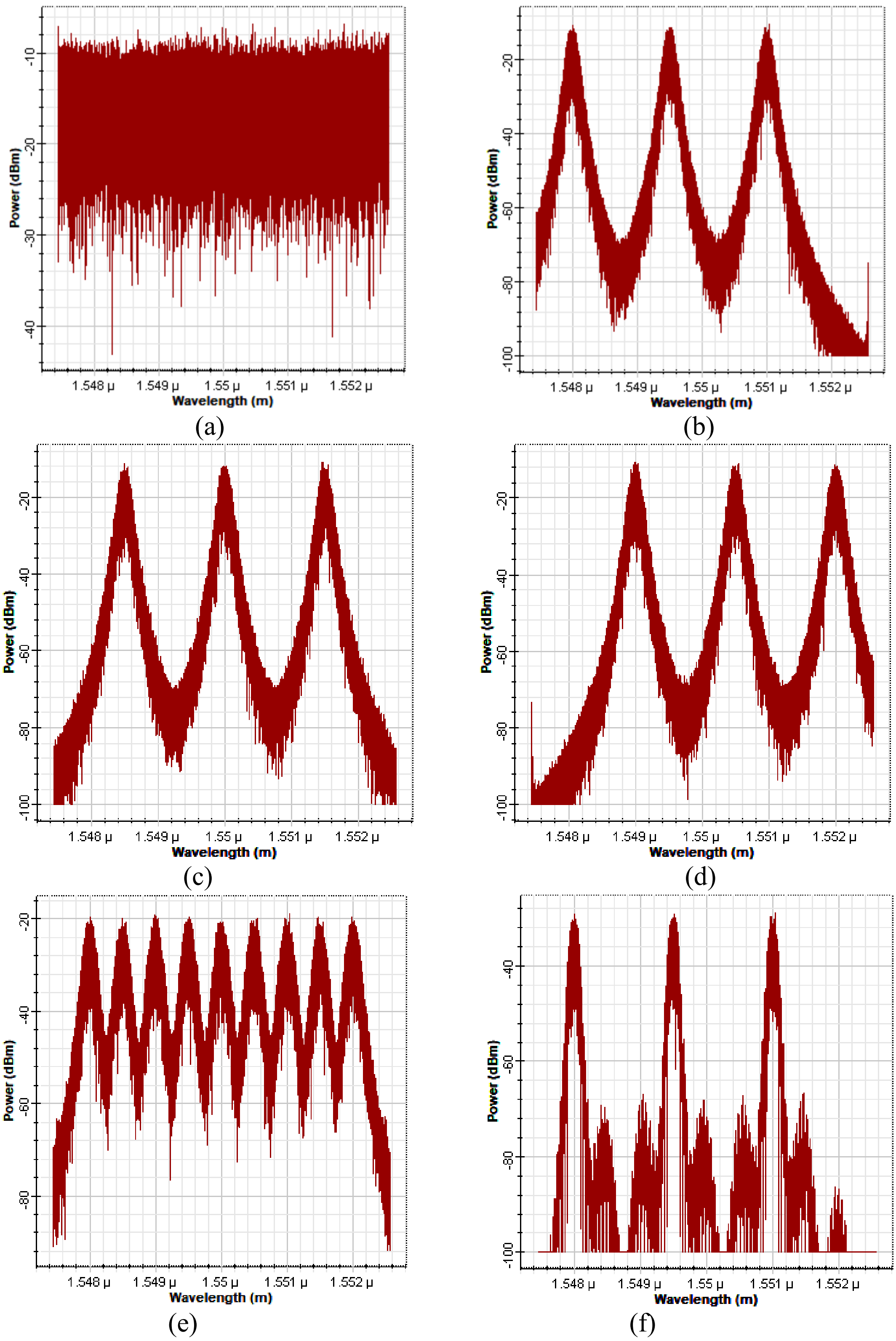


Fig. 4.4: Optical spectrum of (a) the white light source, (b) the modulated signal of first user, (c) the modulated signal of second user, (d) the modulated signal of third user, (e) all users signal after 20 km of SSMF length, and (f) the first user signal at the receiver, for 3 users 1D-MD OCDMA system with W=3.

Figure 4.5 shows the relationship between the 1D-MD, 1D-ZCC, 2D-MD and 2D-ZCC codes and distances in the single mode OFS taking into account the effects of attenuation, dispersion and nonlinearities. It also shows that 2D codes are more vulnerable to attenuation and dispersion in single-mode optical fiber cables and the performance of the 1D codes is much better presented compared with 2D codes. This is due to the differential group delay (DGD), PMD, additional noise and power dissipation of the extra devices in the system of 2D OCDMA. However, with this white light source (broadband source) and for 25 Km of fiber reaching about 10^{-20} of BER of 2D codes is quite enough for FTTH network.

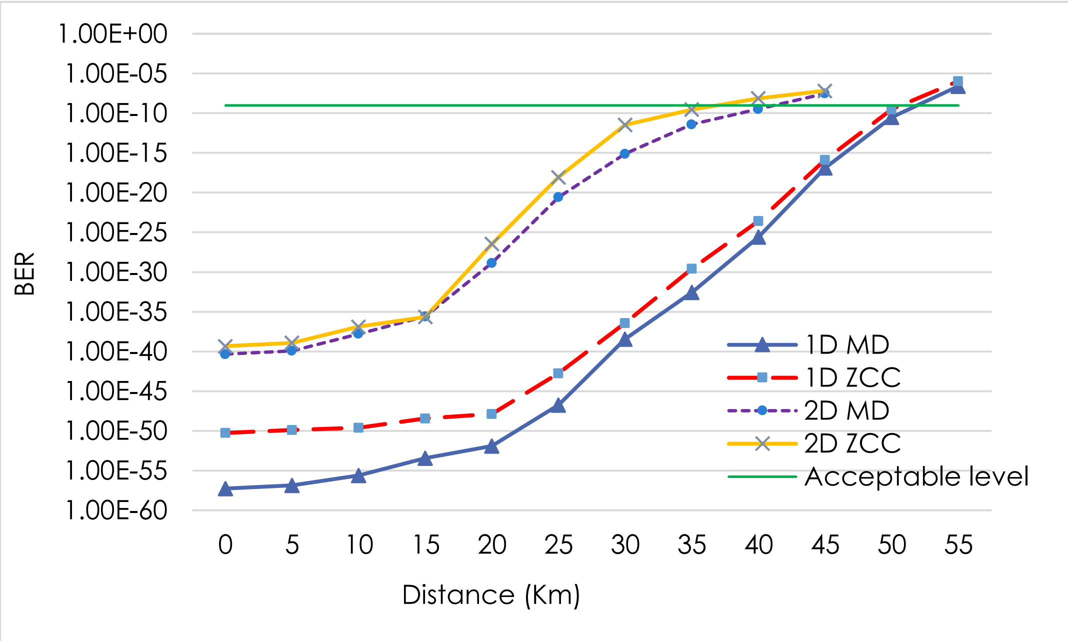


Fig. 4.5: BER versus distance for 1D MD, 1D ZCC, 2D MD and 2D ZCC codes with K=4, W=2 and 622 Mbps in OFS scenario

While Fig. 4.6 shows the relation between the 1D-MD, 1D-ZCC, 2D-MD and 2D-ZCC codes and distances in the FSO system at a heavy rain condition. The performance of 2D OCDMA is closer to the 1D OCDMA in this scenario. Additionally, for short distances, the power received does not have a powerful effect on the performance, and on contrary in the large distances.

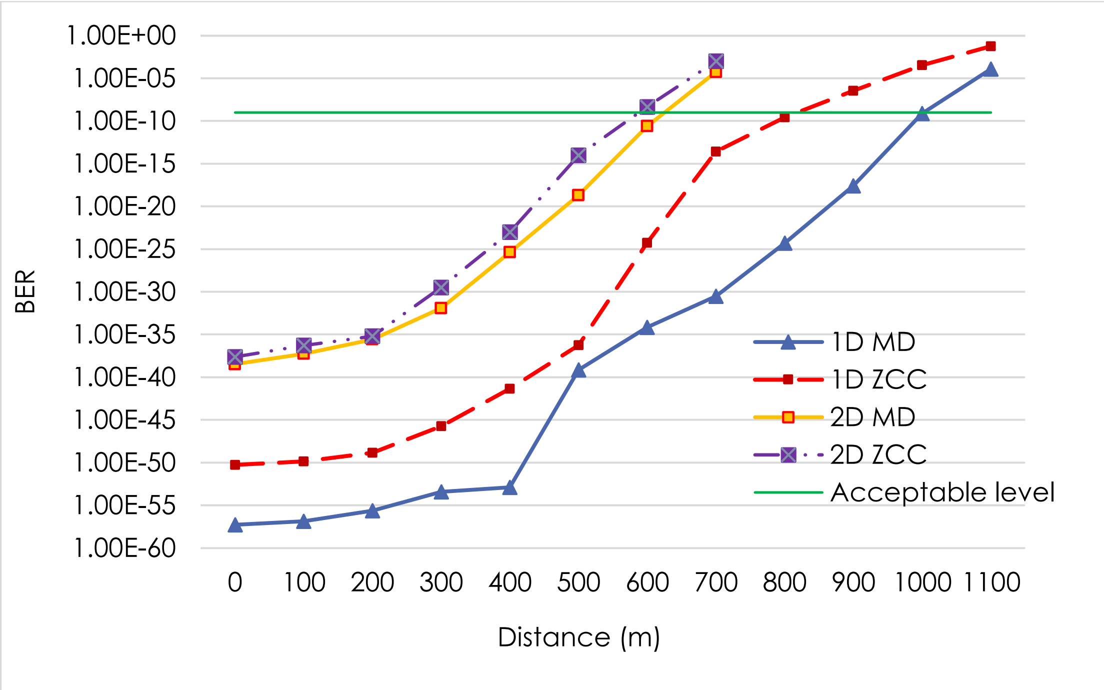


Fig. 4.6: BER versus distance for 1D MD, 1D ZCC, 2D MD and 2D ZCC with K=4, W=2 and 622 Mbps in FSO scenario under heavy rain condition

From Figures 4.5 and 4.6, it is noted that the MD code presented better performance than ZCC code in spite of the fact that both of them have the same code length and weight. This is due to the MD code has depended on the unity matrix only and has less susceptibility to turbulence effect.

