Design and Performance Analysis of Passive Optical Networks using Dicode coding

Submitted By

MUKESH KUMAR GUPTA

Research Scholar

(ID-2012REC9041)

Under Supervision of

Dr. Ghanshyam Singh

Associate Professor, Dept. of ECE, MNIT Jaipur

Submitted for the partial fulfillment of degree of

Doctor of Philosophy

To

DEPARTMENT OF ELECTRONICS & COMMUNICATION ENGINEERING

MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY JAIPUR

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Certificate

It is certified that:

1. This thesis has not been submitted in part or full to any other University or Institute for the award of any degree.
2. I have fulfilled all the requirements for submission of the thesis.

Mukesh Kumar Gupta
ID: 2012REC9041

This is to certify that the thesis entitled "DESIGN AND PERFORMANCE ANALYSIS OF PASSIVE OPTICAL NETWORKS USING DICODE CODING" being submitted by Mr. Mukesh Kumar Gupta to the Department of Electronics and Communication Engineering, Malaviya National Institute of Technology Jaipur for the award of the Degree of Doctor of Philosophy, is a bonafide research work carried out by him under our supervision and guidance. The results obtained in this thesis have not been submitted to any other University or Institute for the award of any other Degree.

22.09.2017

Dr. Ghanshyam Singh
Associate Professor & Supervisor
Department of ECE, MNIT, Jaipur

Thesis was examined and approved for the award of the Degree of Doctor of Philosophy.

Dr. Ajeet Kumar
Assistant Professor & External Examiner
Department of Applied Physics,
Delhi Technological University (DTU), Formerly DCE, New Delhi, 110042

Declaration of Authorship

I, Mukesh Kumar Gupta, declare that, this thesis titled as, 'Design and Performance Analysis of Passive Optical Networks using Dicode coding' and the work presented in it are my own. I also confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
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- I have acknowledged all main sources of help.

Mukesh Kumar Gupta

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Abstract

The rapid growth in access network demands huge bandwidth to provide voice, data and video (triple play) services for residential and corporate subscribers. The passive optical network (PON) has emerged as one of the most promising solution for higher bandwidth requirement for the optical broadband access network. Passive optical network is a point-to-multipoint tree topology network that connects optical line terminal (OLT) with many optical network units (ONUs) via a long fiber feeder and many short distribution fibers. Passive Optical Networks is cable to provide a lucrative, highly flexible and scalable network for end subscribers. Practical implementation of PON gives rise to various technical challenges, such as colorless ONUs, burst mode transmission, bi-directional transmission with mitigated backscattering noise, long-reach PON, and integrating network functionalities. All such technical requirements are motivated by the "original requirements" of telecommunication – faster, cheaper, and more robust.

To fulfill the technical requirements, researchers investigated various aspects of system designs and studied the upcoming technologies such as devices, system architectures, network protocols, etc. This thesis deals with the performance evaluation of PON systems by designing new structures, finding out suitable modulation format to improve the overall performance by mitigating & analyzing the crosstalk and implementing with different topologies with tracking several system level challenges while acknowledging the limitations of existing networks. In specific, we have studied Non-return to zero (NRZ), Dicode coded NRZ, Duobinary, and Manchester formats, including the modulation/demodulation techniques, transmission properties, and system applications. The research topics are classified according to the capacity of the network with different applications.

In the investigation at the system level, where many components are involved, it is difficult to describe the system performance fully. The system performance is investigated with the aid of split-step Fourier (SSF) simulation. The performance is evaluated on the basis of two criteria. The first criteria sets the probability of bit error below 10^{-9} and in second, timing recovery is facilitated by preserved eye profile at the receiver output.

Firstly, dicode – coded NRZ format is proposed for optical signal transmission. It has desirable properties of large dispersion and Raman crosstalk tolerance (as compared to Conventional NRZ/RZ) and finite optical power in each bit. In this study, we first show the advantages of dicode coded NRZ and the corresponding modulation techniques. We analyzed the effects of dispersion on conventional wavelength division multiplexing-time division multiplexing (WDM-TDM) system at a data rate of 10 Gbps using NRZ and dicode. Further, we demonstrate a 10-Gbps video overlay PON system to provide voice, data, and video (triple play) services to end user in two different wavelength bands (1480 nm and 1550 nm) for data and video. The video has high power, and this band lies in the Stokes shift ~100 nm of silica hence the data signal act as a pump for video, resulting in the reduction of the power of data signal. This reduction in power can be minimized by dicode, and remote Raman pump can be used as an amplifier to increase the reach of network.

Secondly, we propose a design of high capacity PON using dicode as ring WDM-PON and conventional WDM-PON. Ring WDM-PON can be used in mitigation of Rayleigh backscattering power by using downstream and upstream signal in the same direction as well as using the concept of remodulation at ONU as a light source used at OLT to avoid the problem of colorless ONU. Optical network unit is simple to operate and do not requires laser sources for generation of the carrier at its end. A carrier at the central office is remodulated as upstream transmission at the subscriber end. In this way, by using the additional carrier at Optical Line Terminal (OLT), we have reduced the laser sources equal to the number of ONUs. Dual fiber ring is used to avoid any fiber fault. An 80 Gbps conventional WDM-PON system is designed with two 40 Gbps WDM channels using FBG (Fiber brag grating). Dicode coded NRZ and FBG as a dispersion compensator, can achieve 1500 Km long transmission system.

In the present scenario, concepts of hybrid (WDM/TDM) PON which uses the advantages of both TDM as well as WDM network, are under investigation by the scientific community at large. It is utmost necessary to design, characterize and investigate hybrid PON for high capacity access systems. Finally, we design and analyzed numerically a cost effective 77 KM reach flexible hybrid WDM-TDM-PON system for 64×4 subscribers at 10 Gbps down -stream and upstream signal. The cost of OLT is better shared among the ONUs as used in higher splitting ratio. The proposed system is very simple, flexible, expandable and profitable. This design uses a cost-effective system which solves the problems of colorless ONU, bi-directional transmission, and long-reach simultaneously. However, there are difficulties in interfacing with existing GPON network which would be overcome in the near future.

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List of Acronyms

AMI	Alternate Mark Inversion
AON	Active Optical Network
APD	Avalanche Photodiode
ASE	Amplified Spontaneous Emission
ASG	Analog Signal Generator
ASK	Amplitude Shift Keying
ATM	Asynchronous Transfer Mode
AWG	Array Waveguide Grating
B&S	Broadcast and Select
BER	Bit Error rate
BPON	Broadband Passive Optical Network
CAPEX	Capital Expenditure
CATV	Cable TV
CDMA	Code Division Multiplexing
CL	Correlative Level
CO	Central Office
CPE	Customer Premise Equipment
CSRZ	Carrier Suppressed Return to Zero
CW	Continuous Wave
CWDM	Coarse Wavelength Division Multiplexing
DB	Duobinary
DC	Direct current
DCF	Dispersion Compensation Fiber
DD	Direct Detection
DML	Directly Modulated Laser
DMT	Dispersion Managements technique
DPSK	Differential Phase shift Key
DQPSK	Differential Quadrature Phase Shift Keying
DS	Downstream
DSF	Dispersion Shifted Fiber
DSL	Digital Subscriber Line

DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
EOM	Electro-Optic Modulator
EPON	Ethernet Passive Optical Network
ER	Extinction Ratio
FBG	Fiber Bragg Grating
FDM	Frequency Division Multiplexing
FEC	Forward Error Correction
FSAN	Full Service Access Network
FSK	Frequency Shift Keying
FTTB	Fiber to the Building
FTTC	Fiber to the Curb
FTTH	Fiber to the Home
FTTX	Fiber to the X
FWM	Four Wave Mixing
GBPS	Gigabit per Second
GEM	GPON Encapsulation Method
GEPON	Gigabit Ethernet Passive Optical Network
GPON	Gigabit Passive Optical Networks
GVD	Group Velocity Dispersion
HDTV	High Definition Television
HPON	Hybrid PON
IM	Intensity Modulation
IP	Internet Protocol
IPTV	Internet Protocol Television
ITU	International Telecommunication Union
LAN	Local Area Network
LASER	Light Amplification by Stimulated Emission of Radiation
LED	Light Emitting Diode
LPF	Law Pass Filter
MZDI	Mach-Zehnder Delay Interferometer
MZI	Mach- Zehnder Interferometer
MZM	Mach- Zehnder Modulator

NGPON	Next Generation Passive Optical Networks
NLSE	Nonlinear Schrodinger Equation
NRZ	Non Return to Zero
NTSC	National Television System Committee
OADM	Optical Add Drop Multiplexer
ODN	Optical Distribution Network
OFC	Optical Fiber Cable
OFDM	Orthogonal Frequency Division Multiplexing
OLT	Optical Line Terminal
OMI	Optical Modulation Index
ONT	Optical Networks Terminal
ONU	Optical Network Units
OOK	ON-OFF Keying
OSNR	Optical Signal to Noise Ratio
OSU	Optical Subscriber Unit
P2MP	Point to Multipoint
P2P	Point to Point
PM	Phase Modulation
PMD	Polarization Mode Dispersion
PolSK	Polarization Shift Keying
PON	Passive Optical Network
PR	Partial Response
PRBS	Pseudo Random Binary Sequence
PSD	Power Spectral Density
PSK	Phase Shift Keying
Q	Quality Factor
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RB	Rayleigh backscattering
RF	Radio Frequency
RN	Remote Node
RSOA	Reflective Semiconductor Amplifier
RZ	Return to Zero

SBS	Stimulated Brillion Scattering
SCM	Sub Carrier Multiplexing
SMF	Single Mode Fiber
SNR	Signal to Noise Ratio
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
SSMF	Standard Single Mode Fiber
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TWDM	Time and Wavelength Division Multiplexing
US	Upstream
VoD	Video on Demand
VoIP	Video over Internet Protocol
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WDMA	Wavelength division Multiple Access
WS	Wavelength Select
XPM	Cross Phase Modulation

List of Symbol

α	Loss in optical fiber
Dm	Material dispersion
τ	Pulse broadening
λ	Wavelength of light
n	Refractive index
c	Velocity of light in vacuum
D_{wg}	Waveguide dispersion
f	Frequency of wave
R	Data rate
ω	Angular frequency
β	Propagation Constant
V	Mode V number
A_{eff}	Effective area of fiber
G_e	Raman gain
g_R	Raman gain coefficient
γ_R	Nonlinear strength
P_p	Pump power
P_s	Signal power
Δf	Channel spacing
γ	Nonlinearity coefficient
A	Slowly varying electric field
β_2	Group velocity dispersion parameter
T_0	Pulse width
L_D	Dispersion length
P_0	Peak power of input pulse
T	Absolute temperature
Ω	Raman shift

Dedicated to my family members for extending their unconditional support, strength and love to accomplish the task.

Chapter 1

Introduction

1.1 Preface

Communication is defined as a process involving the exchange of information from one point to another. In the ancient time, a piece of information was conveyed from smoke and fire signal, reflecting mirrors and more recently signaling lamp [1]. The use of low capacity communication links invented in the early part of the twentieth century was limited due to the line of sight and atmospheric disturbance [2-3]. Low-frequency electromagnetic wave is considered suitable for transmission up to the considerable distance, but information and bandwidth varied as per their carrier frequency. It may be noted that the optical communication is the only available choice for potential large bandwidth which is 10^4 times larger than the microwave frequency. The system which uses the light carrier for the communication is known as light wave system. Fiber- optic system is the example of the light wave system, in which the carrier frequencies are selected from the optical range (particularly the infrared part) of the electromagnetic spectrum [4].

1.2 A Fiber- optic communication system

Fiber optics is an essential unit in the telecommunication infrastructure. Characteristics such as high bandwidth capabilities, low attenuation make it suitable for gigabit or higher transmission rates [5]. With the recent developments, fiber optics offers a lossless medium for transmission of information over long distances using light as the carrier wave. Conventional transmission using copper wire is electrical in nature while fiber optics is not the same. A standard fiber optics system mainly consists of three parts transmitter, optical fiber cable as a channel and receiver. The electric signal is converted into a light signal at the transmitter end which is carried by optical fiber cable and finally received at the receiver [1]. The receiver converts the received light back into an electric signal. The generalized fiber optic communication system is depicted in Figure 1.1, consisting mainly of three-part optical transmitter, communication channel and an optical receiver.

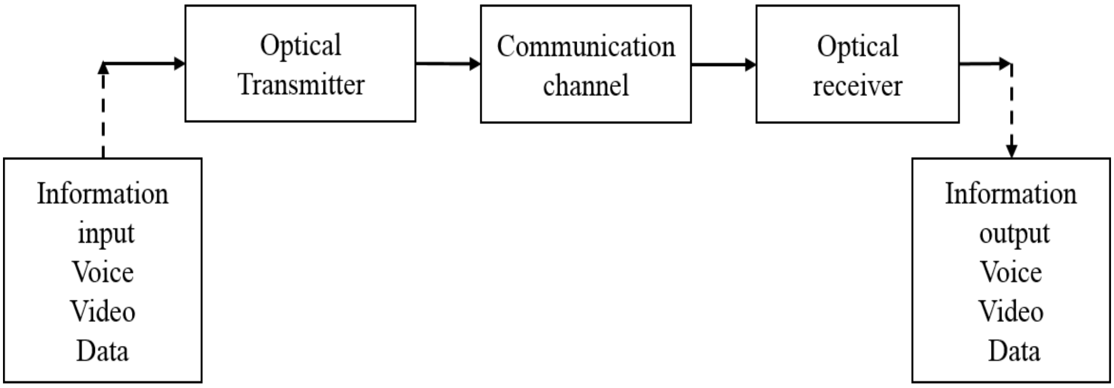


Fig. 1.1 Generalized fiber- optic communication system [5].

The original information input which can be in any physical form, e.g., voice, video, or data is converted to electrical input signal using suitable transducer at the transmitter [1].

1.2.1 Optical Transmitter

The optical transmitter consists of the optical source, modulator and channel coupler. The light source such as a semiconductor laser or Light-emitting diode (LED) is compatible with optical communication channel, hence used to generate the light pulse [3]. The light pulse could be modulated by two-ways. First, directly modulated laser, by changing the injection current and another is external modulator [5]. The modulation by changing the injection current is economical and simple but it can produce chirp especially in the high data rate signal. Now, external modulator is used to modulate high data rate signal so that chirp can be avoided. Modulated light signal focuses to optical fiber efficiently by channel coupler that uses the micro-lens. The launch power is a critical parameter, by increasing it, repeaters and amplifier spacing can be increased and it is limited by the nonlinear effects. As per usual standards, dBm is used as a unit for launched power with reference level as 1mW [5].

1.2.2 Communication channel

Most of the light wave systems use the optical fiber as a communication channel that is used to transport optical signal from the transmitter to receiver with less distortion and other possible transmission losses. Usually, it is made by silica material that has property of less attenuation in useful bands. It shows 0.2 dB/Km at 1550 nm band hence it is very useful as a communication channel for lightwave system [5]. The basic arrangement of core clad as an optical fiber is shown in Fig. 1.2. The optical fiber has cylindrical glass rod known as the core, which is used to propagate light.

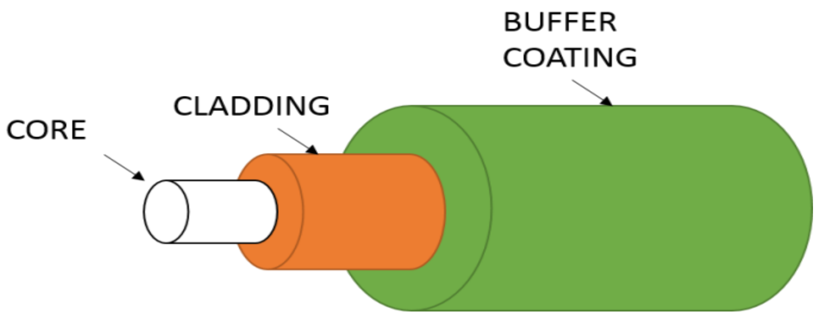


Fig. 1.2 Optical Fiber; reproduced from ref. [4].