Figure 4.7 shows a comparison between different weather states of free space optic channel for 2D-MD OCDMA system with K=4, W=2 and 622 Mbps. In the FSO, the attenuation is a weather state dependent where in the very clear air the visibility can reach 50 km while in the dense fog it can be visible for only 50 m. However, the worst case in Iraq in the normal circumstances is the heavy rain, table 4.2 shows the International Visibility Code for various types of weather conditions [59].

Table 4.2: International visibility codes for different weather conditions

Weather conditions/ Precipitation (mm/hr)	Visibility (km)	Attenuation (dB/km)
Heavy rain/storm (75)	1	13.8
Very light fog /Strong rain (25)	1.9	6.9
Light mist / Average rain (12.5)	2.8	4.6
Very light mist/Light rain (2.5)	5.9	2
Clear air/ Drizzle (0.25)	18.1	0.6
Very clear air	50	0.19

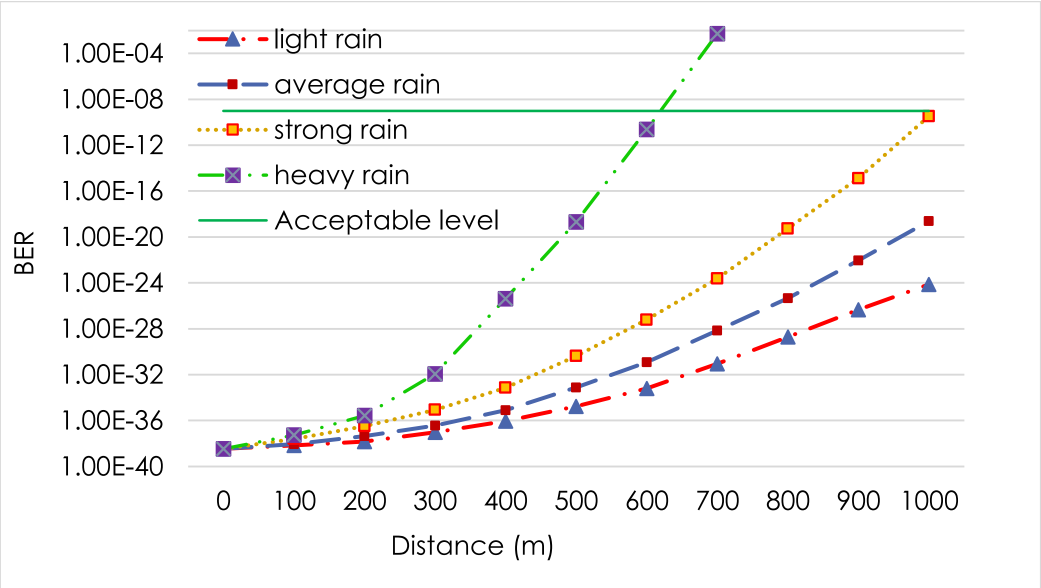


Fig. 4.7: BER versus distance of OCDMA system with 2D-MD, K=4, W=2 and 622 Mbps in FSO Scenario for different weather condition

Figures 4.8 and 4.9 show the 2D-MD at 10 Gbps (with CW laser source) and the 2D-MD at 622 Mbps (with white light source) eye diagrams respectively with W=2, K=4 and 30 km of SSMF distance. It can be noted that the 2D-MD with source of CW laser system gives better performance than 2D-MD with white light source system where the narrower eye diagram, even the first system has much higher data rate. This behaviour is due to the level of power spectral density that depends on the optical bandwidth range of the light source, which is broad bandwidth in the white light source on the contrary of CW laser source that has a low linewidth. In the eye diagram, closer eye leads to harder distinguish between ones and zeroes of the received signal.

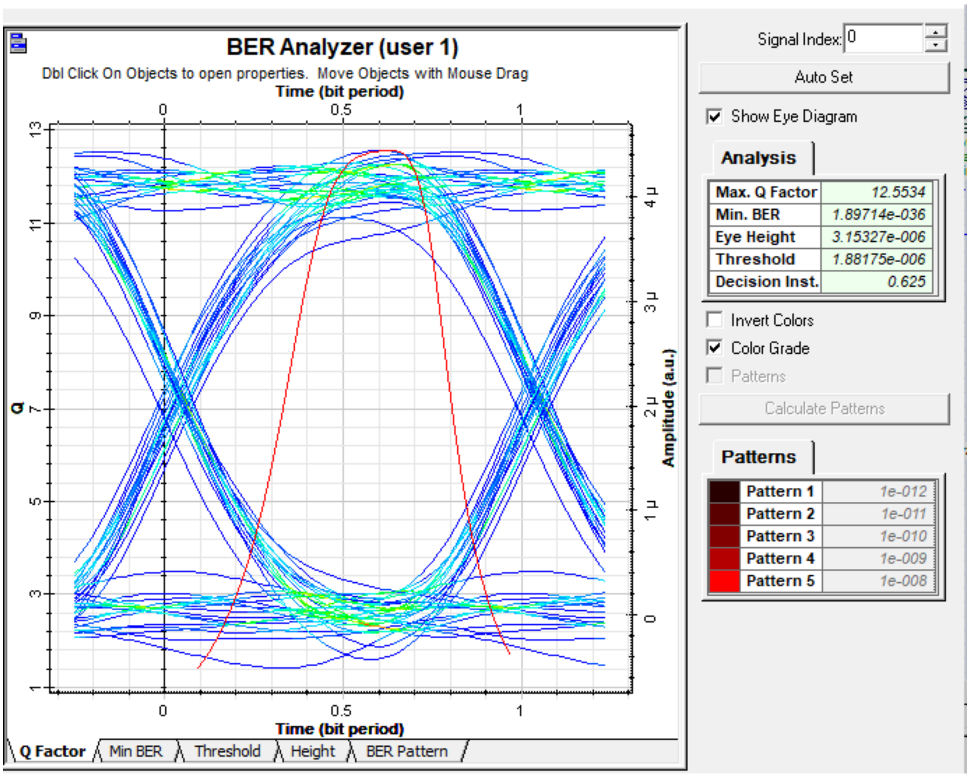


Fig. 4.8: Eye Diagram of the 2D-MD Code at 10 Gbps and 30 km of SSMF with W=2 and K=4.

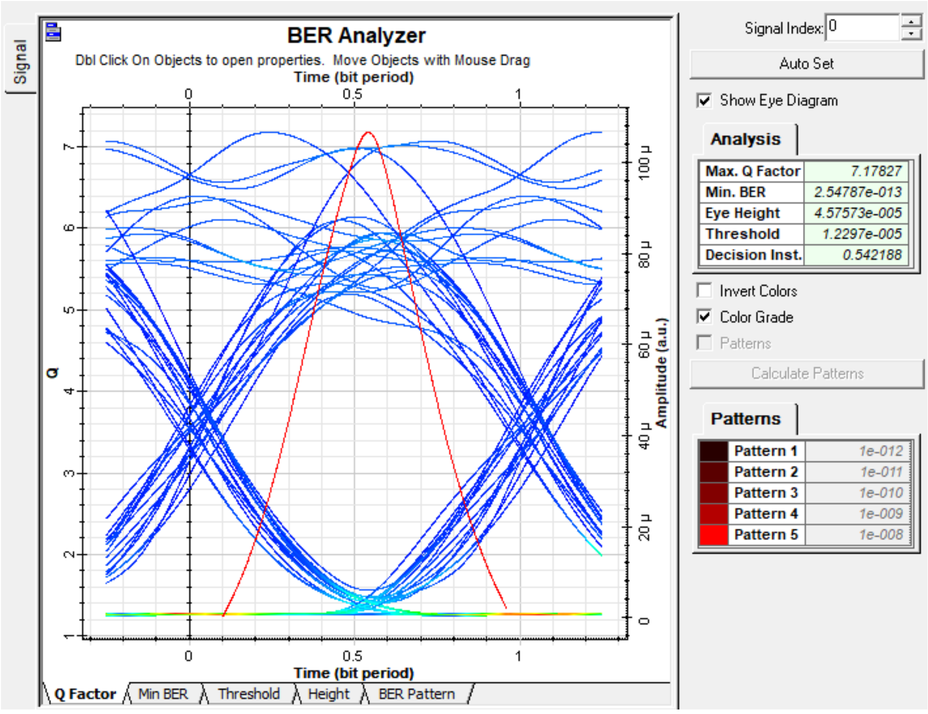


Fig. 4.9: Eye Diagram of the 2D-MD Code at 622 Mbps and 30 km of SSMF with W=2 and K=4.

The results of the OCDMA systems can show clearly that an OCDMA network using 2D-MD code is preferable in the FTTH network, which supporting larger number of ONUs and powerful with a high data bit rate.

4.3 Performance Analysis of TDM-PON System

To evaluate the performance of the proposed dispersion compensators of TDM-PON system (section 2.6.7), a comparison of dispersion compensation based on FBG and DCF by eye diagrams are considered in this work, as shown in Figures 4.10 and 4.11, with the same parameters of transmitters, channels (SSMF range of 110 Km without amplifier) and receivers. It can be noted that the RZ TDM-PON system with dispersion compensation based on DCF gives better performance than the RZ TDM-PON system with dispersion compensation based on FBG because eye in Fig. 4.11 has the larger eye opening. In the eye diagram, as the received pulses are more distorted in either phase or amplitude, the eye will appear more closed.

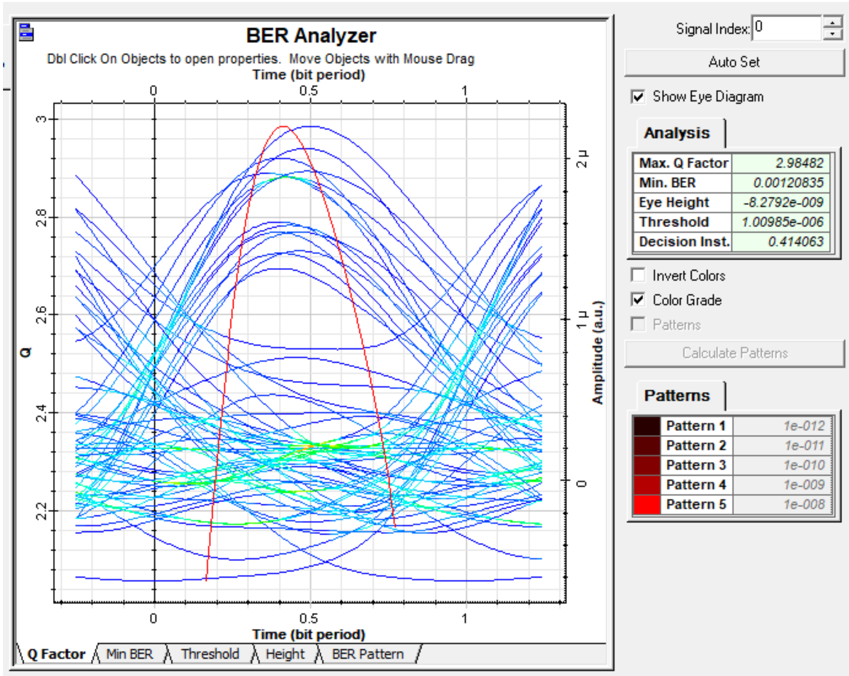


Fig. 4.10: Eye diagram of RZ TDM-PON system with 25 Gpbs, SSMF range of 110 Km without amplifier, and FBG as dispersion compensator.

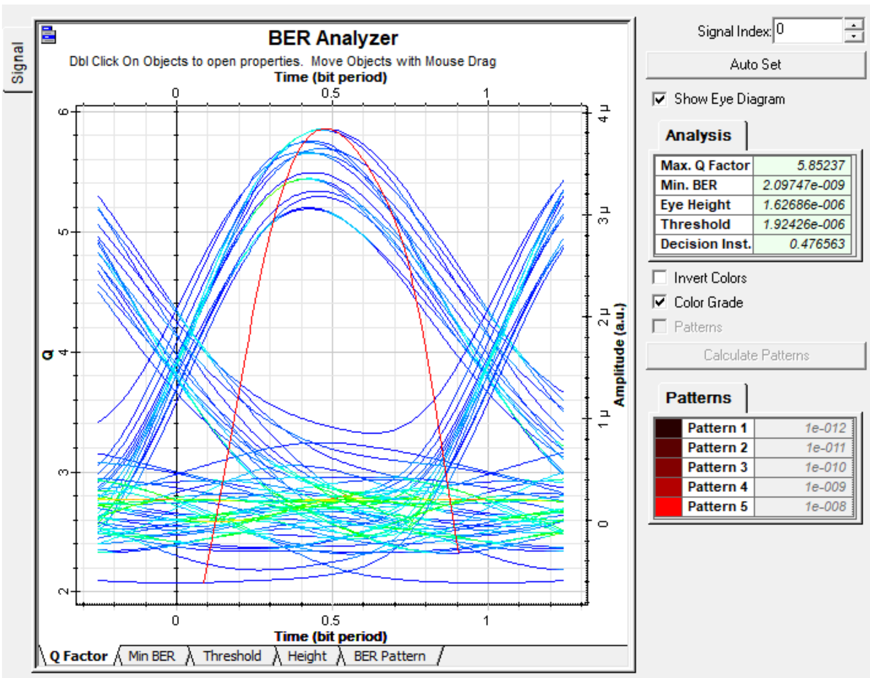


Fig. 4.11: Eye diagram of RZ TDM-PON system with 25 Gpbs, SSMF/DCF/SSMF range of 110 Km and DCF (without amplifier).

To evaluate the proposed TDM-PON system performance three scenarios have been used for the channel: SSMF with using FBG, FSO with heavy rain and the third scenario is SSMF/DCF/SSMF with EDFA (for more details see section 3.3).

Figure 4.12 shows the comparison between the Q-factor performance versus optical fiber distance of the first scenario of the channel (four users are linked to the OLT by SSMF without any amplifier and using FBG filter as a dispersion compensator). For TDM-PON, two types of transmitter have been used in the OLT (downstream): the first one uses four MZM as an external modulator to modulate data toward four users, while the second type of transmitter uses only single MZM for all those users as mentioned in section 3.3. However, Figure 4.12 shows that the first system (TDM-PON with transmitter of 4MZM) gives lower performance than the second system with 1MZM at 10 Gbps where the launched power is higher although the same laser diode with power of 5 dBm has used for both systems. The reason of using Q-factor for this comparison is the very low BER that has achieved with this system where CW laser has been used.

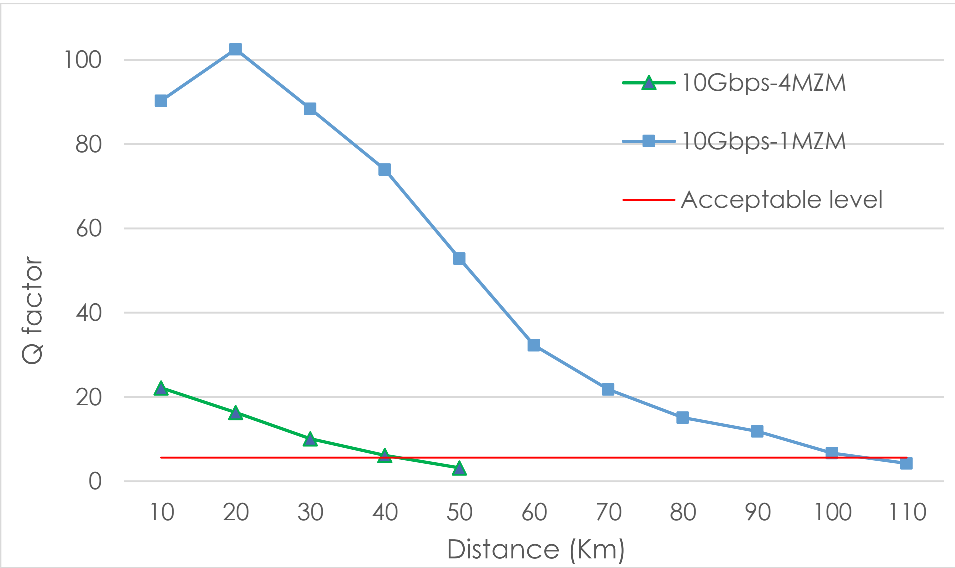


Fig. 4.12: Comparison Q factor performance versus optical fiber distance for two TDM-PON proposed systems with FBG (four users)

In the second system (with only one MZM) different bit rates are also evaluated as shown in Fig. 4.13. The signal of 25 Gbps per line stays above the acceptable level for about 92 Km without amplifier which gives better performance more than 40 Gbps, while the 50 Gbps is the worst case where low Q-factor even with short distances. According to those results, it can be noted that the increase of the bit rate leads to reduce the Q-factor at the same fiber length where this because the effect of dispersion is higher in a high bit rate system.