This core is surrounded by the cylindrical coaxial shell of glass, known as cladding, which has less refractive index [4]. The buffer coating is used to protect the fiber from damage and moisture [1].

1.2.3 Optical receiver

An optical receiver converts the optical signal into the original electrical signal. It consists of a coupler, a photodetector, and a demodulator. The coupler focuses the received optical signal at the photodetector, which converts it into the electrical signal [5]. Design and type of demodulator depends on the format which is used in lightwave system. Frequency shift key (FSK) and phase shift key (PSK) format generally uses the heterodyne and homodyne demodulation techniques. Most of the light wave systems use the Intensity Modulation (IM) format which is known as amplitude shift keying (ASK). As per the received modulated signal, the decision circuits are used to detect the 1 and 0 at the receiver end. The signal to noise ratio (SNR) of the signal generated by the photodetector at receiver is the critical parameter defining the accuracy of decision circuits [5].

1.3 Access Network

Access networks are responsible for connecting the service providers to their customers (either business and or residential). Most common local access networks such as the telephone networks are still based on the twisted- pair technology and coaxial cable [6-8]. The bandwidth required by customers has been increasing quickly in the last few years and twisted- pair / coaxial cable technologies are not able to realize such high speed requirements [9]. However the demand for bandwidth is increasing exponentially due to advanced internet application and standard high definition Television (HDTV). To solve these problems, fiber was taken close to the residential and small business houses. There are several ways to deploy the optical network, which is commonly referred as Fibre to the X (FTTX)[10-14]. FTTX network has an arrangement of twisted pair, coaxial cable and optical fiber as shown in Fig. 1.3 and these types of arrangments and upgrading of network showed the bottleneck in term of data rate and bandwidth. To overcome this problem, renewal and reconfiguration of access network is required so that bandwidth could be freed up. In the contemporary scenario, many players are letting go off their traditional copper networks, paving the way for the optical fiber network. The optical fiber is coming closer to the end users, giving a faster connection. Services like fiber to the home (FTTH) emerge as clear choice for the long term because of its capability to accommodate the future bandwidth on the same hardware thus future proofing popular services like video on demand (VoD), online gaming, HDTV and video over internet protocol (VoIP) [15].

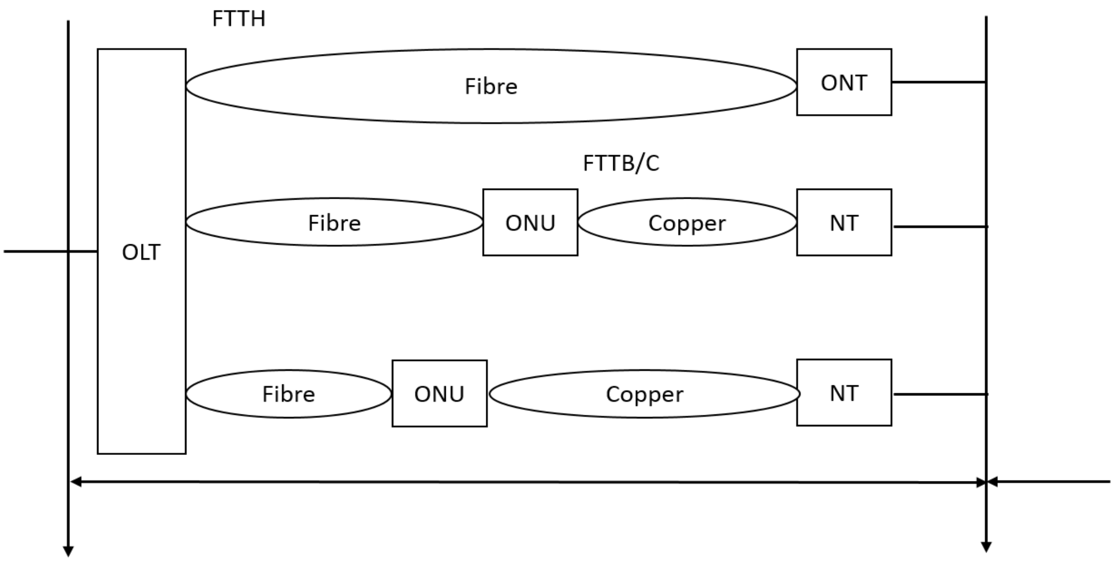


Fig. 1.3 Network Architecture; reproduced from ref. [17].

The foundation of fiber to the home lies on 100% deployment of optical fiber, from center office (CO) to subscriber end in the access network. It has mainly two types of configuration. First, it provides a dedicated connection to each user by individual fiber and this kind of topology known as Point to Point (P2P) connection. This type of network has high cost and is not able to use the available bandwidth of the single fiber effectively. In second type of single network, fiber is shared by the multiple users varying from 16 to 32 by splitting the signal by power splitter. These types of network are known as passive optical networks (PON) [17]. Each of these networks has advantages and disadvantages involving financial, bandwidth and component parameters. The both architectures discussed above are the solutions to be deployed as FTTH for a major operator. The PON is mainly recognized for access networks due to the economic and future-safe solution and overcome the problem of bandwidth bottleneck [18].

1.4 Motivation and Objective

With increase in continuous bandwidth demand for supporting high-speed applications such as Video on demand, High-definition television (HDTV), video conferencing, etc., the broadband access networks are the most promising solutions [19-22]. The researchers are focusing more on the design and implementation of innovative access network architectures, sustaining huge data at high speed with larger bandwidth for expected future demands [23-24]. PONs are attractive as they provide a profitable, highly flexible and scalable system for all end users [25-30]. Optical wavelength division multiplexing networks offer tremendous promise in meeting this demand. While going through several research article, got familiar with the challenges in the optical network like the bidirectional transmission in optical fiber, burst mode transmitter-receiver, colorless ONU, reach, network flexibility, integration to the legacy of PON, energy saving and cost of the networks [31-35]. Over the past decade, the scientific community had suggested various techniques to handle these challenges [36-40].

In the initial phase of fiber optic communication, the modulation techniques used was mainly intensity modulation (IM) [35, 41]. The techniques were very simple to implement but suffered from dispersion, crosstalk and nonlinear effects along the length of the channel. Recently, it has been realized that alternative forms of modulation format should be utilized to improve system capacity so that it can handle the ever-increasing bandwidth demand with low cost. Performance evaluation and enhancement of Passive Optical Networks may be improved by designing new architectures and incorporating suitable modulation formats (Line coding) [42]. In such system, the performance is a function of characteristics of the modulation schemes employed. The numerous significant applications and developments inspired us to study the different line coding schemes [42].

Despite the merits like less bandwidth requirements, high noise immunity, low crosstalk, etc. of dicode code, the application of this coding has not been adequately addressed in high-speed optical communication [43-48]. An objective of proposed research work is to design and analyze the Dicode code in optical domain in high-speed optical communication. Simultaneously, various system level challenges and limitations of existing networks are considered during the design. Major objectives of this thesis are:

- Investigation and study of Dicode coded non return to zero (NRZ) coding including the mechanism for Dicode signal generation.
- Investigate the effects of Dicode coding in PON Architectures.
- To keep simplified transmitter and receiver configuration for low cost and long reach transmission

This thesis work aims at system level innovation for the next generation optical access network, with main focus on modulation format and its corresponding transmitter and receiver to fulfill the system requirement. There are challenges in optical networks such as colorless ONUs, burst mode transmission, bi-directional transmission, long-reach PON, and cost. Next generation optical access network requires joint consideration of all the challenges mentioned above. Our research work aims at solving one or multiple research problems with innovation in signal modulation format, transmitter, and receiver techniques.

1.5 Organization of Thesis

Chapter 2 reviews the basics of optical communication and passive optical networks as well as differentiate between past, current and next Generation PON (10G PON and WDM-PON) in terms of standardization, maturity, cost and power consumption. It describes the main requirement to improve the performance of PONs and various channel impairments like dispersion, attenuation, nonlinearity, etc.

Chapter 3 explains different line coding and their characteristics that would match with channel frequency response and make them suitable for the different application and developments. The conversion of the electrical signal into an optical signal by the suitable modulation format are studied which impetus the use of low loss transmission window of optical fiber effectively.

Chapter 4 describes effects of dispersion on the WDM-TDM networks utilizing NRZ and dicode. How this will affect system bit error rate (BER) and Quality factor is also discussed. It will also analyze the effect of Raman crosstalk in the communication channel using the multilevel coding like Duobinary and dicode.

Chapter 5 depicts and summarizes the design of high bandwidth WDM-PON and ring WDM-PON systems. Ring networks upstream and downstream signal will travel in the same direction. Hence it minimizes the occurrence of Rayleigh backscattering noise. In this chapter, implementation of long haul network using dispersion compensation with FBG is designed.

Chapter 6 study the implementation of a cost-effective system which can fulfill future bandwidth demand as well as flexibility. A flexible hybrid PON system is analyzed in the presence of dicode coding.

Chapter 7 concludes the results and observations made in this work and summarizes possible solutions. Some future trends and possibility of enhancement of PONs working and application areas also presented, that may encourage the future research community to work upon.

Chapter 2

Passive Optical Networks: Overview

2.1 Introduction

In this chapter, details of passive optical networks and their evolution with time is presented. As bandwidth demand increases, new access networks have been developing to support and fulfill this growth. This chapter also explains important parameters such as flexibility, scalability, etc. which are necessary to improve the system performance. Different impairments in the channel are also studied.

In today's world, the high-speed internet has become as essential part of life. This development is driving research and innovation for possible upgradation of access technologies to meet true broadband requirements [50-53]. Thus the market itself is moving in the direction of rolling out high volume optical fiber-based access networks by major operators [54-55].

At present, FTTH seems the only choice for long term that accommodates the future required bandwidth. Passive Optical Networks do fall in the category of one important architecture of FTTH [23],[56]. PONs have evolved to provide much higher bandwidth than previously deployed access networks such as digital subscriber line (DSL) and cable television (CATV) [57-59]. In a PON, a single fiber between the optical line terminal (OLT) and the remote node (RN) is shared by all users, which are connected to it. The transport path of the network is passive because all the information traveling from OLT to ONU is in optical form but the components used between both units are passive, which means no power is required from outside nor electrical devices are used.

A PON is a fiber network which utilizes fiber and passive components like splitter and combiner, instead of the active components like shaping circuits, repeaters, and amplifiers [18]. Networks based on PON technologies are cost effective, but their application is limited by the shorter range of coverage due to weak signal strength. Optical network with active component (active optical network: AON) is suitable for upto 100 km transmission as compared to passive optical network, which is typically limited to 20 km. A standard passive optical network is a point to multipoint network where multiple subscribers of size 16 to 128 receive the internet or television services from central optical line terminal. The signal is split into equal low- power signals to distribute it to the multiple users. An ONU terminates the PON at the customer's home. Usually, ONU communicates with ONT and therefore can be considered as a single unit also [24].

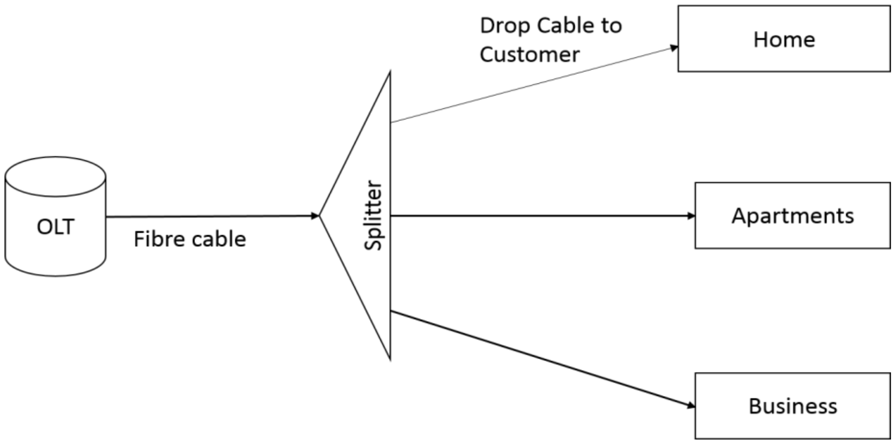


Fig. 2.1 Basic PON architecture,

The point-to-multipoint (P2MP) structure of a PON is depicted in Fig. 2.1. The optical line termination (OLT) distributes data in the downstream direction toward the optical network units (ONUs), located at the subscriber's premises. The subscriber uses time-division-multiple-access (TDMA) scheme to send upstream data toward the OLT [60]. There is continuous development in the passive optical networks as per requirements of the customers from time to time.

2.2 Evolution of Passive Optical Networks

In past three decades, various types of PONs have evolved and are classified as past (APON & BPON), current (EPON & GPON), next (10G EPON, XG-PON1 & XG-PON2) and future generation of PONs (WDM-PON).

2.2.1 Past Generation PONs (APON & BPON)

In the mid -1990s, an initiative of the full-service access networks (FSAN) group developed the first PON system referred as Asynchronous Transfer Mode Passive Optical Networks (APONs) [61]. The electrical layer is built on Asynchronous Transfer Mode (ATM) for commercial availability. How to extend the high-speed services with speed? British Telecom in 1995 addressed this topic while organizing FSAN coalition which aimed at developing the most economical and efficient way to perpetuate the emerging market services like Internet Protocol (IP), 10/100 Ethernet, video etc to business and residential customers globally. ATM and PON appeared as two most logical choices for the protocol and physical plant. Multiple protocols were best served by ATM while PON was the most inexpensive broadband solution catered optically. FSAN used APON format which was later accepted as an International Telecommunications Union (ITU) standard (ITU-T Rec. G.983.x series) [62-63].

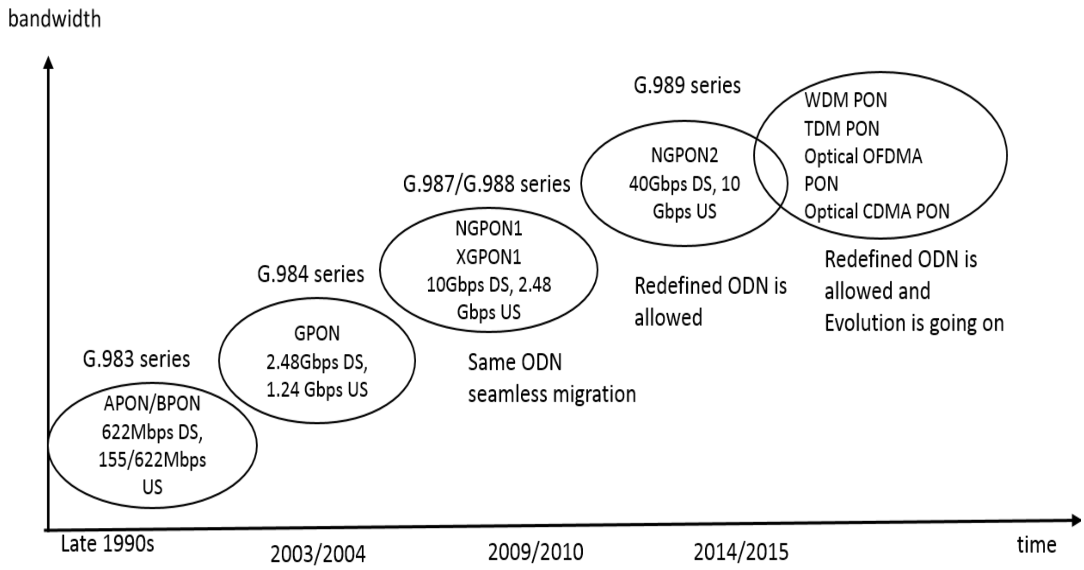


Fig. 2.2 PON evolution; reproduced from ref. [64].