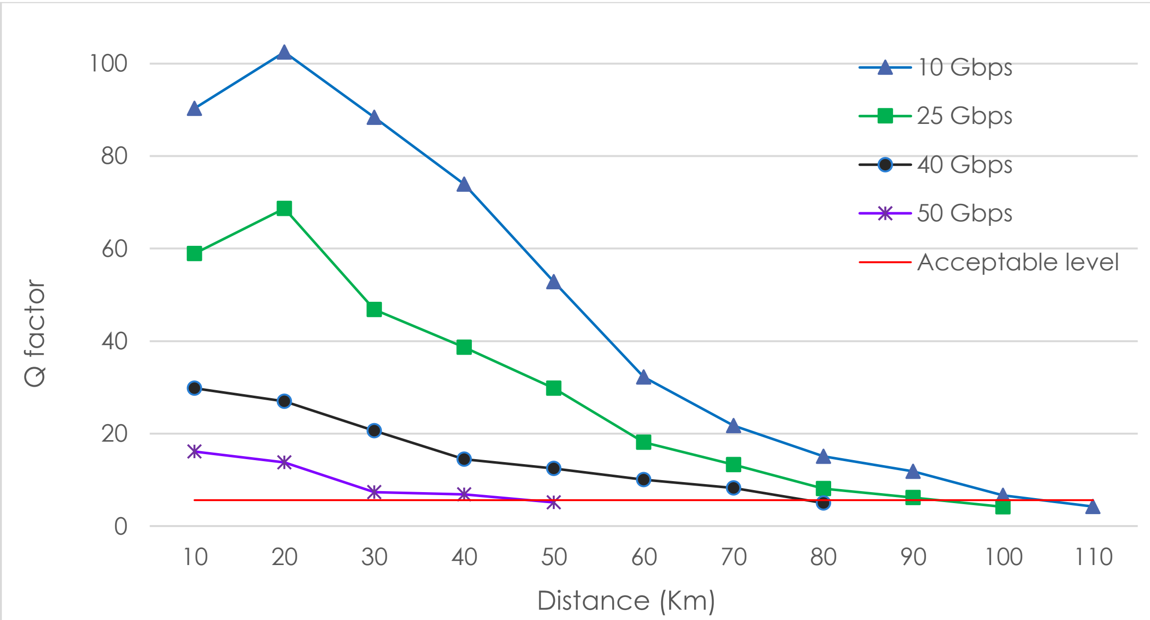


Fig. 4.13: Comparison Q factor Performance versus optical fiber distance for different bit rate of TDM-PON proposed system with only one MZM and FBG as a dispersion compensator (four users)

Figure 4.14 illustrates the comparison between the Q-factor Performance versus optical fiber distance of the second scenario, Four ONUs are linked to the OLT by long range of SSMF with EDFA amplifier of 4 dB noise figure and 22 dB gain and with using DCF as a dispersion compensator. Also, in this scenario, the TDM-PON of transmitter of one MZM gives better performance than the system that uses single laser and individual MZM per user at the same distance and bit rate. It can be noted from these results that the high bit rate signals do not reach long distances despite the existence of dispersion compensator. The steep drop in the Q-factor with the comparison to the performance of 10 Gbps TDM-PON due to the effect of dispersion is more in a high bit rate system.

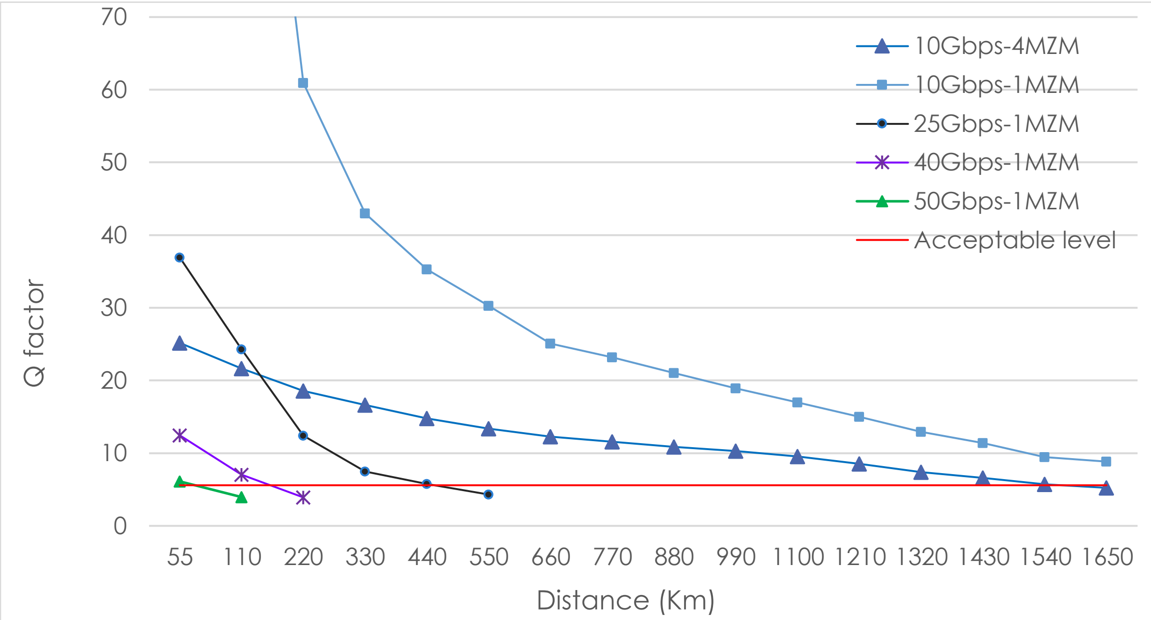


Fig. 4.14: Comparison Q factor Performance versus optical fiber distance for different bit rate and both TDM-PON proposed systems with DCF and EDFA (with four users)

In the result FSO system, as shown in Fig. 4.15, it can be noted that the increase of the bit rate has less Q-factor relative decrement than SSMF system because in the FSO system the light travels through the atmosphere instead of fiber. So there is no dispersion and only an attenuation can affect the light signal. As the attenuation is varying with the climate change, a large variation will occur to the power of the received signal. In this simulation a heavy rain attenuation of the FSO link is considered. Also it can be noted that the worst case is a 10 Gbps with single laser diode shared to four users and four MZM system where the launched power is less than the other systems. On the contrary the best performance is for 50 Gbps with EDFA amplifier. Hence, the author recommends to the use an optical amplifier before transmitting the signal through the free space.

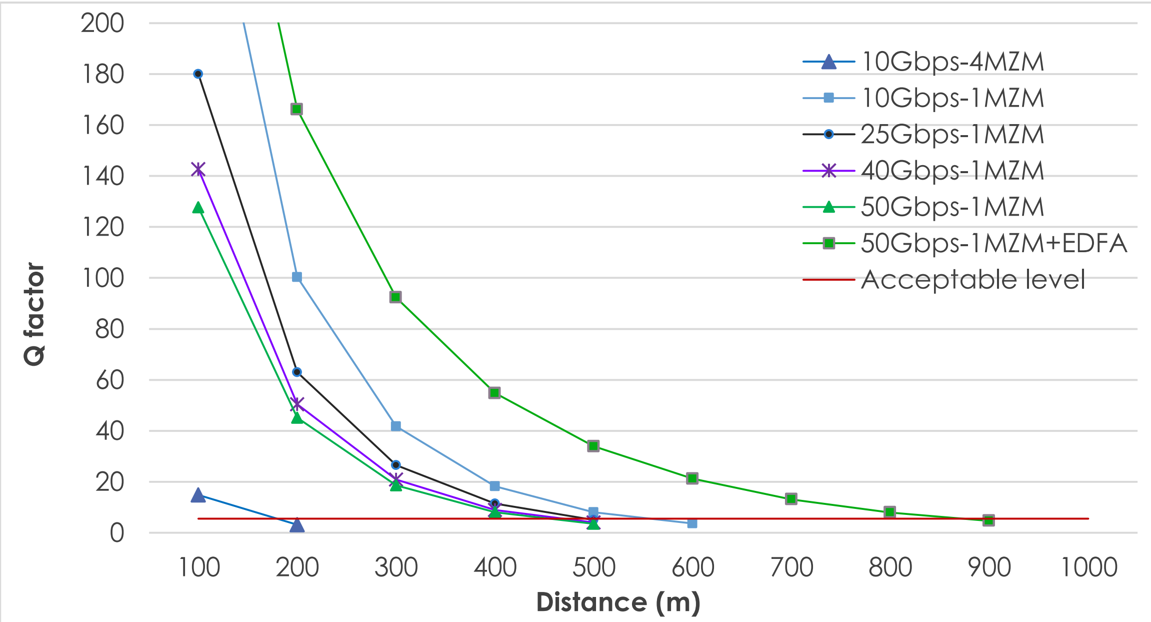
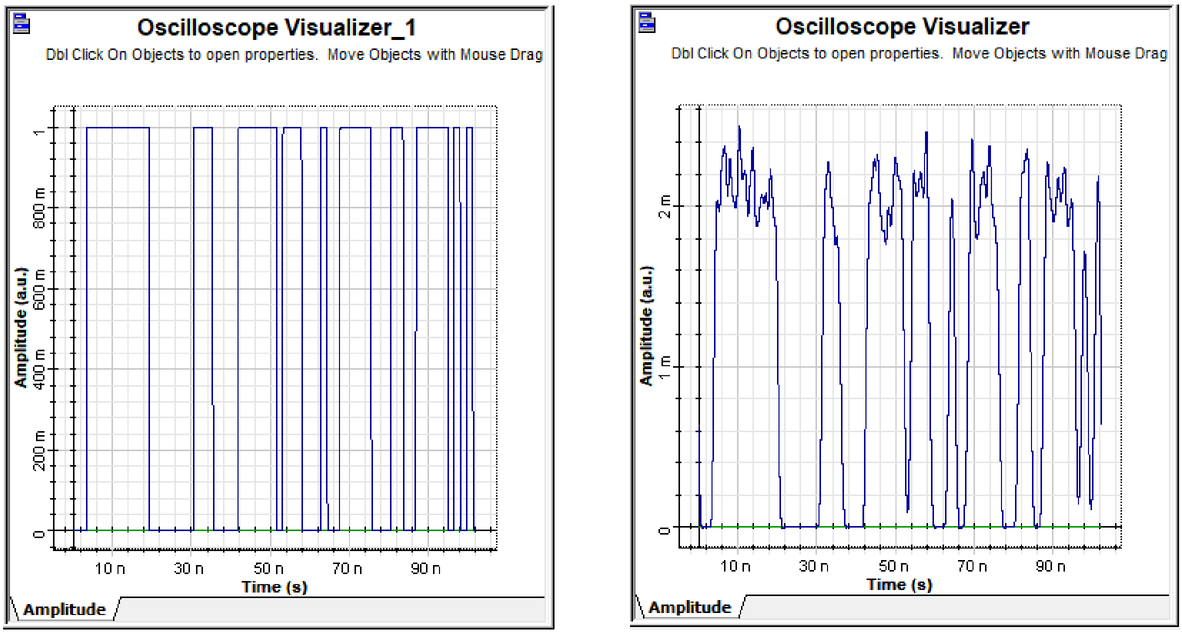


Fig. 4.15: Comparison Q factor performance versus FSO distance under heavy rain for different bit rate and both TDM-PON proposed systems (simulated with four users)

4.4 Performance Analysis of Hybrid System

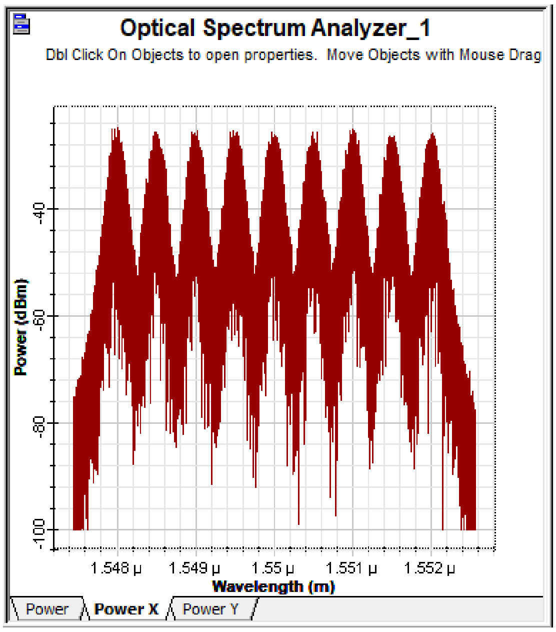
Figure 4.16 shows the difference between oscilloscopes screen of NRZ signal at the transmitter and the receiver after 20 km of the hybrid 1D-OCDMA-OTDMA system with weight of three. Where (4.16b) is the output of the LPF of cutoff frequency (0.75*Signal Bit rate) which is next of PIN diode photodetector with dark current 5 nA, responsivity of 1 A/W and thermal noise 1.8e-024 W/Hz. The transmitted signal will face many optical and electrical impairments and noises during the transmitter, channel and receiver. In Fig. 4.16 it can be seen that the maximum amplitude of the received signal is only 2.5 ma.u (arbitrary units) where the transmitted signal has 1 a.u of amplitude.



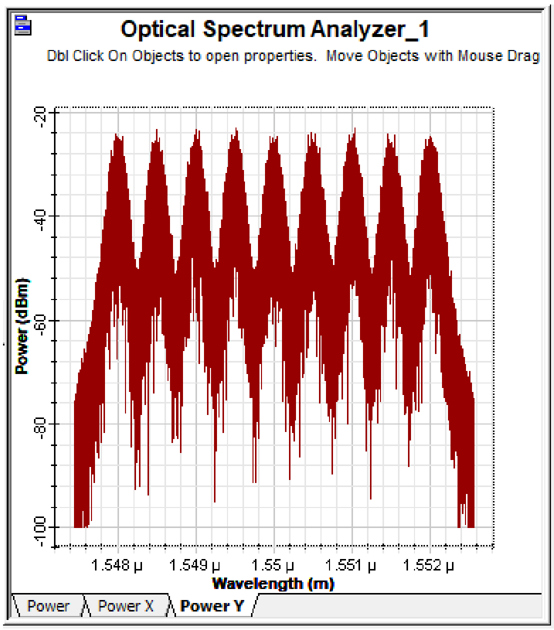
(a) (b)

Fig. 4.16: The NRZ signals of the hybrid system at the (a) transmitter and (b) receiver.

Figure 4.17 demonstrates a sample of the optical spectrum of 2D code (P/W) with weight of three for 6 SAC-OCDMA users. To generate SAC codes of W=3 and K=6 it must provide eighteen wavelengths (see section 3.2.1.1), since two polarization states have been used. So only nine wavelengths will be utilized in the state X and once again utilized in the state Y, as in Figures 4.17a and 4.17b. The difference between (a) and (b) is 90° of polarization. In other words, the weight is divided into two angles of polarization (X and Y) as this allows the reusing of those wavelengths one more time with other codes.



(a)



(b)

Fig. 4.17: The optical spectrum of 2D code (P/W) with weight of three for 6 SAC-OCDMA users.

To evaluate the increasing effect of the simultaneously homes number with distance of an optical fiber a comparison between Q-factor performances versus SSMF distance for different numbers of Homes at the hybrid bi-directional 10G-TDM-OCDMA-PON FTTH system has been done. Figure 4.18 demonstrates this comparison for downlink direction with using of FBG as a dispersion compensator. For the same purpose, a comparison between Q-factor performances versus SSMF distance for different numbers of homes with using of DCF as a dispersion compensator has been shown in Fig. 4.19. As depicted in both figures, the Q-factor of 10G-TDM-OCDMA-PON system at the downstream is slightly enhanced with the decreasing of Homes number at the same distance. This occurs because the performance is increased for lower OCDMA code overlapping between M of OCDMA users. Where the total number of premises in the hybrid system is depending on both OCDMA M users number and OTDM channels N number, the increment of total premises number in this test has done by increasing the OCDMA codes only. In additional, it can be noticed that the performance of the system with DCF is better presented than the system with dispersion compensation of FBG.

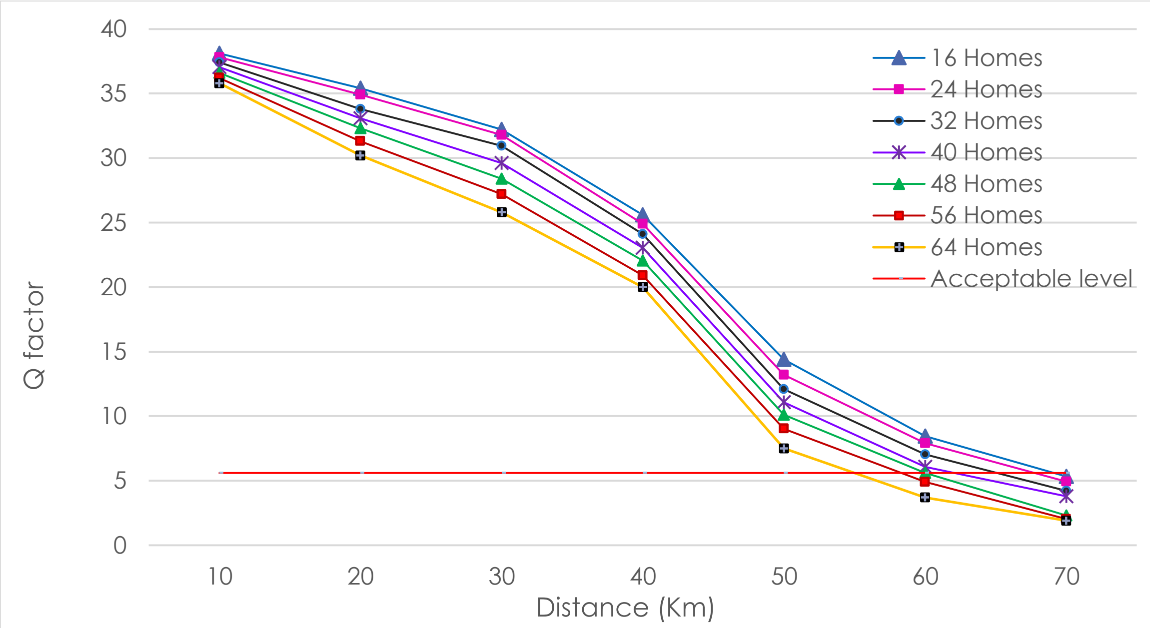


Fig. 4.18: Q-factor performance versus optical fiber (SSMF) distance for different numbers of simultaneously homes with FBG for downlink direction

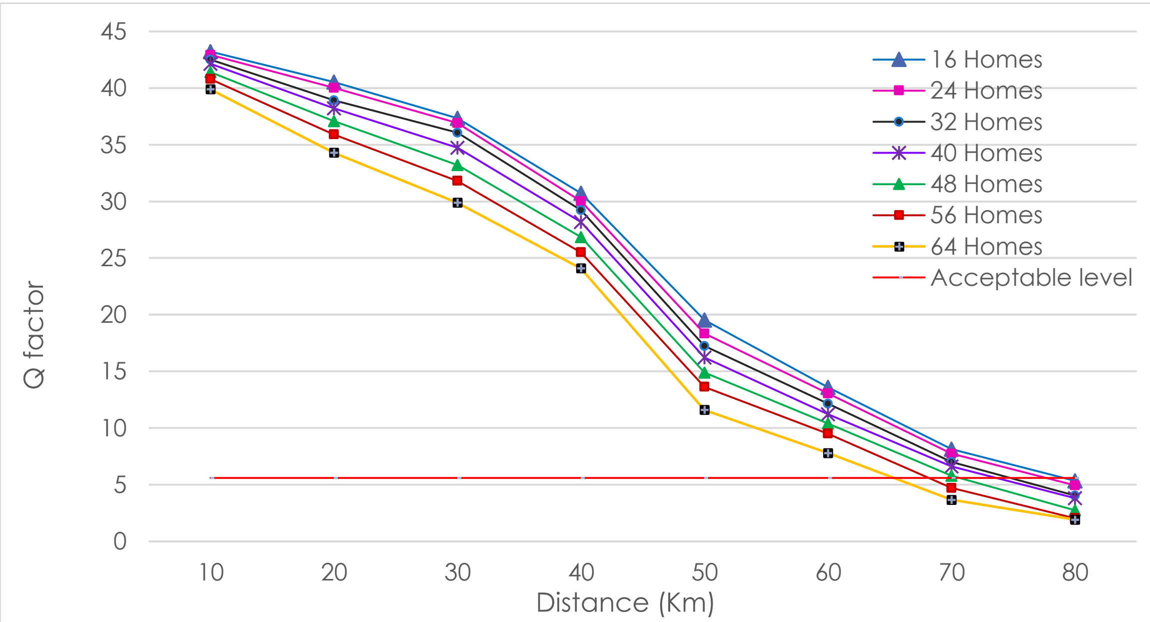


Fig. 4.19: Q-factor performance versus optical fiber (SSMF) distance for different numbers of simultaneously homes with DCF for downlink direction