ITU-T updates and recommendations on G.983 series started in 1998 dealing with the BPON based broadband optical access system [64]. The last mile of communication infrastructure is addressed by PONs between the service provider's Center office (CO), head end, or point of presence (POP) and business or residential customer locations. The APON format previously developed soon became a basis for international standard released by ITU-TS (Rec. G.983.x) also called as BPON (broadband PON), and it is enhanced subsequence of APON, in which the downstream and upstream data rate is 622 Mbps and 155 Mbps respectively [65-67]. It added some feature like dynamic bandwidth distribution, protection, and other feature. However, it was realized with early deployment that BPON ODN could not upgrade to the next upgraded technologies in the future. The evolution of PON is shown in Fig. 2.2.

2.2.2 Current Generation PONs (EPON & GPON)

Two visionary startups perceived the weakness in APON standard viz its lack of video capabilities, low bandwidth, complexity, and cost. With the market moving towards fast Ethernet, gigabit Ethernet, and 10-gigabit Ethernet, these startups soon realized that the need for conversion in the wide area network (WAN)/ local area networks (LAN) connection between ATM and IP protocols would be eliminated by Ethernet passive optical networks (EPONs) which uses similar optical frequencies as TDMA and Giga bit passive optical network (GPON). In fact, (EPON) 802.3ah specifies comparable passive optical network such as those based on Ethernet standard 802.3 with a range up to 20 km [68]. In such networks, the data rate as high as 1.25 Gbps could be obtained in both uplink and downlink.

A frequency band 1550 nm reserved for future extensions and video services, a 1490 nm based bidirectional 1 Gbps link is provided by EPON [69]. Owing to its compatibility with other Ethernet standards, handshake becomes easy and avoids any conversions or encapsulations. Ethernet being the primary networking technology used in local area networks and MAN (Metro area networks), payload up to 1518 bytes is efficiently served by the same Ethernet frame. A PON system which supports the data rate of 2.5 Gbps downstream and 1.25 Gbps in upstream is recommended by ITU-T G 984 series with the specified protocol is known as Gigabit Passive Optical Networks [70]. EPON is based upon Institute of Electrical and Electronics Engineers (IEEE) 802.3ah and GPON on ITU-T G984.x standard.

GPON is the most widely used PON architecture that uses single fiber for both downstream and upstream transmission by utilizing wavelength division multiplexing [71] with operational wavelength ranges viz. downstream: 1480-1500 nm, upstream: 1260-1360 nm and downstream RF video distribution: 1550-1560 nm. A 1490nm laser wavelength transmits over the channel for downstream while the wavelength of 1310 nm transmits as upstream data as shown in Fig. 2.3. At remote end, each user is allotted a time slot specific to them using time division multiple access (TDMA) format by GPON, which not only allows each ONU to get a downstream data

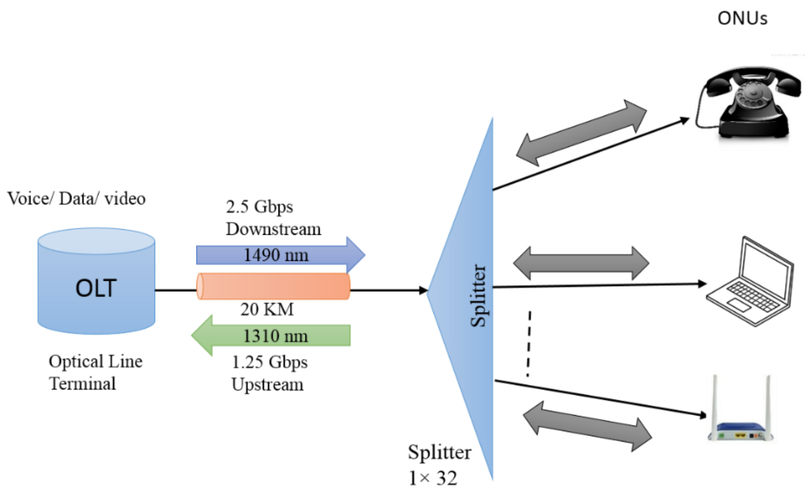


Fig. 2.3 GPON network; reproduced from ref. [71].

rate of 2.488 Gbps but also divides the bandwidth to ensure that each user gets a fraction of 100 Mbps speed depending on allocation by the service provider [71-72]. However, upstream rate is less than the maximum due to its sharing with other ONUs in a TDMA scheme. OLT determines the time and distance delay for each subscriber and paves the way of allotting upstream time slots to each user. Each fiber can serve up to 32 or 64 subscribers based upon its typical split of 1:32 or 1:64 respectively which extends to 1: 128 in some systems. The most practically deployed system use class B+ devices which have a length of 20 KM and split ratio of 1:32. It has a transmission data rate of 2488 Mbps and 1244 Mbps for downstream and upstream respectively, and this types of specification lead to a power budget of 28 dB [70].

2.2.3 Next Generation PONs (10G EPON, XG-PON1 & XG-PON2)

In late 2006, FSAN group begin to work on a system that would proceed after GPON, however in 2007 the focus shifted to define new system itself. Different architecture such as TDM-PONs, WDM-PONs, and CDMA-PONs were investigated. There was a difficulty to compare these systems in a reasonable way because they were quite different in architecture and service profile. Due to high bandwidth demand required from consumers and business applications, the most crucial requirements for next generation PON (NGPON) is to provide higher bandwidth than GPON. The migration GPON to NGPON of the subscribers must be smooth, and NGPON must be able to protect the major investments spent on time and money [72-73]. Fig.2.4 gives the solution to the problem by dividing the system proposal into two groups. The first group

NGPON1 systems could coexist with GPON by sharing the same optical distributed network ODN. NGPON2 included all system that either required a different ODN or that required new technologies.

10 GEPON: - To increase the data rate of EPON from 1 Gbps to 10 Gbps, 10 GEPON was developed on IEEE P802.3av PON by keeping ethernet interface [73]. 10 GEPON with EPON shared many protocols and coexisted with EPON and operated at the same ODN. It operates at a downstream transmission rate of 10 Gbps and upstream data rate 2.5 Gbps. For downstream two wavelength band (1480-1500 nm and 1575-1580 nm) are used for 1 Gbps and 10 Gbps channels respectively. In the upstream direction, two bands are overlapped [73-74].

XGPON1: - XGPON (X stands for10) is one of the most promising solutions for NGPON1. A mechanism of migration for acquiring a signal for 10 Gbps for downstream and 2.5 for upstream transmission is standardized in ITU-T Rec. G987.x for XGPON technology. NGPON2 technology is still evolving with growing number of technological suppliers and interested operators [75]. At 10 Gbps data rate, a high-speed burst mode trans receiver and dispersion are the most significant challenges for the realization of XGPON. XGPON is better as compared to WDM-PON regarding capacity and delay. XGPON2 has a symmetric data rate of 10 Gbps for downstream and 10 Gbps for upstream transmission and provides high capacity for upstream signal [76-77].

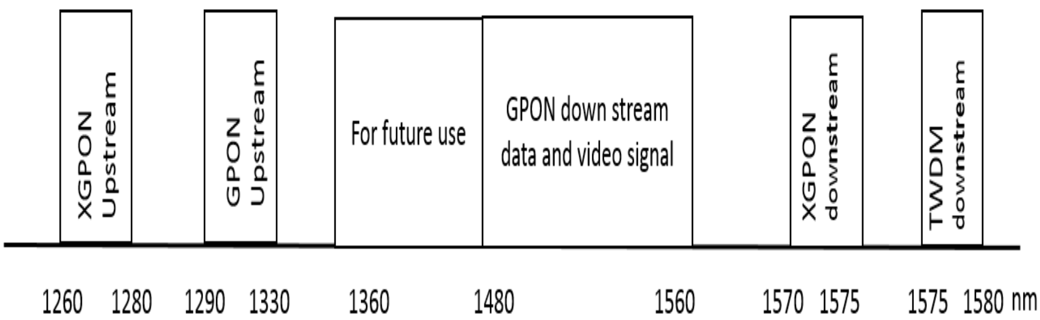


Fig. 2.4 XGPON frequency spectrum band as ITU-T G.987 recommendations; reproduced from ref. [78].

NG-PON 2: The basic requirement of NGPON2 is to support the 40 Gbps downstream for the residential and commercial application. FSAN group considered many option for NGPON2 which supports 40 Gbps aggregate capacities like WDM-PON, UDWDM, OFDM-PON, hybrid system and TWDM [78]. TWDM-PON technology was chosen by FSAN to be the prominent solution for NG-PON2 as from the operators' perspective it is more reliable, less disruptive and cost effective than the other solutions, which provides a significant advancement in the NG-PON2 standardization [79]. This type of advanced system can increase PON bandwidth capacity by a minimum 40Gbit/s and can provide 1Gbit/s or more services that may be rolled out in the near future [78].

As we study the coexistence of the various PON architectures, the planning of wavelength band with which NG-PON2 technology has to coexist must be taken into account. Fig. 2.5 gives the spectrum for NG-PON2. Here we consider Four wavelengths of 10 Gbit/s which are combined by the multiplexer in the Central Office and transmitted as a downstream signal [78]. At the remote end, ONU chooses the required wavelength by selecting one of the wavelengths from downstream signal. For the upstream, the ONU/ONT operate in one of the four upstream wavelengths, which was chosen by the OLT receiver. By placing the WDM filter at the center office it can coexist with the legacy of PON, but ODN is left untouched in all possible NG-PON 1 solutions.

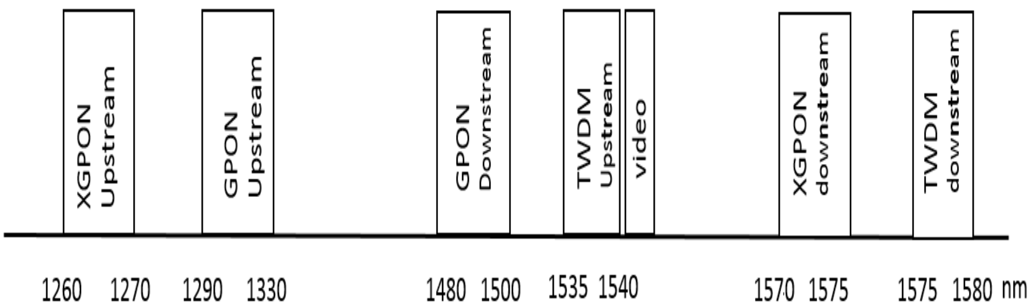


Fig. 2.5 NGPON 2 spectrum band; reproduced from ref. [78].

Several studies revealed that TWDM PON [80] is the most lucrative solution for fulfilling the requirements. ITU-T G.989.1 recommended in March 2013, the possible wavelength bands as per requirement of operators.

2.2.4 Future PONs (WDM-PON)

Wavelength division multiplexing passive optical network (WDM-PON) is known as a promising technology for future networks to provide high data rates to the end users. The Optical Add/Drop Multiplexer (OADM) improves the performance of a WDM-

PON Network architecture, which supports high dense geographical area with unlimited scaling [81-82]. Higher installation and maintenance costs can be reduced by the types of WDM architecture as shown in Fig. 2.6. The network design can support 10 Gbps downstream and upstream for distance up to 30 km. WDM-PON gives an alternative to the GPON scheme by providing each ONT transmission and reception at a specific wavelength [82].

As WDM-PON standards are still under development, manufacturers and operators anticipate that it will be using the same physical network as used by PON systems, having an OLT serving of 32 ONTs. Each ONT will be provided a different wavelength, which enables each customer to get higher bandwidth. WDM-PON expands on the idea of increasing the number of wavelengths in the fiber from the OLT to a nearby node [83-86]. Therefore, the key difference between WDM-PON and GPON is that WDM-PON may not use the GPON protocol but can use point-to-point communication Gigabit Ethernet.

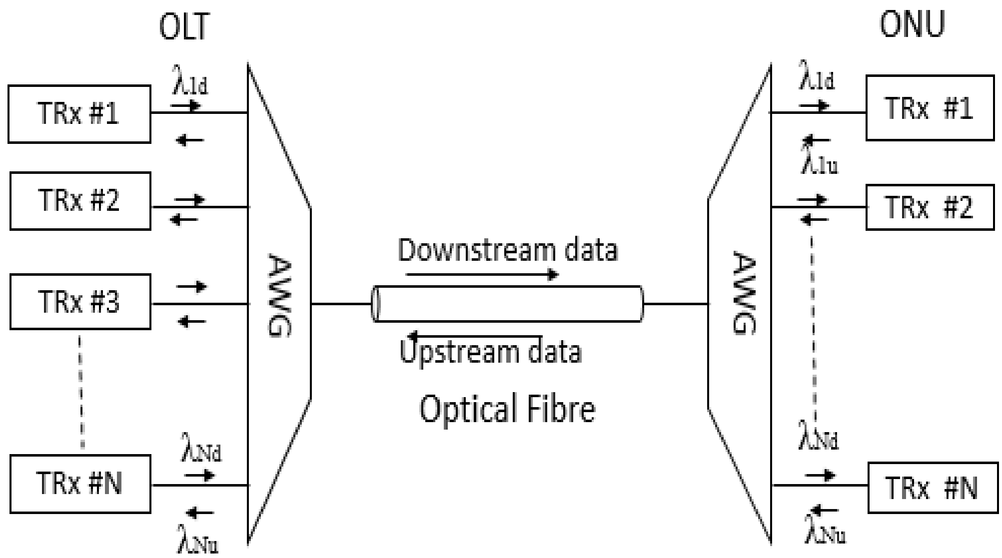


Fig. 2.6 WDM-PON Architecture; reproduced from ref. [82].

In the near future a high bandwidth will be required by the end users for high definition TV (HDTV). Daily activities that are now in use also consume a significant amount of bandwidth to support data voice and video services [83]. The basic difference among the various PON technologies and generation is summarized in Table 2.1 given below.

Table 2.1 Comparison of various PON technologies [62-83].

	A/BPON	*EPON, 10 EPON*	*GPON*	*XGPON1/ XGPON2*	*WDM-PON*
Standard	ITUG 983/FSAN	IEEE 802.3-ah (1Gbps) IEEE 802.3-av (10 Gbps)	ITU-T G-984	ITU-TG987/FSAN	ITU-T G-983
Protocol	ATM	Ethernet	ATM, Ethernet	GEM	Protocol independent
Subscriber cost	Low	Only 10% of GPON subscriber cost	Moderate	High but less than WDM-PON	Very high
Management system	Single layer	Single layer	Three layer		Dual management mechanism
Multiplexing	TDM	TDM	TDM	TDM	FDM
Downstream bitrate	Maximum 622 Mbps	1.25 Gbps, 10.3 Gbps	1.2, 2.5 Gbps	10 Gbps	1-10 Gbps/channel
Upstream bitrate	155/622 Mbps	1.25 Gbps, 1.25 or 10.3 Gbps	1.2, 2.5 Gbps	2.5 Gbps, 10 Gbps	1-10 Gbps/channel
Downstream wavelength	1490 nm, 1550 nm	1490, 1550 nm	1490 nm	1577 nm	Separate wavelength for each channel
Upstream wavelength	1310 nm	1310 nm	1310 nm	1270 nm	Separate wavelength for each channel
ONUs	32	32 and 64 (with FEC)	128	128	16-32
Per user BW	20-40 Mbps	30-60 Mbps, >100 Mbps	40-80 Mbps	>100 Mbps	1-10 Gbps
Reach	20 Km	≤ 20 Km	≤ 60 Km	≤ 20 Km	≤ 20 Km

The main advantages of WDM-PON [82] are summarized below :-

- It provides separate bandwidth to users by using the different wavelength i.e. no bandwidth scheduling is needed.
- Transmission bandwidth of the fiber is used effectively, up to 64 subscribers/fiber.
- A low loss AWG is used in contrast to the high-loss power splitter which ensures longer reach.
- Physical separation of subscriber signals.

The cost of the WDM-PON is increased, as a separate wavelength requires individual transmitters. At the user end, it will effect severely. However, at the center office side, the cost can be lowered by optical integration.

2.3 Performance Requirements of PON

Compatibility and Flexibility: - Designed system should be integrated with legacy PON network and should be adaptable to new upcoming technologies and protocols. Flexibility is related to the possibility of each user in the network, who can use any wavelength that is provided by the transmitter end that will help to support the random traffic pattern [87].

Scalability: - The network is said to be scalable if a particular user can access the variable bandwidths according to the immediate traffic demand and a growing amount of work [88].

Resiliency: - The network is called resilient when services are continued without any interruption in case any wavelength failure, this is achieved by diverting any available wavelength [89].

Immunity to interference: - The PON is immune to electromagnetic interference that is produced by same and different media [90].

Optimization of Networks: - The number of users can be increased by reducing the channel spacing, but it also increases interference due to overlapping of the signals in the channel [90,91]. So, there is a requirement to optimize amplifiers and other components to utilize maximum bandwidth and receiver capability.

Improving the capacity of Networks: - The existing WDM network with large spacing wavelengths can be converted into dense wavelength division multiplexing (DWDM) network by multiplexing these wavelengths with narrower spacing without disturbing the existing fiber [85].

2.4 Impairments in Optical Fiber Transmission

In this section, we will discuss various linear as well as nonlinear impairments which affect the quality of the signal such as reduction in amplitude, distortion as well as contamination.

2.4.1 Linear Impairments

The optical fiber offers huge transmission bandwidth. The application of optical fiber system for longer distance and the higher bit rate suffers from linear effects of the fiber such as attenuation and dispersion imposing limiting factor. In order to have high performance, high bit rate, long distance point to point optical transmission networks, both linear and nonlinear effects should be managed well. The present chapter gives the brief overview of various fiber induced impairments and their adverse effects on the performance of the networks.

2.4.1.1 Attenuation

Attenuation in an optical fiber plays very crucial role in designing a light wave system. This causes the decay of signal strength and loss of light power over fiber. Scattering, absorption, and bending loss are the main source of attenuation in the optical fiber [5]. The other reasons that contribute to attenuation are extrinsic, such as stress during the manufacturing process, environmental effects as well as physical bending [4-5].

When light travels in fiber over a length then power at the origin of fiber is P(0) and at the distance z is P(z) that can be related as given in Equation (2.1) [5]

$$P(z) = P(0)e^{-\alpha Z} \tag{2.1}$$

Then attenuation loss as Equation (2.2)

$$\alpha(dB/Km) = \frac{10}{z} \log\left(\frac{P(0)}{P(z)}\right) \tag{2.2}$$

The loss in optical fiber is expressed in dB/Km as shown in Equation (2.2). For silica material at 1550 nm (C-band) and 1310 nm (O-band), the possible losses are 0.25 dB/km and 0.4 dB/km respectively.

2.4.1.2 Chromatic Dispersion

A light pulse which has a fixed spectral width represents data and information. We consider a laser light as a monochromatic, but in practice it has some different wavelengths. Hence when this light pulse travels through the fiber, then each different component of light will travel at a different velocity at fiber end, and all wavelengths will reach at the various time hence pulse become broadened. This phenomenon is known as chromatic dispersion. If this is not managed properly, then light pulse gets overlapped resulting in inter-symbol interference in an adjacent bit, and at the receiver end, error free signal detection is not possible [92].

The main causes of chromatic dispersion or intramodal dispersion (also known as Group velocity dispersion: GVD) are material dispersion and waveguide dispersion. Material dispersion arises due to intrinsic properties of glass such as the variation in refractive index of the core. Refractive index is the function of wavelength hence pulse spreading occurs even though different wavelengths follow the same path. Material dispersion in term of material dispersion parameter given by [5]

$$Dm = \frac{1}{L}\,\frac{\tau}{\Delta\lambda} = \frac{\lambda}{\mathrm{c}}\left|\frac{d^2 n}{d\lambda^2}\right| \tag{2.3}$$

L is the fiber length, $\Delta\lambda$ is the full width at half maximum at peak spectral power of the source at λ, c is the velocity of light in vacuum, n is a refractive index, and τ is pulse broadening of pulse. Waveguide dispersion arises mainly due to the bound structure of the fiber, where degree of waveguide dispersion depends on the fiber design. The waveguide dispersion due to nonlinear b-V diagram is obtained as [5]

$$D_{wg} = -\frac{n_2\,\Delta}{\mathrm{c}\lambda}\,V\,\frac{d^2(bV)}{dV^2} \tag{2.4}$$

Generally, V and b is the substitution of ω and β respectively in the two normalized parameter of fiber. The total chromatic dispersion is given by Equation (2.5)

$$D = D_{mat} + D_{wg} \tag{2.5}$$

2.4.1.3 Polarization Mode Dispersion

When we move towards high data rate (more than 10 Gbps) light wave system to fulfill the future bandwidth demand, then polarization mode dispersion (PMD) limit the reach of the system. In practical optical fiber, the core is not completely cylindrical hence there is non-uniformity in core diameter along the fiber. This leads to differences in propagation constant of two polarization components and fiber become birefringence. Light pulse travelling through single mode fiber, has two orthogonally polarized components with two different velocity V_{gx} and V_{gy} arriving at the end of the fiber at different times [5].

$$\triangle T = \left| \frac{L}{V_{gx}} - \frac{L}{V_{gy}} \right| \tag{2.6}$$

This above Equation (2.6) is valid for the only assumption of constant birefringence. For conventional single mode, fiber PMD induce pulse broadening can be given by

$$\triangle T = D_{PMD}\sqrt{L} \tag{2.7}$$

Where D_{PMD} unit is ps/km$^{1/2}$, value varies from 0.01 to 10 ps/km$^{1/2}$, L is the length of the fiber, and $\triangle$T is a time delay. This difference in propagation time leads to pulse broadening, and degrade the transmission performance through Inter-symbol interference [5].

2.4.1.4 Amplified spontaneous emission noise

For long haul network, signal travelling through fiber gets degraded due to loss. This loss can be compensated using erbium doped fiber amplifier (EDFA). During amplification amplified spontaneous emission (ASE) noise is generated by the spontaneous decay of electrons in the higher energy levels to lower energy levels. Hence the wide frequency range of photon emitted [93].

2.4.1.5 Linear crosstalk in WDM systems

As advances in optical networks leads towards use of transmission bandwidth of fiber more effectively, more than two wavelengths are used and multiplexed into the optical fiber. As spacing of the wavelength is reduced for dense wave division multiplexing, adjacent channel cross talk is very common for a communication system. This crosstalk is very significant which affects the minimum separation of two channel, and there is a partial overlap of the channel in the frequency domain. Linear crosstalk in WDM-PON mainly arises due to channel spacing, filtering characteristics of the multiplexer as well as de-multiplexer [94]. Linear crosstalk is classified as in-band and out –band as per their passband of an optical fiber [95]. The optical out band is defined in WDM for different wavelength hence this is not much harmful due to easy separation by the narrow band optical filter as shown in Fig. 2.7(a). In the in-band crosstalk, the desired signal and leaked signal have nominal identical wavelength shown in Fig 2.7 (b).

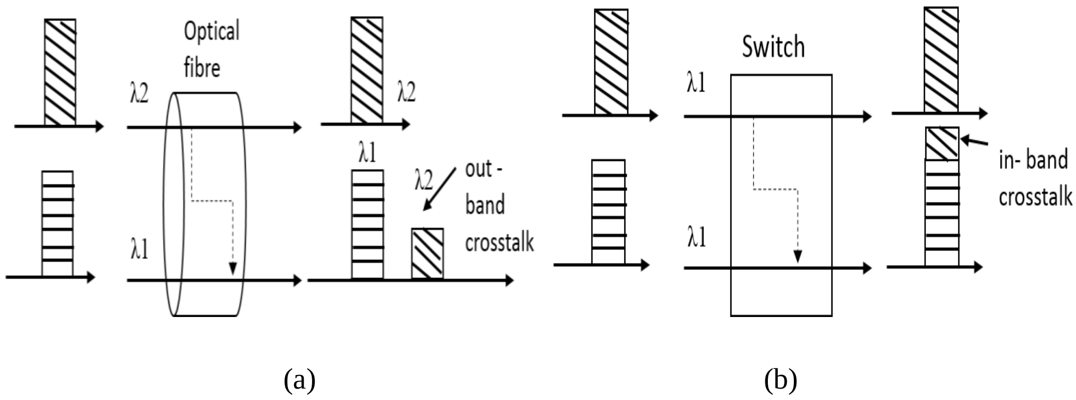


Fig. 2.7 (a) Out-band cross talk (b) in-band cross talk; reproduced from ref. [95].

2.4.2 Non- Linear impairments

A high bit rate system operated at high transmitter power, suffers from several nonlinear effects. These effects are the results of the intensity dependence of refractive index of the medium. In WDM-PON, multiple wavelength multiplex into the single optical fiber due to which transmitter power and bit rate start to play role for the nonlinearity. There are nonlinear phenomena which occur due to intensity dependence of refractive index known as Kerr effects, and another one is inelastic scattering phenomena. Kerr effect includes self-phase modulation (SPM), cross phase modulation (XPM) and Four-wave mixing (FWM). Stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) is the part of inelastic scattering [5]. As the fiber length increases, the nonlinear effects start to decay due to power loss in the fiber hence nonlinear phenomena are more dominant at the start of the fiber. The nonlinearity will contribute towards the signal impairment in the optical communication system, and additional power is required at the transmitter to maintain the same BER.

2.4.2.1 Stimulated Raman Scattering (SRS)

SRS is a phenomenon that occurs when two and more wavelength signals travel into the optical fiber, lower wavelength channel power is transferred to higher wavelength channel [96]. It is an interaction between light waves and molecular vibration of silica. In this interaction, the scattered light is generated which is downshifted by Stokes frequency. If any signal is present at higher wavelength, then it will experience gain means it gets amplified and this gain process is known as SRS as shown in Fig. 2.8. In WDM system where multiple channels are equally spaced and easily find the separation of 110 nm between two wavelengths, which is appropriate for Raman gain, then low wavelength channel is treated as a pump for higher wavelength channel [96-97].

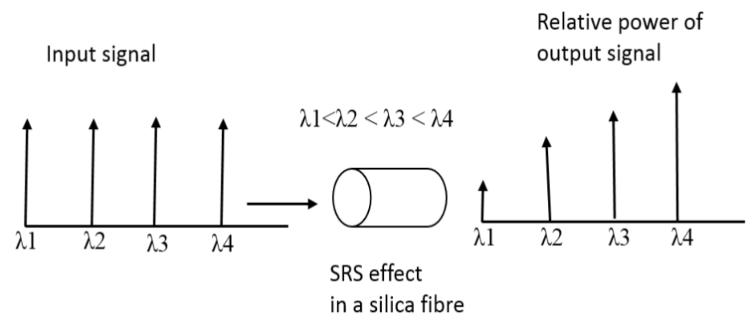


Fig. 2.8 SRS transfer of lower wavelength power to higher wavelength; reproduced from ref. [4].

2.4.2.2 Stimulated Brillouin Scattering (SBS)

It is a nonlinear process occurring in fiber due to the launching of high power optical signal. It includes the interaction of incident light with acoustic phonons in the silica glass and produces the variation in refractive index of fiber [98]. This variation in fiber works as a grating hence a particular frequency gets backscattered and down shifted by 11 GHz from the original signal [4]. The Brillouin line width is 20 MHz at 1550 nm and is very narrow compared to Raman. SBS effect is confined within a single wavelength channel and occurs in WDM in each channel for same power level.

2.4.2.3 Self Phase Modulation (SPM)

A single light wave's passage through the optical fiber can be affected by the nonlinearity.Its own optical field modifies the phase of the optical signal. This phenomenon is known as self-phase modulation. The edge of pulse shows the time varying intensity, which rises rapidly from zero to maximum value then return to zero.

Since the phase fluctuation is intensity dependent, different parts of pulse undergo a different phase shifts. This leads to frequency chirping [4]. For some fibers, the time varying phase may result in a power penalty owing to a group velocity dispersion (GVD) induced pulse broadening of the pulse as it travel along the fiber and resulting overlap between itself and the adjacent bit and increases the bit error rate of the system as shown in Fig.2.9.

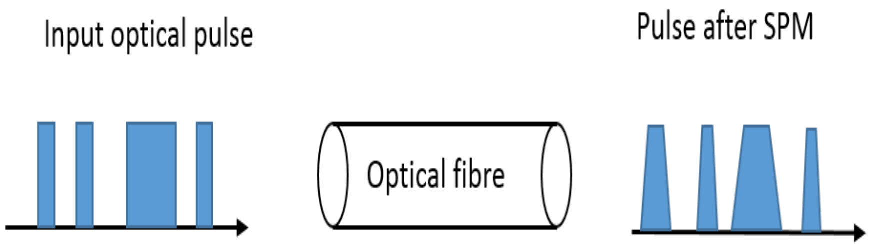


Fig. 2.9 Self phase modulation; reproduced from ref. [100].

2.4.2.3 Cross Phase Modulation (XPM)

XPM is known as another cause of nonlinear effects which affects the WDM transmission performance. In this, signal phase is modulated according to the neighboring channel of DWDM system [101].

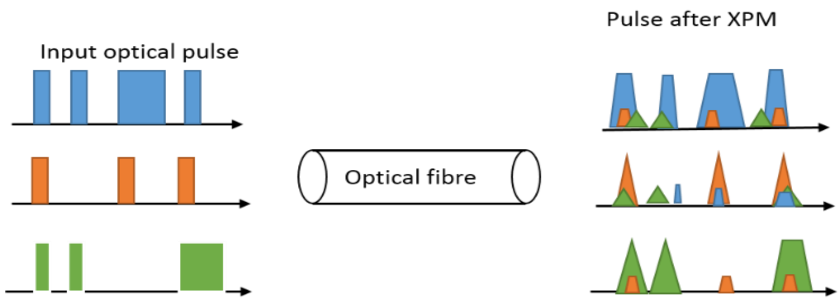


Fig. 2.10 Cross phase modulation; reproduced from ref. [102].

This happens due to refractive index change by the power of adjacent channel as well as central power channel in a nonlinear fashion. If XPM occurs in DWDM channel, the SPM will also be present and coupling the power among the DWDM channel as shown above Fig. 2.10. The dispersive walk-off phenomena will also exit due to the different frequency component of DWDM hence affecting the adjacent channel power [4] as shown in Fig. 2.10. Dispersive walk-off among the channels affects the power of the adjacent channel and reduces the effects of XPM [5].

2.4.2.5 Four Wave Mixing (FWM)

If three or more frequency signal using WDM travel through optical fiber, a new frequency signal is generated, this phenomenon is known as FWM. It is a third order nonlinearity [103]. Three frequency signal f_1, f_2, and f_3 induce phase shift in the neighboring channel by the intensity dependence of refractive index, together with this it will generate a new frequency as $2f_i$-f_j and f_i-f_j-f_k. In general, two frequency f_1, f_2 generates new frequency due to FWM which has little power as compared to another original signal as shown in Fig. 2.11.

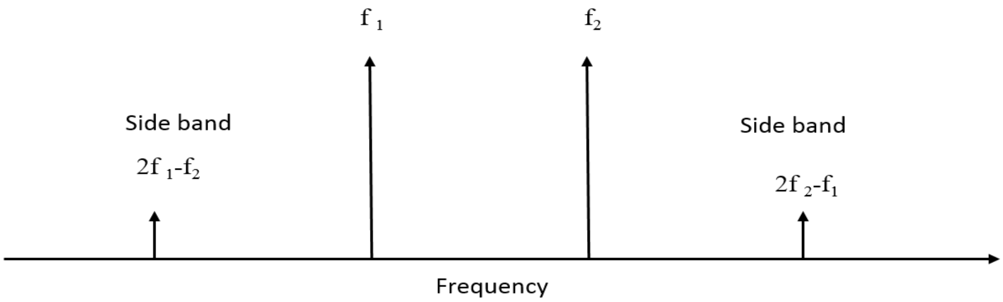


Fig. 2.11 FWM with two signal frequency; reproduced from ref. [4].

This critically depends on channel spacing and dispersion of DWDM system in contrast to SPM, XPM which are significant on high bit rate system [4-5].