In the proposed design of hybrid 10G-TDM-OCDMA-PON FTTH network, as shown in Fig. 3.17, 1.3/1.5 μm bands have been utilized for the upstream/ downstream traffics. The 1.5 μm downstream band permits the utilization of erbium-doped fiber amplifiers (allowing power boosting) thus enhanced link power budgets for broadcasting services of high-speed downstream. On the other hand, uncooled and cheap Fabry-Perót laser diodes (FPLD) can use with 1.3 μm upstream band in the side of ONUs that usually located at various distances from the local exchange, also this helps ONUs to co-exist this system with other services like XG-PON, G-PON and video services.

Figure 4.20 shows a comparison between Q-factor performances versus SSMF distance for different numbers of homes for the uplink direction of hybrid 10G-TDM-OCDMA-PON FTTH system. From these results, it can be clearly noticed that the performance of the downlink is better than the uplink direction, this because of the higher attenuation level at the wavelength of 1.3 μm band where it is 0.35 dB/km for SSFM while 0.2 dB/km for 1.5 μm, [4].

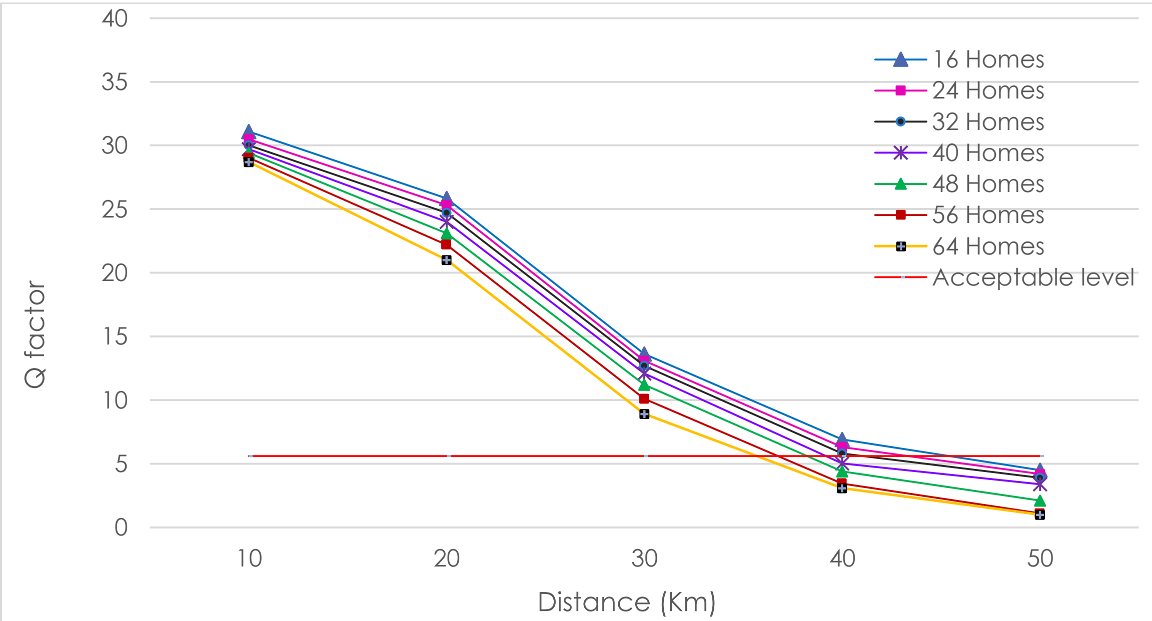


Fig. 4.20: Q-factor performance versus optical fiber distance (SSMF) for different numbers of simultaneously Homes for uplink direction

Figure 4.21 is a comparison between optical received powers versus SSMF distance for the downlink/uplink directions of hybrid 10G-TDM-OCDMA-PON FTTH system without any power amplification. It demonstrates that the signals which have been received in downlink direction own less affect with fiber distance than uplink direction. This is also due to the composition of optical SSFM which has higher attenuation level at the wavelength of 1.3 μm band that had been utilized in the uplink.

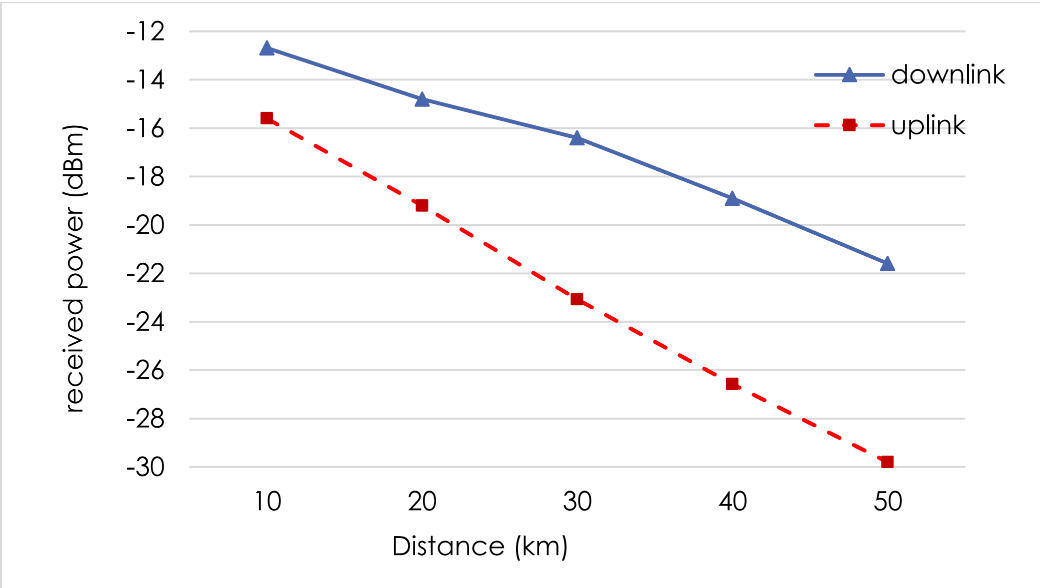


Fig. 4.21: Optical received power versus optical fiber distance (SSMF) for the uplink and downlink directions of 16 homes of hybrid FTTH network.

Figure 4.22 illustrates Q-factor against SSMF distance when different launched power of uplink and downlink directions are used in the system of 16-homes of hybrid 10G-TDM-OCDMA-PON FTTH. It shows that, at the same distance, maximum Q-factor performance achieved with higher launched power at the transmitter for both downlink and uplink.

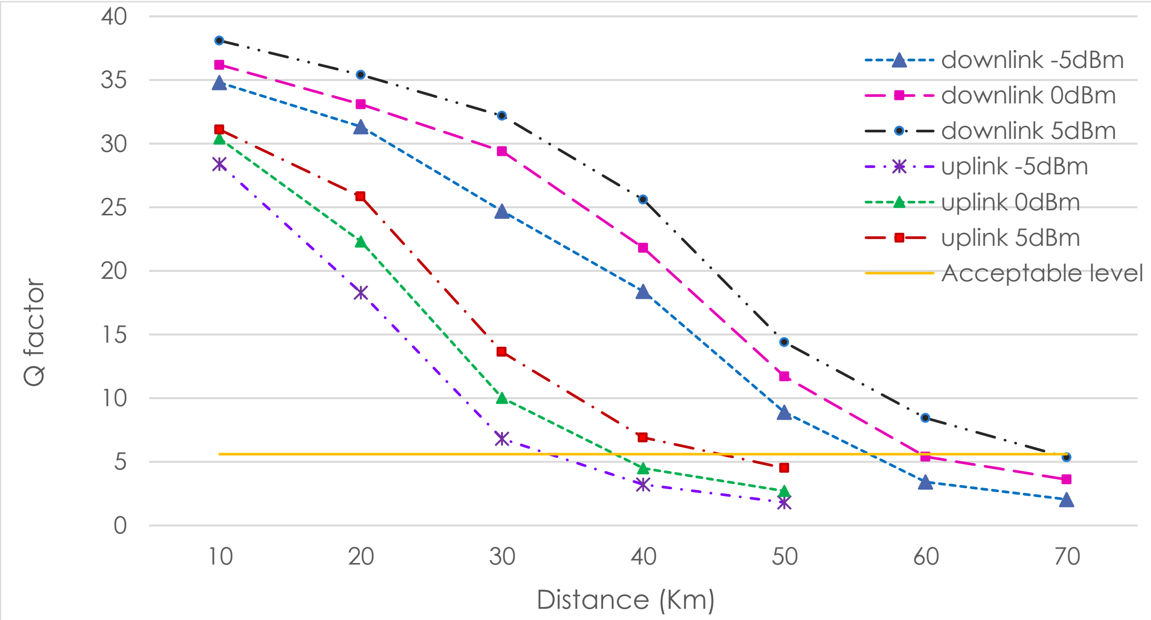


Fig. 4.22: Q-factor versus optical fiber distance (SSMF) for different launched power of uplink and downlink directions of 16 homes hybrid FTTH network.