2.5 Chapter Summery

In this chapter, most commonly used passive optical network standards such as APON, BPON, GPON EPON and NG PON are discussed. In view of requisite high bandwidth in futuristic network, a detailed study of WDM-PON is presented. Important parameters such as flexibility and scalability have also been studied. Various fiber impairments like dispersion, attenuation, SRS, SBS, SPM, XPM and FWM have been discussed in detail.

Chapter 3

Modulation Techniques for optical communication

3.1 Introduction

In recent times, advancement in optical systems are in the direction to achieve high bit rate and to operate for long distance communication, however the performancedegradation due to impairments in the channel is posing the problems. The improvement in the system performance can be achieved by utilizing the appropriate modulation format. The modulation format finds the transmission quality and spectral efficiency for the optical system. Here we focus mainly on different digital line codes such as NRZ, RZ, Duobinary etc. There is immense scope of research in optical modulation formats. In this chapter, we also discuss various optical modulation formats such as NRZ-OOK, RZ-OOK, DPSK etc. including their important characteristics. The line codes generate the waveform from the binary data information, which is only suitable for transmission in the baseband channels. Modulation is necessary to transmit the information at higher frequency. The Different modulation formats are discussed in the following sections of the chapter.

3.2 Line coding

In optical communication, the line coding is techniques where binary digital data is converted to the real temporal digital waveform and transmitted in baseband channel as shown Fig. 3.1. The development in various line coding is required for the different application, channel characteristic as well as a performance requirement. Each line code has its distinct properties.

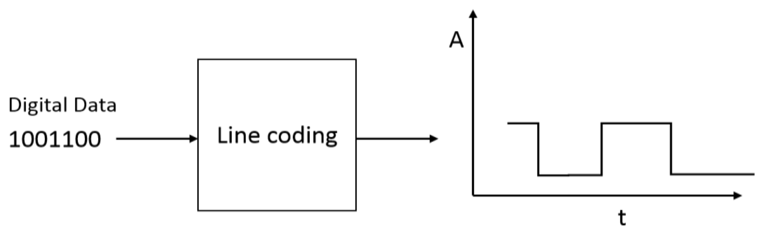


Fig. 3.1 Line coding to convert data to digital signal; reproduced from ref. [42].

Some essential characteristics of line coding are given below, which are useful for selecting the proper line coding according to the application [42].

Number of signal levels: Binary data can be represented by two or more level of digital signal. Digital signal, which has more than two levels, is also known as a multilevel signal. The spectral efficiency can be improved by the increasing the number of level of the signal.

DC components: After line coding, there is zero frequency signal in the spectrum, which is known as direct-current (DC) component. The DC component is undesirable because it cannot pass through some components of an optical communication system. This leads to distortion in the signal and unwanted energy loss of the system

Signal spectrum: The different line coding leads to different power spectrum and bandwidth of the signal. To avoid attenuation and distortion in the channel, the frequency response of the channel should be matched to signal spectrum. The energy should be contained in small bandwidth, smaller the bandwidth; the higher is the transmission efficiency.

Synchronization: To avoid error in received signal, the bit interval of receiver should be exactly same as a transmitter. If any mismatch occurs then signal gets an error and the original signal cannot be recovered. Usually clock signal is generated and synchronized with the received signal. If the signal has minimum one transition per bit interval, then it can be self-synchronized.

Cost of implementation: Cost is the hurdle for the practical application of the system so encoder should be kept as simple as possible.

The classification of line coding is done according to the level and polarity of signal [42]. Binary line coding is classified in two-ways (i) level codes (ii) and transition codes. In level codes, the information is in the voltage level as low and high for particular bit intervals like full bit interval or some part of the bit interval. Non- return to zero (NRZ) and return to zero (RZ) are the example of the full bit interval and partial bit interval respectively. The level codes are instantaneous, encode instantaneous binary data to signal waveform and does not depend on the previous binary number. Another types of line coding is transition codes which carry information in the change in the level of the waveform and also possess memory stage, so the generation of waveform depends on the previous binary bit information [104]. Further, the line codes are classified according to the polarity of the signal such as unipolar, polar and bipolar as shown in Fig. 3.2.

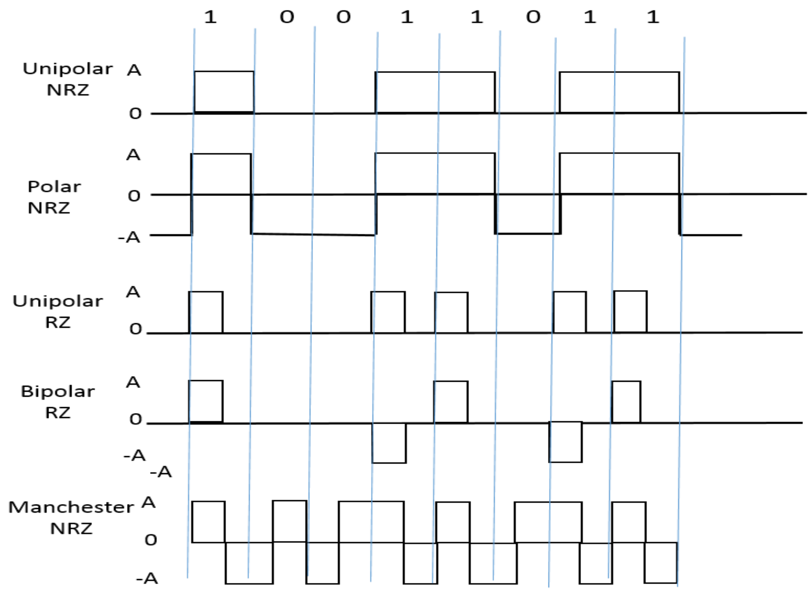


Fig. 3.2 Common line coding; reproduced from ref. [42].

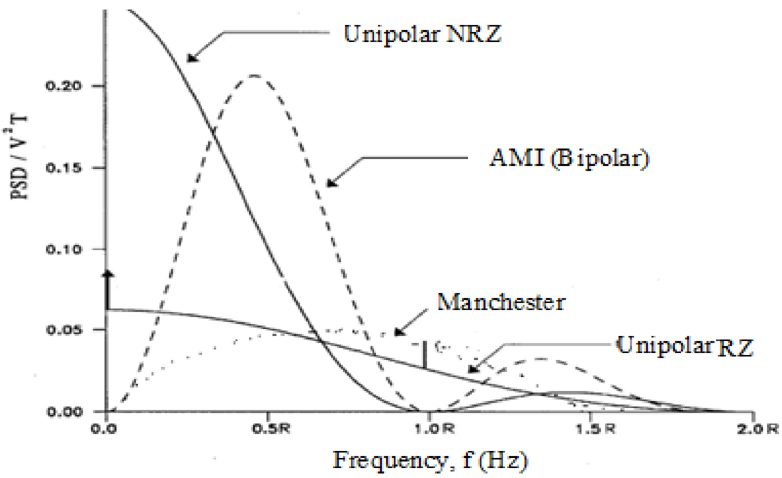


Fig. 3.3 Power spectral density of different line codes; reproduced from ref. [42].

For unipolar signaling, one of the polarity either positive or negative voltage is used to represent the data information. If both positive and negative level of voltages are used to represent information or not using voltage level zero, is known as polar signaling [104]. In bipolar signaling, both negative and positive voltage level along with zero voltage level are used to represent information. The term bipolar signaling is utilized by some researchers in past to designate a specific line coding scheme with positive, negative, and zero voltage levels [105]. Some of the main line codes shown in the Fig. 3.2. the frequency response of the channel can be matched to power spectral density as dipicted in Fig. 3.3 as a requirement of the application. In the next section, we have explained the modulation techniques for different line codes such as NRZ, RZ, Manchester, and DPSK along with advanced coding like Duobinary, dicode.

3.3 Optical Modulation

To transmit the information through an optical fiber, the line coding has to be transformed in the optical range at THz frequency band to match the frequency response of the channel [106]. The process of transformation is known as modulation [42]. The three physical features of optical field distribution which are considered to transmit information are intensity modulation, phase modulation (as well as frequency) and polarization modulation. The selection of appropriate modulation format is the essential key to build the flexible and cost-effective high-capacity optical networks.

Intensity modulation (IM): - In intensity modulation, the amplitude of the source switches between two states ON and OFF, so it is also known as ON-OFF keying. The amplitude shift keying (ASK) is the type of intensity modulation [107]. The high-frequency optical carrier signal is modulated by the message signal as shown in Fig. 3.4.

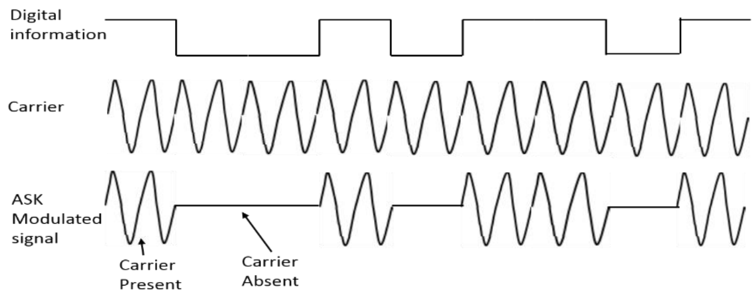


Fig. 3.4 ASK modulation; reproduced from ref. [107].

The message signal is imposed on the carrier signal such that binary ‘1’ is represents ON states with a fixed width amplitude and zero voltage level represents binary ‘0’ or the OFF state .

Frequency Modulation: - The frequency of carieer signal is varied as per data signal information between two frequencies as shown in Fig. 3.5 known as frequency shift keying (FSK) [107]. In this technique envelope of the optical signal does not change, so generation and receival of a signal are costly and circuit complexity of FSK is high on comparison to ASK.

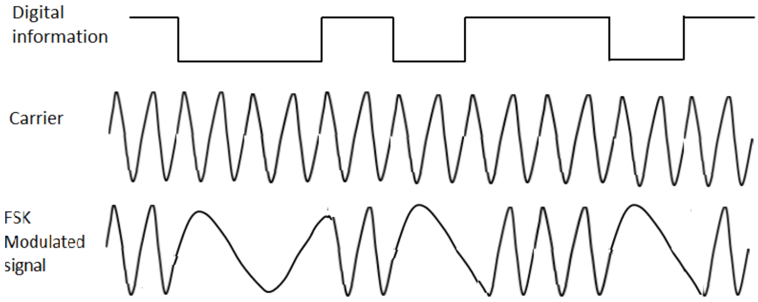


Fig. 3.5 FSK modulation; reproduced from ref. [107].

Phase modulation (PM): - One of the property (phase) of the carrier signal is changed according to the digital information or binary data as shown in Fig. 3.6. This improves the nonlinear tolerance for the system due to the presence of constant signal envelope and narrow spectral. The phase shift keying (PSK) uses the finite number of phases to represent the unique pattern of binary digits.

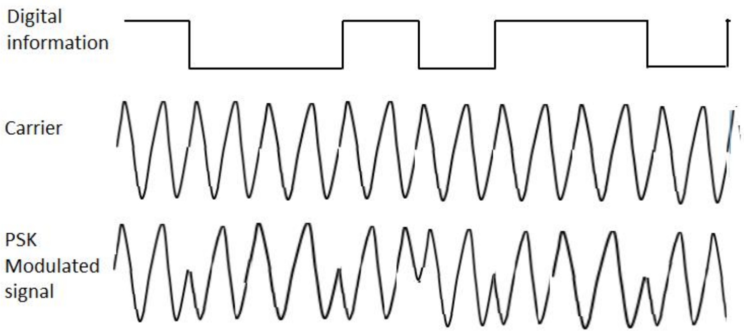


Fig. 3.6 PSK modulation; reproduced from ref. [107].

Moreover, each pattern of bits forms the symbol which is represented by the particular phase. The effects produced by the multichannel are very sensitive to this type of modulation. Due to its complex receiver circuit, it did not receive much interest.

Polarization Modulation: - In the polarization modulation, two orthogonal polarizations exist which can be changed according to binary bit information like one for 1 bit and other for 0 bit. It is known as polarization shift keying. It also has constant signal envelope which improves the sensitivity and nonlinear tolerant uses the system bandwidth effectively [107]. It is very sensitive to any polarization disturbance in the channel and receiver and detection of the signal is complex. In the next section, we study the intensity modulation with different line coding. Intensity modulation is very popular for the light wave system because the receiver is simple due to direct detection and less cost at the subscriber end.

3.3.1 NRZ- ON-OFF keying

For a long time, non-return-to-zero on-off-keying (NRZ-OOK) has been the dominant modulation format in intensity modulation/direct detection (IM/DD) fiber-optical communication systems [42]. In NRZ line coding any positive voltage represents binary bit 1 and zero voltage represents bit 0 as shown in Fig.3.2. This is instantaneous level codes, and PSD for an equal probable sequence of 1 and zero is given by Equation (3.1)

$$S_1(f) = \frac{V^2\,T}{4}\left(\frac{\sin \pi f T}{\pi f T}\right)^2 + \frac{V^2}{4}\delta(f) \qquad (3.1)$$

Where V is binary 1-bit voltage, T=1/R bit duration and R is the data rate in bit per second. There is several reasons to use this level coding in an optical communication system as it requires electrically low bandwidth compared to RZ for the transmitter and receiver. Additionally, this is less sensitive to laser phase noise as compared to PSK and efficiently used in DWDM system and not affected by disturbance of multichannel. To convey information from the optical fiber channel, this line code is modulated by the light source as Intensity modulation or OOK. The transmitter block diagram is shown in Fig. 3.7.

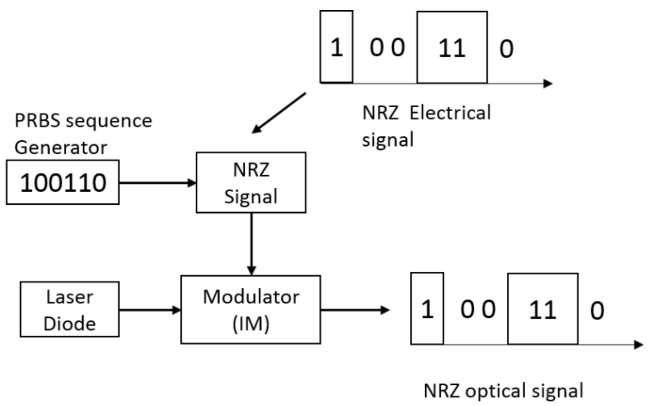


Fig. 3.7 NRZ- OOK transmitter; reproduced from ref. [109].

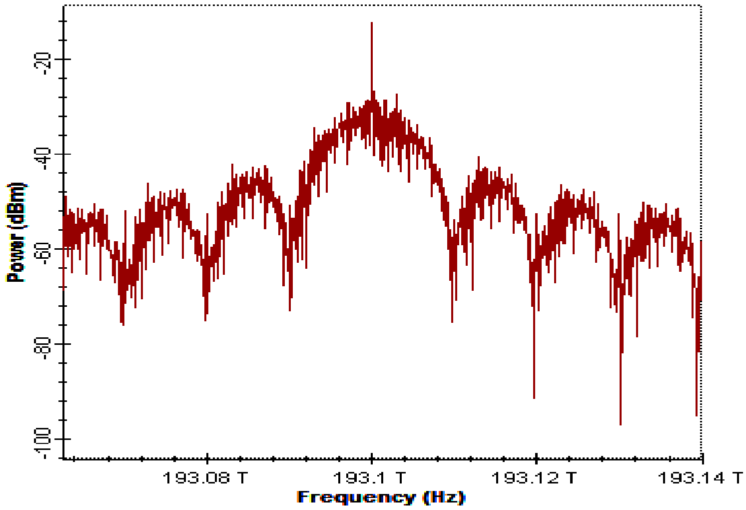


Fig. 3.8 Optical signal spectrum.

The block diagram of an NRZ-OOK transmitter is shown in Fig. 3.7, where pseudorandom binary sequence (PRBS) generator generates randomly binary bits as data information, which are converted to the electrical waveform as NRZ level signal [108-110]. Laser diode generates continuous light pulse which is modulated with an intensity modulator (IM) as according to information waveform with using proper biasing at Modulator. Two types of IM which are mainly used in optical communication are Mach Zehnder modulator (MZM) and electro-absorption modulator. Both converts NRZ electrical signal to NRZ-OOK optical signal with same data rate. At receiver, we can detect this NRZ-OOK signal by using PIN or APD photodiode which converts the optical power of signal into electrical signal. These types of detection methods are known as direct detection (DD). This receiver circuit of direct detection is simple hence cost is also less compared to others. The optical signal spectra are shown in Fig. 3.8 indicates the zero frequency components and DC contents, which are undesirable. These types of coding are not good choices for circuits where inductive and capacitive components are used. At high data rate and long distance NRZ is not the best choice in optical communication [111]. The RZ is becoming popular nowadays for high bit rate long haul networks. Previously much attention was not given to this due to larger bandwidth requirements compared to NRZ. However, in recent years, it is shown that RZ has superior performance over NRZ in the presence of chromatic dispersion, fiber nonlinearity and due to other many advantages like these. In recent years, it has been shown that RZ can have superior performance over NRZ in certain regimes where chromatic dispersion and fiber nonlinearities [112]–[114] also exhibit solitons like properties. In addition, RZ has greater tolerance to polarization mode dispersion than NRZ [115].

3.3.2 RZ-OOK

Level coding which is Return to zero (RZ) and the optical signal width is less then its bit period. RZ means ‘return-to-zero,' so the width of the optical signal is smaller than its bit period. A clock signal with an equal data rate to an electrical signal is used to generate RZ shapes of the optical signal [42]. In this line code, a binary one is represented by a voltage level with half bit interval and 0 bit is represented by the 0 voltage of the full bit duration. Thus this is the instantaneous level codes. The waveform of unipolar RZ signal is shown in Fig. 3.2. The PSD of unipolar RZ line codes for equally likely bit is given by Equation (3.2)

$$S_2(f) = \frac{V^2T}{16}\left(\frac{\sin\frac{\pi f T}{2}}{\frac{\pi f T}{2}}\right)^2 + \frac{V^2}{4\pi^2}\left[\frac{\pi^2}{4}\delta(f) + \sum_{n=-\infty}^{\infty}\frac{1}{(2n+1)^2}\delta(f-(2n+1)R)\right] \qquad (3.2)$$

Where V is the binary one voltage level and T= 1/R is the bit periods. Fig. 3.3 shows the spectrum of RZ signal. The advantages of RZ are easy generation, and self-clocking means no need of extra component and allows simple timing recovery [113-115]. The generation of RZ –OOK signal is shown in Fig.3.9.

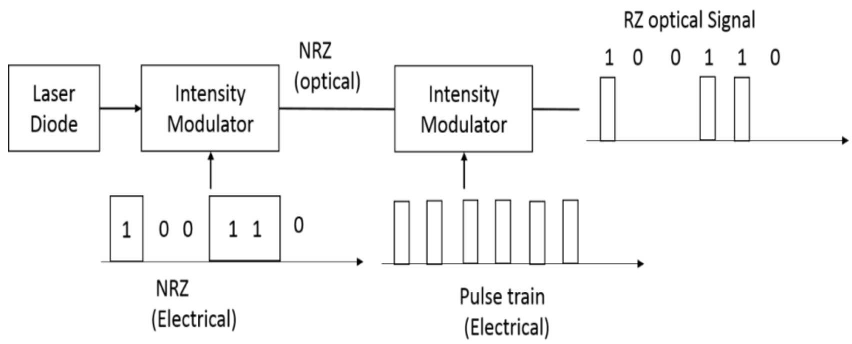


Fig. 3.9 Block diagram of a RZ transmitter.

First intensity modulator generates the NRZ optical signal followed by another intensity modulator, which generates RZ optical signal using a synchronized electrical pulse train with the same data rate.

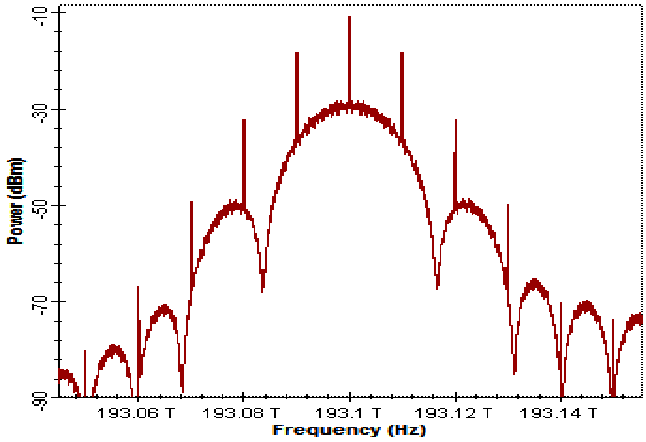


Fig. 3.10 Power spectra of RZ-OOK.

The spectrum of RZ-OOK is also shown in Fig. 3.10. It has wide spectra compared to NRZ that leads to less spectral efficiency for WDM system also have the presence of zero Frequency components which lead to DC wander. For continuous zero bit, it could lead to the loss of synchronization. It has no error detection capability hence it will not be suitable for performance monitoring. In the next section, we will review the Manchester coding which has no DC content at zero frequency.

3.3.3 Manchester Coding

In the Manchester level coding binary bit (1) is represented by positive half period pulse followed by negative half bit period pulse [42]. Zero bit (0) is represented by the negative half bit periods followed by a positive half bit period as shown in Fig 3.11. It is classified under instantaneous transition code, which has no memory.

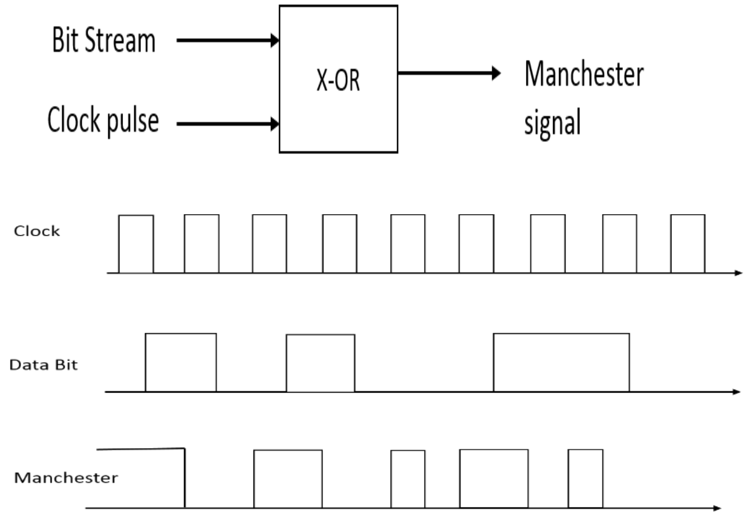


Fig. 3.11 Binary to Manchester generation of waveform; reproduced from ref. [42]

For equally likely bit of 0 and 1 then power spectral density (PSD) is given by Equation (3.3)

$$S_3(f) = V^2 T \left(\frac{sin\frac{\pi f T}{2}}{\frac{\pi f T}{2}} \right)^2 sin^2 \left(\frac{\pi f T}{2} \right) \tag{3.3}$$

This coding has advantage of no DC components as well as provides good synchronization due to 1 and 0 are represented by the transition from the high to low and low to high respectively. These transitions are sure for each bit of one or zero so easy to extract timing information. The optical modulation can be done by applying the Manchester signal to intensity modulator as discussed in previous techniques. The optical power spectra are shown in Fig 3.12. The major drawback of this coding is that it has twice of the bandwidth of the NRZ or other common code and the twice of the data rate (2Rd). Also, performance monitoring is not possible because it has no error detection capability. In the following section, we will study about the Differential phase shift keying (DPSK) in which information is in the phase of the carrier and useful to improve the spectral efficiency as well as nonlinearity tolerant for optical communication.

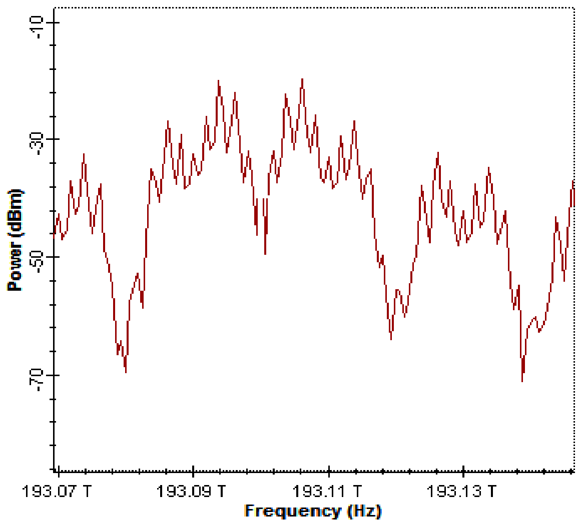
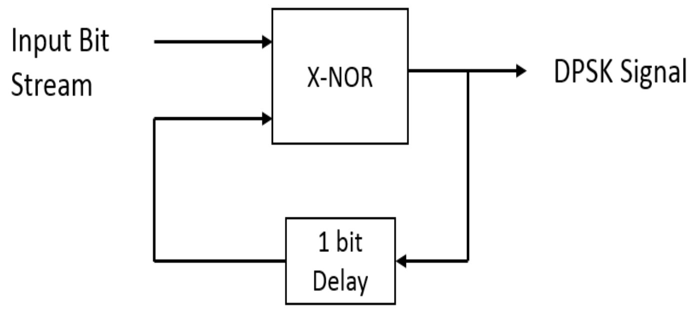


Fig 3.12 Manchester optical spectrum

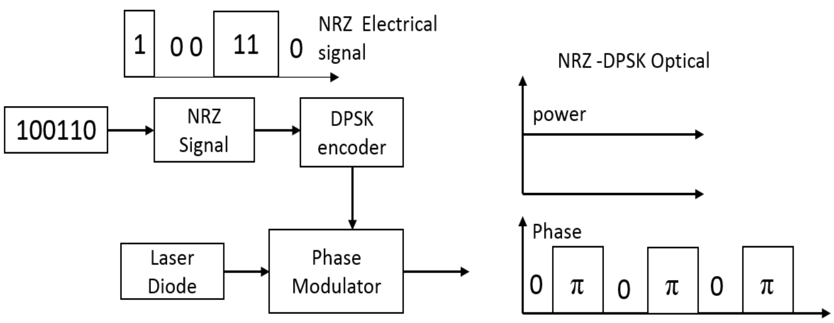
3.3.4 Differential Phase shift keying

The line coding studied till now represents the instantaneous optical power level with intensity modulation. Similarly, the digital information is represented by the phase of carrier signal known as phase shift keying (PSK) [42]. In starting, the laser source was immature to generate the single frequency and stable phase. Hence phase based modulation was not possible. However, now due to rapid growth in the light source technology, use of PSK is feasible for practical optical system especially differential phase shift keying (DPSK) is most often used modulation format.

Fig. 3.13 (a) shows the block diagram of a typical NRZ-DSPK transmitter. Electrical NRZ signal converted to DPSK signal as Fig. 3.13 (a) then it is modulated by external electro-optic phase modulator. The optical signal 1 bit is represented by phase π and 0 bit is represented by no change in phase.



(a)



(b)

Fig. 3.13 NRZ- DPSK (a) Encoder (b) Modulator; reproduced from ref. [109].

The optical signal power of DPSK signal is always constant. To detect the signal at the receiver side, a complex circuit is used with Mach-Zehnder- interferometer (MZI) as shown in Fig. 3.14 (b).

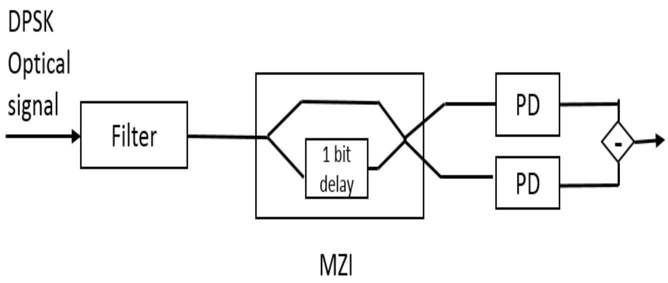


Fig. 3.14 DPSK Receiver circuit; reproduced from ref. [109]

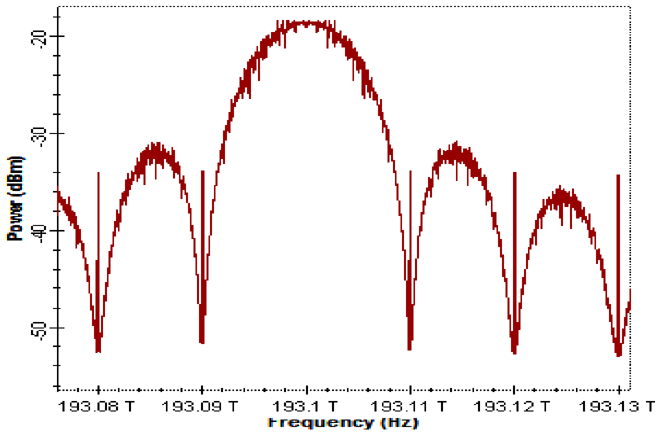


Fig. 3.15 Power spectrum of DPSK

The MZI is mainly correlating each bit to its previous neighbor bit to convert phase information into the intensity. It has two port, one is constructive and other is a destructive port. At constructive port, if two consecutive bit is in the same phase it adds and gave high signal power otherwise for different phase, they cancels one another, and it shows a low level of power, Vice versa occurs at the destructive port. The photodiode converts these signal into photocurrent and combine (logically subtracted) them to double the signal strength.

In the NRZ DPSK, the power level is a constant and optical phase shift between 0 to π (as 1 and -1), and average optical field gets zero [116-117]. So there are no carrier components present in power spectrum of NRZ- DPSK as shown in Fig. 3.15 compared to NRZ OOK which has strong carrier components shown in Fig. 3.8. The main drawback of this coding is complex receiver circuits hence cost increases at the user end. In the next section, we will study the Duobinary and dicode which is the part of multilevel signaling.

3.3.5 Multilevel signaling

Till now we studied about two level (zero and one) signal and their characteristics, but these level of signal can be increased from more than two. The multilevel signal allows higher transmission efficiency and useful in the band limited application [42]. Transmission bit rate can be given as Equation (3.4)

$$R_b = R_\delta \log_2[L] \tag{3.4}$$

Where R_b is bit rate, R_s is baud rate or signaling rate and L is the number of level and symbol rate is less than the bit rate. The multilevel signaling compresses the required transmission bandwidth at the same bit rate and allows improvement in transmission efficiency also known as partial response signaling [42]. In the partial response signaling the controlled amount of inter-symbol interference is allowed that can be removed at the receiver end. This allowed interference is used to reshape the spectra that will make it less sensitive to timing error.

3.3.5.1 Duobinary

Duobinary Coding is the special case of partial response coding, which requires the minimum bandwidt which is the half of the bit rate. Duobinary Signals can be generated digitally by applying a unipolar binary data signal to the input of a one-bit delay shift register with subsequent addition of the delayed and undelayed versions of the original data signal as shown in Fig. 3.16. The generated electrical duobinary signal is modulated by Intensity modulator and waveform is shown in Fig. 3.17.

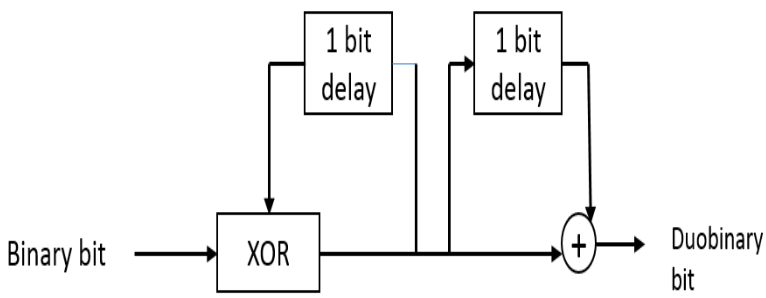


Fig. 3.16 Duobinary encoder [118].