Figure 4.23 shows the total supported number of homes (K) of the hybrid system for M-home of a single OCDMA group over N-channel OTDM system. According to equation 3.37, the total number of ONUs in the hybrid system depends on both OCDMA users number and OTDM channels number where $K = M \times N$. Figure 4.1 (as it mentioned in section 4.2 and according to equations 3.13, 3.14 and 3.31) shows that more FTTH's homes lead to more BER. Those numerical calculations of zero-cross correlation SAC-OCDMA system have been utilized to build up the calculation of the hybrid system. From those calculations, various samples of OCDMA users' numbers have been adopted in different codes' weights and dimensions. All those samples have been chosen at BER of 10^{-9} (the acceptable level).

The other factor of the hybrid system improvement is the number of OTDM channels N, as in Fig. 4.23, where more channels lead to increase the total number of the supported simultaneous households (if the number of the customers' homes in an OCDMA group is 144 it will be doubled with two channels, 576 with four and so on). Nevertheless, at the same time the bandwidth of each ONU will decrease with this OTDM channel increment.

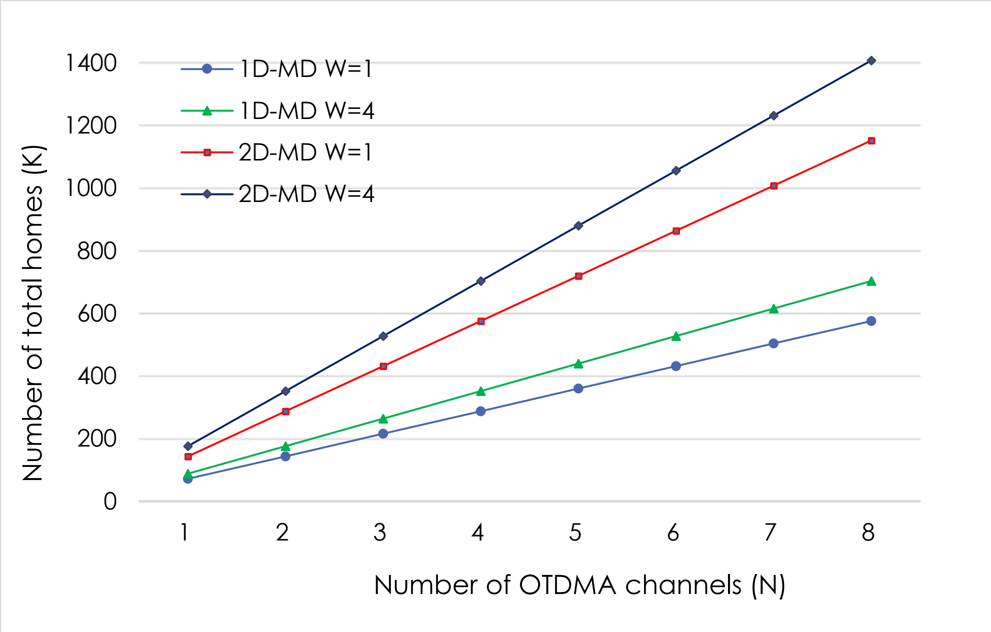


Fig. 4.23: Number of ONUs achievable with proposed OCDMA-OTDMA hybrid system.

4.5 Results Summary

In this chapter, the results of OCDMA, OTDM and hybrid systems have been discussed. Figure 4.24 shows a comparison between those systems with the same parameters, as shown in Table 4.3, for 16 users. The signals of those users are multiplexed according to the system properties itself. In the OCDMA system, 16 2D-MD codes were required where this is initiate more overlapping between the signals with high bit rate optical transmission, and this system will provide very high bandwidth per user. In the OTDM system, the 10 Gbps will be shared by 16 users via 16 dedicated time slots, where in this system the more users the less bandwidth will be per user. The hybrid system is combining the features of the OCDMA and OTDM techniques. Four time slots and four 2D-MD codes will provide a network with 16 users, the bandwidth will be shared for those 4

OCDMA groups. Where the bandwidth in the hybrid system is lower than the OCDMA and much higher than OTDM.

Table 4.3: Common parameters between OCDMA, OTDM and hybrid system

Parameter	Value
Operating centered wavelength	1550 nm
Linewidth of CW laser	0.1 MHz
Transmitted power	0 dBm
Signal bit rate	10 Gbps
Dark current	5 nA
Photodetector responsivity	1 A/W
Attenuation	0.2 dB/Km
Dispersion	16.75 ps/nm/Km
Dispersion slope	0.0075 ps/nm^2/Km
Differential group delay	0.2 dB/Km
Cutoff frequency	7.5 *10^9 Hz

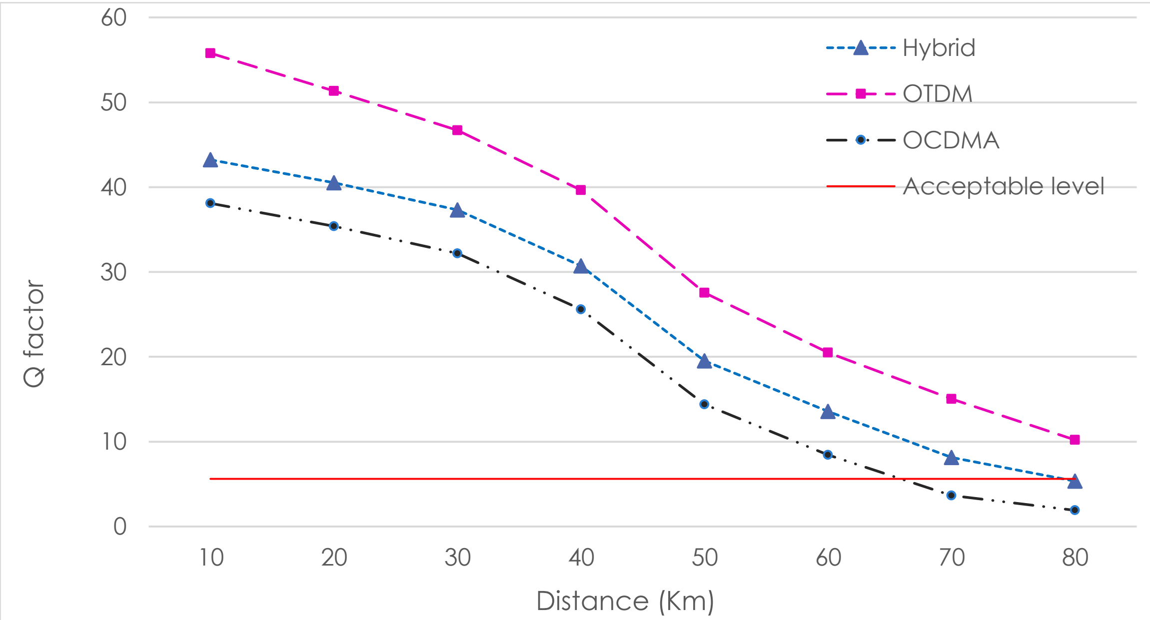


Fig. 4.24: Q-factor versus optical fiber distance (SSMF) for OCDMA, OTDM and hybrid systems with 16 users

Figure 4.24 shows that the OTDM system has higher Q-factor level with less bandwidth and the OCDMA system has lower Q-factor level with high bandwidth while the OCDMA-OTDM hybrid system provides the users high bandwidth with lower bit error rate. This can be more effective with high scalable network. For example, FTTH network with 1024 homes per single fiber can be designed by 10G-OCDMA-OTDM system with N=128 time slot and K=8 OCDMA codes providing sufficient bandwidth and acceptable bit error rate, where cannot meet this number of user with system based on single multiple access.

To evaluate the results of this thesis, the results of the OCDMA system have been compared with the results of reference [60] as shown in Tables 4.4 and 4.5. Where this research is focusing on different kinds of code techniques that are low cross correlation and zero cross-correlation in two scenarios (OFS and FSO). The low cross-correlation technique include RD and KS, and for the zero cross-correlation technique both ZCC and MD have used.

Table 4.4: 1D-OCDMA comparison in the OFS scenario with 622 Mbps

Research	Number of user	Code weight	OCDMA code	Distance (Km)	BER
S. Mostafa [60]	3	4	MD	20	10^{-58}
				40	10^{-36}
	3	4	ZCC	20	10^{-45}
				40	10^{-30}
This thesis	4	2	MD	20	10^{-52}
				40	10^{-26}
	4	2	ZCC	20	10^{-48}
				40	10^{-24}

Table 4.5: 1D-OCDMA comparison in the FSO scenario with 622 Mbps

Research	Number of user	Code weight	Weather condition	OCDMA code	Distance (m)	BER
S. Mostafa [60]	3	4	Light mist / Average rain (12.5)	MD	200	10^{-62}
					500	10^{-30}
	3	4		ZCC	200	10^{-54}
					500	10^{-25}
This thesis	4	2		MD	200	10^{-58}
					500	10^{-41}
	4	2		ZCC	200	10^{-56}
					500	10^{-38}
S. Mostafa [60]	3	4	Very light fog /Strong rain (25)	MD	200	10^{-60}
					500	10^{-17}
	3	4		ZCC	200	10^{-45}
					500	10^{-14}
This thesis	4	2		MD	200	10^{-55}
					500	10^{-34}
	4	2		ZCC	200	10^{-51}
					500	10^{-31}

CONCLUSIONS & FUTURE WORK

This chapter provides a summary of the simulation results of this thesis. Furthermore, some suggestions and future work are indicated which can lead to a more robust FTTH system.

5.1 Conclusions

The model of the 2D-MD OCDMA system based on polarization /wavelength is successfully designed and simulated, where two polarization angles have been used as a second dimension.

The theoretical results of 2D P/W MD and ZCC optical codes provide double number of customers' homes in comparison to 1D optical coding in the FTTH network. In addition, the results show that the higher number of weight the better performance of the system, obviously seen in the 1D-MD W=1 compared to the 1D-MD with W=4. Moreover,

The simulation results of four OCDMA users using MD and ZCC in both OFS and FSO scenarios along different distances have shown that the performance of MD code is a better presented than ZCC, where both MD and ZCC are zero cross correlation codes. These results also show that 2D codes are more vulnerable to attenuation and dispersion in single-mode optical fiber cables and the performance of the 1D codes is a better compared with 2D codes along the optical fiber. This is due to the additional noise and power dissipation of the extra devices in the system of 2D OCDMA. This behaviour is attributed to the fact that the OCMDA codes performance depend on media. However, with broadband white light source and for 25 Km of fiber reaching about 10^{-20} of BER of 2D codes is quite enough for FTTH network. So, according to the result, it can be found that the 2D-MD P/W code is the best choice for FTTH networks.

High speed bit-interleaving TDM-PONs of 10, 25, 40, and 50 Gbps have been simulated in three scenarios. It can be noted from the results that the high bit rate signals do not reach long distances despite the existence of dispersion compensator, where the steep drop in the Q-factors of 25, 40, and 50 Gbps with the comparison to the performance of 10 Gbps TDM-PON due to the effect of dispersion is more in a high bit rate system.

The new proposed scheme of TDM transmitter that use a single MZM and single laser diode to carry the data of multiuser, which has cost effective, high-transmitted power and easy implementation system, provides better performance in the TDM-PON linked by SSMF with DCF or FBG as a dispersion compensation and provides much better performance in the FSO system based on different bit rates.

The simulation results of the bit-interleaving TDM-PON in the FSO scenario, where there is no dispersion occurs, have shown that the 50 Gbps TDM-PON with EDFA amplifier is a better than 10, 25 and 40 Gbps without amplifier.

In contrast, TDM-PON with the SSMF based on a wavelength of 1550 nm, the 50G TDM show poor performance even with the addition of an amplifier. Hence, the author recommends using more complex modulation techniques than RZ and NRZ, more sensitive receiver and using a wavelength within O-band where there is a zero dispersion wavelength (ZDW) for a TDM-PON of 50 Gbps per channel.

The major contribution of the present thesis, to the best of my knowledge, a TDM-OCDMA-PON hybrid system has been successfully designed for FTTH network, which offers an increment in the network scalability while ensuring sufficient data rate and bit error rate. M-user OCDMA signals can be transmitted in different channels of an OTDM system.

The theoretical results of hybrid system show that more channel of OTDM lead to increase in the total number of the supported simultaneous homes. However, the bandwidth of each ONU will decrease with this OTDM channel increment.

The simulation results of hybrid system show that more number of OCDMA the more bit error rate (especially in high bit rate), also the uplink direction has more vulnerable to the attenuation with distance where 1.3 μm of wavelength had been utilized.

Hence, a trade-off should be done between the network scalability and the bandwidth/complexity/performance of each home before the selection of the OTDM channels number, OCDMA code number and the weight/dimension of the OCDMA code.

5.2 Future Work

In this thesis, the proposed hybrid system of TDM-OCDMA-PON is successfully simulated. Based on the high scalable 2D-MD P/W OCDMA that was the primary focus of this work, the following further work suggestions can be carried out:

1- An experimentally work of the proposed system can be carried out to compare the results between the practical and simulation systems.
2- A study of power saving architecture to propose and investigate 2D-OCDMA transmitter for lower power consumption.

3- It will be useful to investigate the system based on 3D OCDMA combines Polarization, Wavelength and Temporal (P/W/T) for more simultaneous users.
4- It is also possible to investigate the TDM-OCDMA-PON based on 25 and 50 Gbps data rate.
5- A higher scalable system could be obtained by the hybrid system involving another possible multiple access technique like the subcarrier multiplexing (SCM) combining with our proposed system to design SCM-TDM-OCDMA-PON hybrid system.

5.3 Drawbacks and Limitations

- The 2D-OCDMA system has provided the double number of users with comparison to 1D-OCDMA but using two states of polarization as a second dimension adds some additional noise and complexity versus this scalability increment of FTTH network.
- The RZ encoding needs double bandwidth with comparison to NRZ, hence more space between the wavelengths is required.
- The using of the CW laser in the systems of high bit rate (10 Gbps and beyond) is essential, which means adding more cost for each user.
- In the high bit rate system especially with TDM-PON, the dispersion compensation is a critical point, so using a dispersion compensation technique is very important.
- The different length of optical cables between the network access point and the ONUs in the different homes needs to take into consideration where time delay will be adding for the longer distance.

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الخلاصة

يمكن أن تدعم الشبكات الضوئية الزيادة الكبيرة في طلبات الاتصالات عالية السرعة التي تتناسب مع متطلبات العملاء الحديثة بطريقة موثوقة وفعالة من حيث التكلفة. في هذه الرسالة، تم اقتراح أنظمة مختلطة من OCDMA وOTDM لزيادة عدد المستخدمين المتزامنين. في العقد الماضي، شهدت شبكات الألياف الضوئية (FTTH) قبولًا كبيرًا من الجمهور في جميع أنحاء العالم. لتلبية الطلبات المستقبلية، يجب تحسين شبكات الوصول FTTH الحالية. لتحقيق هذا الغرض، تم تصميم ومحاكاة بنية FTTH جديدة تستند إلى نظام هجين TDM–OCDMA–PON ذي معدل بت مرتفع مما يزيد من قابلية التوسع للشبكة.

من أجل زيادة عدد المستخدمين، تم التحقيق في تقنية تشفير/فك تشفير OCDMA تستخدم حالتين من الاستقطاب المتعامد للشفرة ثنائية الأبعاد. حيث يضم هذا الرمز الثنائي الأبعاد كلاً من الاستقطاب والطول الموجي (P/W). بالإضافة إلى ذلك، تم استخدام سيناريوهات أنظمة الألياف الضوئية (OFS) وبصريات الفضاء الحر (FSO) مع بعض رموز الشفرة (SAC–OCDMA) غير المتناسقة. هذه الرموز هي رموز متعدد الأقطار (MD) وصفرية الارتباط المتبادل (ZCC). حيث يتم اختيارهم بسبب تقليل تأثير تداخل الوصول المتعدد (MAI) الذي يعتبر أهم عامل للضوضاء والتداخل في SAC–OCDMA.

أعتبر ال TDM–PON حلاً جيدًا لمعدل بت مرتفع ونظام عرض نطاق مرن. في الرسالة، تم تنفيذ محاكاة لمرسل TDM عالية السرعة بتشذير البتات. يعتمد المخطط المقترح لمصادر FTTH على مضمن Mach–Zehnder مفرد وصمام ثنائي ليزري مفرد لنقل البيانات الكهربائية متعددة المصدر. بالإضافة إلى ذلك، تم محاكاة معدل بت مختلف من TDM–PON في سيناريوهات مختلفة. لمحاكاة تلك الأنظمة، تم استخدام حزمة برامج Optisystem V.15.

تُظهر نتائج نظام OCDMA أن إجمالي عدد المستخدمين المدعومين من رموز ثنائية الأبعاد يتضاعف مقارنةً بالرموز احادية البعد. إضافة إلى ذلك، تظهر نتائج المحاكاة أن أداء كود MD أفضل

من ZCC في كل من سيناريوهات OFS و FSO. بعد ذلك، تظهر نتائج نظام TDM-PON أن مرسل TDM متعدد الإرسال الكهربائي يوفر أداء أفضل من مرسل TDM البصري التقليدي في سيناريوهات مختلفة ذات معدلات بت مختلفة. أخيرًا، توضح نتائج نظام FTTH الهجين OTDM-OCDMA أن هذا النظام يمكن أن يحقق زيادة كبيرة في قابلية تطوير الشبكة من خلال زيادة إما في قنوات نظام ال OTDM أو أعداد رموز نظام ال OCDMA.

جمهورية العراق
وزارة التعليم العالي والبحث العلمي
جامعة الفرات الاوسط التقنية
الكلية التقنية الهندسية - نجف

تصميم شبكات الألياف الضوئية للمنزل (FTTH) باستخدام التقنيات الهجينة

رسالة مقدمة الى
قسم هندسة تقنيات الاتصالات
كجزء من متطلبات نيل درجة ماجستير تقني في هندسة الاتصالات

تقدم بها
حيدر صادق شاكر زائر دهام
بكالوريوس في هندسة تقنيات الاتصالات

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