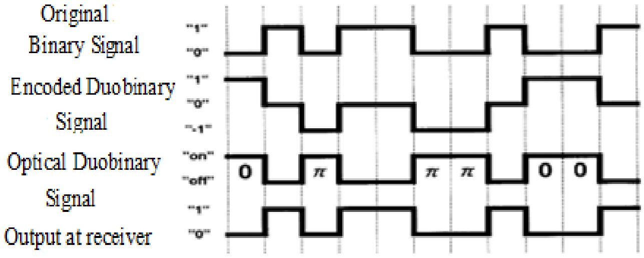


Fig. 3.17 Generation of Duobinary waveform [118].

The power spectral density of encoded Duobinary signal is given as Equation (3.5)

$$P(f) = T.\frac{\sin^2(2\pi fT)}{(2\pi fT)^2} \tag{3.5}$$

The simple intensity modulator can be used for modulation of this signal and optical spectrum after modulator is given as

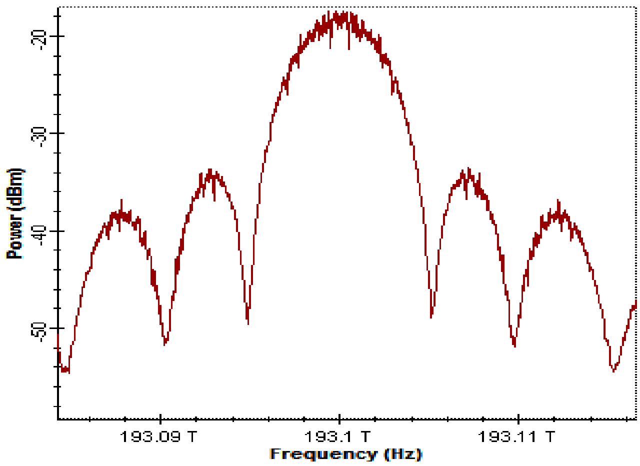


Fig. 3.18 Power spectra of Duobinary after modulation.

From Fig. 3.18 it is clear that for the signal of 10 Gbps data rate the bandwidth achieved is 5 GHz, which means 10 GHz is compressed to 5 GHz. The Optical Duobinary Coding utilizes the optical phasefor 1 and -1 and intensity profile is same as binary IM system, so it has the following advantages [119-120]. First, a Binary IM-DD receiver can be used at the receiver for the detection of the received signal, and same receiver sensitivity can achieve as a binary IM-DD system. Secondly, it has higher tolerance to dispersion due to reduced spectrum width compare to binary IM signal. Also the optical Duobinary signal has no carrier frequency components, so input power limitation is relaxed due to SBS.

3.3.5.2 Dicode

The Dicode is a special spectrum reshaping technique to reduce the low-frequency DC component compared with the conventional NRZ coding which will improve noise performance as well as nonlinearity [43-48]. It is correlative coding which has the advantage to permit some amount of interference at the receiver end to reproduce the original message. The block diagram of the dicode encoder is shown in Fig. 3.19.

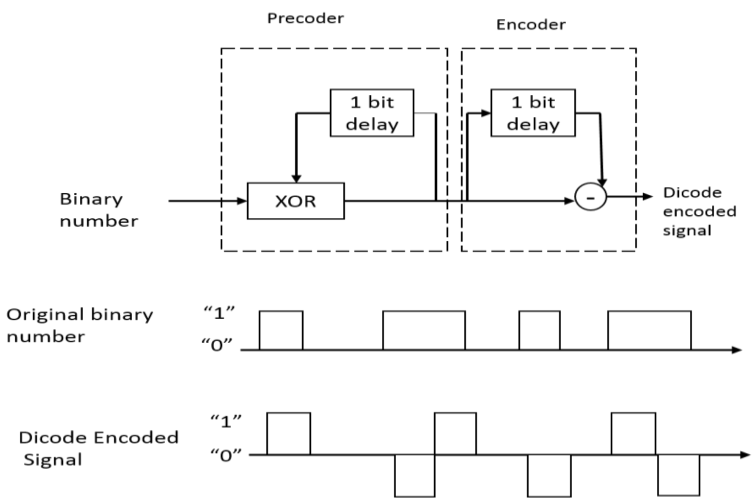


Fig. 3.19 Dicode encoder [48].

Dicode coding can be defined mathematically as [45]

A rectangular pulse $f_1(t)$ can represent as an impulse response

$$\partial(\mathrm{t}) = \lim_{\mathrm{T}\to 0} \mathrm{f}_1(\mathrm{t})$$

Such that

$$\mathrm{A} \to \infty$$

$$\mathrm{AT} \equiv 1$$

For NRZ we find amplitude spectra

$$\left| sinc(\tfrac{\omega T}{2}) \right| \tag{3.6}$$

Then power spectral density (PSD) for NRZ can be express by

$$\left| \sin c^2(\omega T / 2) \right| \tag{3.7}$$

In Dicode

$$\partial\mathrm{T}(\mathrm{t}) = \partial(\mathrm{t}) - \partial(\mathrm{t} - \mathrm{T}) \tag{3.8}$$

T is delay time

The amplitude spectrum can be express as

$$|F[\partial T(t)]| = \left|1 - e^{-j\omega T}\right|$$

$$|1 - cos\omega T + j\ sin\omega T|$$

$$[(1 - cos\omega T)^2 + (sin\omega T)^2]^{1/2}$$

$$[1 - 2\cos\omega T + \cos^2\omega T + \sin^2\omega T]^{1/2}$$

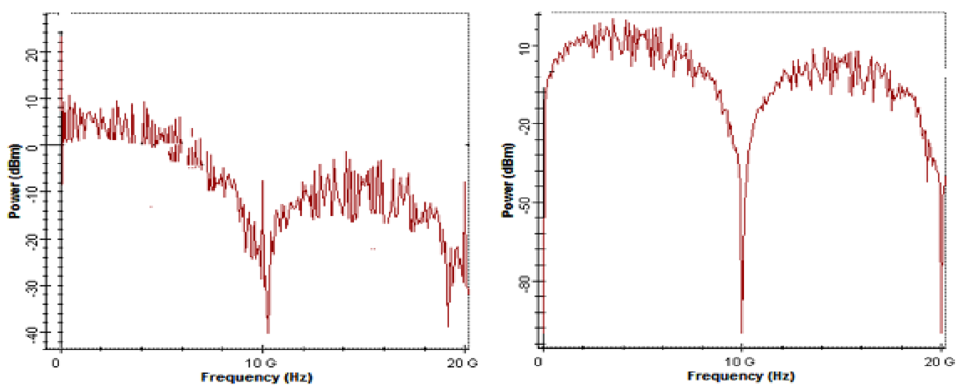
Then finally we get

$$2\left|\sin\frac{\omega T}{2}\right| \tag{3.9}$$

The power spectral density (PSD)

$$4\left|sin^2\frac{\omega T}{2}\right| \tag{3.10}$$

As expressed in equation (3.6 & 3.9), low-frequency component gets reduced which can be verified by a graphical representation of dicode coding as shown in Fig. 3.20. The spectra depicted in Fig. 3.20 have a sine envelope.

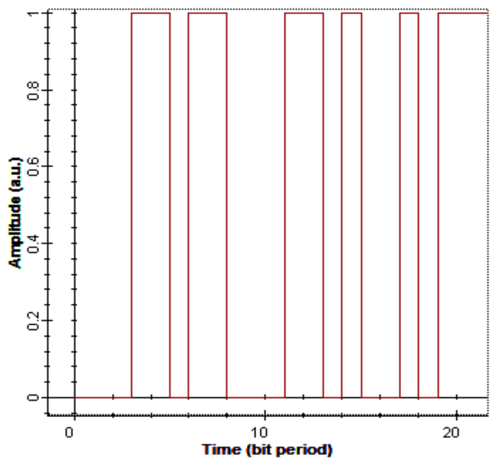


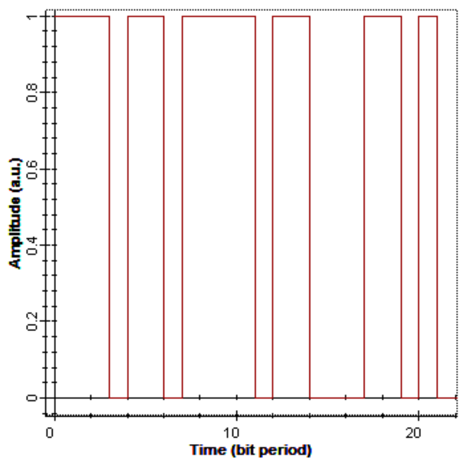
(a) (b)

Fig. 3.20 Power Spectra of (a) conventional NRZ (b) dicode-coded NRZ.

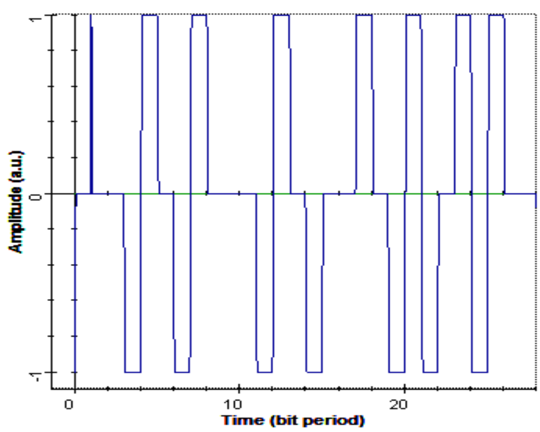
It is observed that at the Nyquist frequency the amplitude is maximum whereas zero at zero frequency and the double frequency of Nyquist frequency. This type of spectral distribution helps to employ the filter having a sharp cutoff frequency for pulse shaping as shown in band limited dicode waveform and also suitable for transmission over a.c. Coupled-channels [48].

Dicode signal can be modulated by the lithium niobate intensity modulator to convert this electrical dicode signal to optical dicode signal by using proper biasing at the modulator. The transmitter block diagram is same as simple binary IM. Now we analyse the generated waveform at transmitter and receiver as shown in Fig. 3.21 and Fig. 3.22.



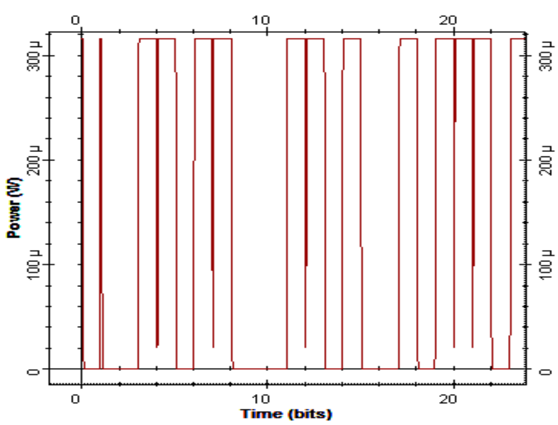


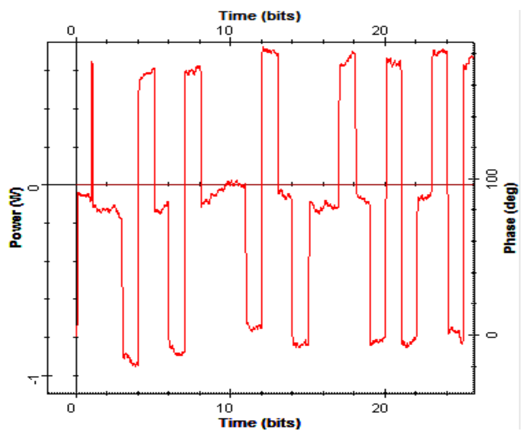
(a) (b)



(c)

Fig. 3.21 Electrical waveform (a) NRZ signal of binary data (b) Output after Precoder (c) Encoded dicode signal.





(a) (b)

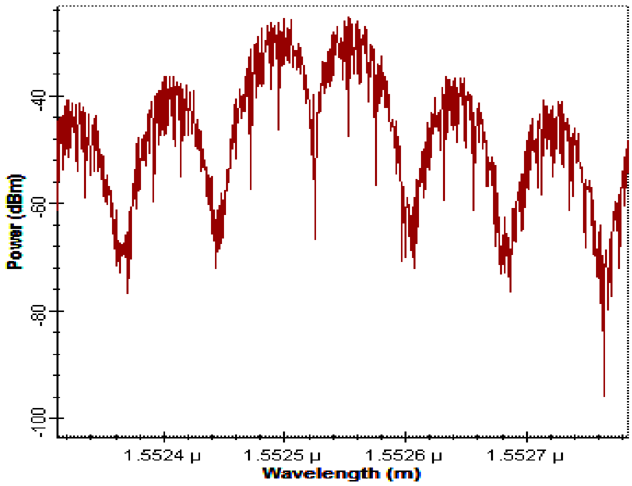


Fig. 3.22 Dicode optical signal (a) Intensity (b) Phase (c) Power spectra.

The effects of dicode coding are analyzed and described in next chapter with different design architecture for different applications.

3.5 Chapter Summary

Different line coding characteristics have been discussed in this chapter in detail. We have observed the impact of different line coding on the various applications. Also, different modulations formats such as NRZ, RZ, DPSK, dicode and Duobinary also have been studied in detail and their transmission characteristics have been observed. We found that dicode coding is more resilient to dispersion and nonlinearity as compared to other coding methods.

Chapter 4

Investigation and Mitigation the various effects in WDM-TDM Networks

4.1 Introduction

As bandwidth demand has increased due to emerging broadband services like video on demand, Internet Protocol television (IPTV) and medical applications,it has motivated the evolution of high-speed passive optical network in order of gigabits. Existing Gigabit Passive Optical Networks (GPON) offers a capacity of 2.5/1.25 Gbps for downstream and upstream for the physical reach around 20 Km with 32 splitters [18]. To minimize the Center offices (CO) in the sparsely populated geographical area, it is necessary to increase the reach and number of users. This further reduces the overall (CAPEX) capital expenditure of networks.

Increasing the number of users at splitters, results in increased power loss and reduction in available bandwidth for users. To address this problem, FSAN and ITU-T proposed NGPON1 and NGPON2 [20]. NGPON1 is upgraded network widely known as XGPON with enhancing capacity supporting higher number of users. In this chapter, we study the effects and mitigation of Raman cross talk that arise due to high power video and data signal with duobinary and dicode, spectral analysis with remotely Raman amplified and effects on dispersion for the long reach network using erbium-doped fiber amplifier.

4.2 Raman Crosstalk

Introducing broadband data, voice and video services to residential and business users together in the same network requires a cost effective and high data rate hybrid WDM-TDM system. [121]. These types of networks works in two different wavelength bands (1480 nm and 1550 nm) for data and video at high power. At short distance ~ 20 Km, the performance of data signal is degraded significantly due to Raman cross talk [122]. Video and data signal lies within the Stokes shift ~100 nm of silica. Hence, the data signal acts as a pump for the video signal, resulting in a reduction of the power of the data signal [123-124]. Some techniques which previously discussed in literature for reduction in cross talk like dynamically varying power of digital signal [125], pre-emphasis of lower channels [123], decreasing wavelength spacing [126], using polarizer scrambler [127], Quadrature amplitude modulation (QAM) for modulating the video signals [128] and by compensating the signal attenuation using remote Raman pump [129]. Generally, for a particular transmission link, received signal quality at receiver is different for different data formats due to their different waveforms and spectra [130]. Crosstalk between reflected light and signal is reduced by a three level Partial response (PR) coding by reforming the signal spectra by altering the signal's power distribution with PR coding. This is done by generating a special 1 bit/symbol multilevel signal via superposition of adjacent symbols [48].

4.2.1 Generation of partial response coding

Balance Duo- binary coding: Balance duobinary coding can be derived from a binary digital sequence by pre-coding the sequence into another binary sequence d_n [45] as shown in Table 4.1.

Table 4.1 Generation of Balance Duo-Binary Code

Binary input	a_n		1	0	0	1	1	0	1	0
Precoding	$d_n = a_n \oplus a_{n-1}$	0	1	1	1	0	1	1	0	0
Duobinary	$b_n = d_n + d_{n-1}$		1	2	2	1	1	2	1	0
Balanced duobinary	$c_n = b_n - 1$		0	1	1	0	0	1	0	-1

Where d_n is the differential code signal, a_n is the original binary signal, b_n duo binary signal and c_n is the balance duobinary signal.

Dicode coding: - A dicode sequence can be obtained by converting the d_n sequence to another sequence b_n by subtracting the previous digit from each member of the d_n sequence [45]. Dicode coder uses one logic gate (X-OR) and 1 bit delay. Dicode coding is power efficient and more tolerable to dispersion and nonlinearity due to the absence of zero DC components. In the section 3.3.5.2, generation of Dicode code with its power spectra characteristics is explained in detail.

Table 4.2 Generation of Dicode Code

Binary input	a_n		1	0	0	1	1	0	1	0
Precoding	$d_n = a_n \oplus d_{n-1}$	0	1	1	1	0	1	1	0	0
Dicode	$b_n = d_n - d_{n-1}$		1	0	0	-1	1	0	-1	0

Table 4.2 Illustrates pre-coded output d_n and Dicode output b_n for the corresponding binary input a_n.

4.2.2 Simulation Setup and Results

In the system shown in Fig. 4.1, five wavelengths each at 10 Gbps are multiplexed and transmitted from the optical line terminal (OLT) to a 20 km long optical fiber. Three out of five wavelengths (1558, 1550, 1542nm) for video services are transmitted with 20 dBm power and remaining two wavelengths (1490, 1482nm) for data services at 0 dBm. The transmitted signals are divided into 64 parts using 1:64 power splitters to serve 63 ONUs. At the ONU, a Gaussian filter separates the video and data signals. Instead of 64^{th} ONU, a counter-propagating Raman pump (*p*~180mW, 300mW) is introduced to amplify the downstream signal.

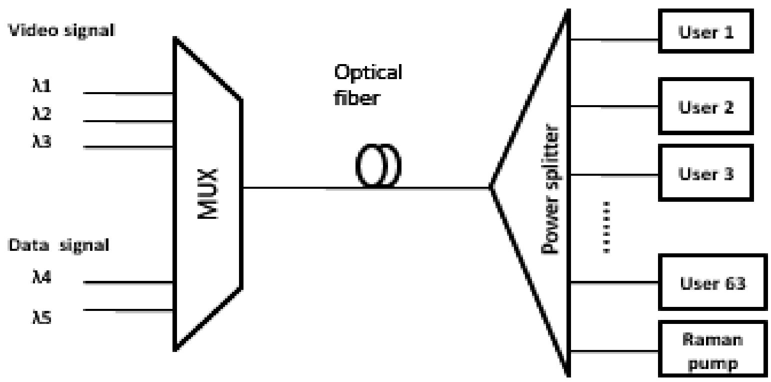


Fig. 4.1 A WDM-TDM system with remote Raman pump

By comparative study from Table 4.3 and Table 4.4, we observed that the power reduced by scattering in Dicode coding is approximately 0.5 dB less when compared to the balance Duobinary code. Raman scattering and fiber loss can be minimized further by amplifying the signal using remote Raman pump by more than 8dBm power as shown in Table 4.4 and length of the system can be increased up to 60 Km.

Table 4.3 for Balance Duobinary Coding

S. No.	*Wave Length (nm)*	*Power without scattering (dBm)*	*Power with scattering (dBm)*	*Power reduced by scattering (dBm)*	*Power with Raman pump (dBm)*	*Power Improved by Raman pump (dBm)*
1.	1482	-10.4	-12.3	1.9	-4	8.3
2.	1490	-10.4	-11.9	1.5	-2.5	9.4

Table 4.4 for Dicode Coding

S. No.	*Wave Length (nm)*	*Power without scattering (dBm)*	*Power with scattering (dBm)*	*Power reduced by scattering (dBm)*	*Power with Raman pump (dBm)*	*Power Improved by Raman pump (dBm)*
1.	1482	-16.2	-17.6	1.4	-9.2	8.4
2.	1490	-16.2	-17.3	1.1	-7.8	9.5

Here, we have analyzed the Raman crosstalk and also reduced it by using Dicode coding. By simulation, we observed that stimulated Raman scattering (SRS) dominate more for balance duobinary code then Dicode and this value is 0.5 dB approximately. Raman scattering and fiber losses are also compensated by amplifying the downstream data signal through remote Raman pump.

4.2 Spectral Analysis

To cover large geographical area, long reach optically amplified hybrid WDM-TDM PONs are in huge demand due to its low cost and high bandwidth [131-132]. A Basic PON system uses a 1490 nm and 1550 nm wavelength for downstream transmission for combined data/voice and video traffic distribution [8], [133]. A data and video signal together in WDM-TDM system at short distance degrades the performance of data signal significantly due to Raman cross-talk [134].

The Raman amplification used in an optical fiber communication system has attracted much attention as they have broad amplification bandwidth and flexible central wavelength [129,135]. The discrete Raman amplification and distributed Raman amplification are two main categories used in Raman amplification [136]. The gain and typical transmission length for distributed Raman amplification is larger and it improves system performance. The transmission rate of WDM system can be enhanced by either increasing spectral efficiency or a wider optical bandwidth or both. The spectral efficiency limit is determined by the information-theoretic capacity per unit bandwidth. The DPSK modulation technique allows information to encode in two degrees of freedom per polarization and its spectral efficiency limits are much higher in typical terrestrial systems [136-137]. The constant intensity modulated systems have only one degree of freedom, which reduces spectral efficiency [138]. There are some other modulations like Quadrature Phase Shift Keying (QPSK) and Differential Quadrature Phase Shift Keying (DQPSK) as they have high Optical Signal to Noise Ratio (OSNR) sensitivity but they are more complex in design and their implementation cost is very high [109,140-141].

In practice, most of the PON systems have 20 Km physical reach with 32 splits and 28 dB of link budget [70]. A FTTH with GEPON system operating at 2 Gbps is proposed by D. Kochar et al. [142] the system was simulated for different users like 32, 48, and 64 at 20 Km fiber length with booster amplifier. The complete set up depicts better performance for 56 users. Hesham et al. [143] observe the effect of power for a GPON system, they proposed that 9 dBm power is suitable to achieve 128 users for 20 Km fiber length. This methodology if implemented for the WDM systems, where more than one wavelength is multiplexed the average power is increased which results an increase in nonlinearity, and degradation of the system performance. R. Kaler et al. [144] propose a GEPON (Gigabit Ethernet passive optical network) for 0-20 km optical fiber length for a different number of user and achieve 15 Km is suitable length for the 10 Gbps data rate system.

N. cheng et al. [145] demonstrates a 20 Km TWDM PON system for dual rate transmitter, delay modulation using Directly Modulated Laser diode (DML) for 10 Gbps transmission. Power over fiber technique is proposed by Rivael S. Penze et.al [146] to achieve the 10 Gbps data rate system for 32 users at 50 Km. This technique can be deployed to amplify entire optical band, but it fails to amplify individual selective wavelength. K. Acharya et al. [129] demonstrated a system with a remote Raman amplification where a continuous wave counter-propagating pump is injected from one of the optical network unit. The set up was tested for 1.25 Gbps data rate for 32 or 64 users for 40 km and 25 Km length respectively. As per our knowledge in video overlay PON network the remote Raman pump is the best choice.

In this section, we have discussed the effective distributed Raman amplification in WDM-PON using DPSK modulation for enhancement of reach and system capacity. The benefit of using DPSK modulation along with Raman amplification is that it results in enhanced spectral efficiency of the signal due to DPSK and increased transmission length by Raman amplification. Hence, the signal can be transmitted for long distance with the higher transmission rate. The spectral efficiency is directly proportional to system capacity which is also a most economical mean to increase DWDM system capacity. It has also been stated in previous work that the spectral efficiency is also reduced in constant intensity or direct detection.

4.2.1 Modeling and Equations Analysis

Effective Raman Gain: - The larger effective area A_{eff} of the fiber is beneficial for optical amplification as it reduces nonlinear effects when we launch high signal power. Moreover, in Raman pumping the gain increases when effective area of the fiber decreases. The effective Raman gain (G_e) is the ratio of Raman gain coefficient over effective area of the fiber. Mathematically it can be defined as $\frac{g_R}{A_{eff}}$, which is more practical parameter than Raman gain coefficient in Raman amplifier. We can determine effective area for Raman gain as $A_{eff} = a_{Eff}\pi\left(\frac{Diameter}{2}\right)^2$, here a_{Eff} is a dimensionless number, which is related to actual effective area of the mode to the core diameter. Similarly the Raman gain coefficient $g_R$describes how stokes power rises as pump power is transferred to it through stimulated Raman scattering (SRS). The Raman gain in terms of power can be described as Equation (4.1)

$$\frac{dP_s}{dz} = \frac{\gamma_R}{A_{eff}} P_p P_s \equiv g_R P_p P_s \tag{4.1}$$

Here γ_R is the nonlinear strength $\gamma_R = 2\pi n_2/(\lambda A_{eff})$, n_2 is nonlinear refractive index and λ is the signal wavelength. The power evolutions for signal and pump waves along an optical fiber can be described by using different equations called propagation equations. The signal and pump equation can be expressed as

$$\frac{dP_s}{dz} = g_R P_s P_p - \alpha_s P_s \tag{4.2}$$

$$\frac{dP_p}{dz} = -\frac{\omega_s}{\omega_p} g_R P_s P_p - \alpha_p P_p \tag{4.3}$$

Where P_s and P_P are signal and pump powers, respectively, $g_R$is the Raman gain efficiency for the wavelength of signal and pump, ω_s and ω_p are the frequencies of signal and pump waves and α_s and α_p are attenuation coefficients of optical fiber at signal and pump wavelength. If we consider the signal power low enough as compared to pump power,pump depletion is negligible. After solving the above Equation (4.2), when pump is off, the obtained output power is attenuated due to fiber loss only.

$$P_{s-off}(L) = P_s(0)exp(-\alpha_s L) \tag{4.4}$$

When the pump power is as large as compare to signal power than the power of weak signal amplified due to SRS. The amplification of the signal can described from the following Equations (4.5)

$$P_{s-on}(L) = P_s(0)exp\left(\frac{g_R P_0 L_{eff}}{KA_{eff}} - \alpha_s L\right) \equiv G(L) \tag{4.5}$$

Where the P_0, $P_s(0)$ are input pump power and stock power at zero fiber length, $G(L)$ is the net signal gain, G (L) in dB is given by $G(L) = 4.34\left[\frac{g_R P_0 L_{eff}}{A_{eff}} - \alpha_s L\right]$, where L is the amplifier length and $L_{eff} = \frac{1-\exp(-\propto_p L)}{\propto_p}$ is effective length of the fiber. The net signal gain $G(L)$ can be less than 1 (net loss) if the Raman gain is not sufficient to overcome the fiber loss. Than the Raman on-off gain G_A in dB can be defined as

$$G_A = 10\log_{10}\left(\frac{P_{s-on}(L)\ with\ pump\ on}{P_{s-off}(L)\ with\ pump\ off}\right) \tag{4.6}$$

Where L is the length of the fiber and $P_{s-on}(L)$ with pump on is considered without amplified spontaneous emission noise (ASE) and thermal noise. After substituting the value of Equations (4.3) and (4.4) the effective Raman gain can be obtained as

$$G_e = \frac{g_R}{A_{eff}} = \frac{2\pi n_2}{\lambda A_{eff}^2} = \frac{G_A}{4.343 L_{eff} P_{pump}} \tag{4.7}$$

Here P_{pump} is the pump power launched into the fiber, $\frac{g_R}{A_{eff}}$ is the depolarized effective Raman gain.

Spectral efficiency limit: - The performance analysis of broadband Raman amplifiers is affected by several factors which should be controlled. The Raman spontaneous scattering in Raman amplifiers appears as a noise signal as random phase associated with spontaneously generated photons. The spectral efficiency in DWDM can be defined as the ratio of channel capacity to the channel spacing. The channel capacity in communication is the maximum number of bits that can be transmitted through a channel without any error. This is common to all modulation formats because it does not depend upon encoding or decoding schemes. Hence this can also defined as the optimal probability density of the transmitted signal. If we consider S as a spectral efficiency, C capacity per channel, B occupied bandwidth per channel and Δf channel spacing, then $S = C/\Delta f$ denotes spectral efficiency limit. The ASE spectral density is defined as Equation (4.8),

$$S_{ASE} = n_{sp} h\nu_0 g_R G(L) \int_0^L \frac{P_p(z)}{G(z)} dz \tag{4.8}$$

The parameter $n_{sp}$is defined as $n_{sp}(\Omega) = 1/[1 - exp(-h\Omega/\kappa_B T)]$, where $\Omega = |\mu - \nu|$is the Raman shift and T denotes absolute temperature of the amplifier. The spectral density is constant and present at all frequencies (white noise). In practice, the noise exists only over the amplifier bandwidth and further can be reduced by placing an optical filter at the amplifier output. According to this consideration, we can calculate the total ASE power after the amplifier as Equation (4.9),

$$P_{ASE} = 2S_{ASE} B_{opt} = 1.4 S_{ASE} R_b \tag{4.9}$$

Here B_{opt} is the bandwidth of optical filter and R_b is the bit rate for signal transmission. The factor of 2 indicates two polarization modes of the fiber span. ASE can be reduced by 50%, if a polarizer is used after the amplifier. In our consideration if we are not using any polarizer, the signal to noise ratio of the amplified signal is given by Equation (4.10),

$$SNR_o = \frac{P_{S-on}(L)}{P_{ASE}} = \frac{G(L) P_S(0)}{P_{ASE}} \tag{4.10}$$

In DPSK modulation technique the information is encoded in an optical signal having nominal constant intensity. Now at high signal to noise ratio (SNR), the capacity can be defined as Equation (4.11) [9].

$$C = B_{opt}\left[\frac{1}{2}\log_2(SNR_o) + 1.10\right] \qquad (4.11)$$

Hence spectral efficiency can be given by Equation (4.12) [9].

$$S = \frac{B_{opt}}{\Delta f}\left[\frac{1}{2}\log_2(SNR_o) + 1.10\right] \qquad (4.12)$$

The unit of spectral density is b/s/Hz. It is necessary to consider a heterodyne or phase diversity homodyne with differentially coherent (one-bit delay) demodulation of DPSK signal. This is only applicable for coherent detection because for non-coherent it never offers high spectral efficiency. Homodyne receiver requires bandwidth approximately equal to the symbol rate R_s which is just half of the heterodyne receiver bandwidth. Hence we prefer homodyne receiver which require a pair of balance receiver for detection. The optical DWDM de-multiplexer is used which provide narrowband filtering of the received signal and ASE. In the absence of fiber nonlinearities, with proper dispersion compensation and matched filtering, all formats of DPSK should provide same SNR and spectral efficiency. Under interferometric detection of DPSK, a Mach-Zehnder interferometric detector is used with path difference of one-symbol duration compares phase transmitted in successive symbols which provides intensity modulated output that is detected using balanced receiver.

4.2.2 Simulation Model

The general features of the proposed topology are illustrated in Fig. 4.2. The highlighted segments for WDM-PON are optical line terminal (OLT) and optical network unit (ONU). The triple play (i.e. voice, video and data) services are considered, with data/voice signals transmission range from 1450 nm-1500 nm and video signals within 1550 nm-1560 nm range. The radio frequency (RF) video signals have wavelength 1542 nm, 1550 nm and 1558 nm and data/voice signals are having wavelength 1482 nm and 1490 nm. All signals are exhibited with pseudo-random bit sequence (PRBS) generator (bitrate-10 Gbps), non-return to zero (NRZ) modulator and phase modulated (PM) continuous wave (CW) lasers. The subcarrier multiplexing (SCM) is the method of combining (or multiplexing) many different communication signals so that they can be transmitted along the optical fiber. The video transmitter consists of an adder to combine two electrical signals and a CW laser modeled with a phase modulator. Each SCM signal is using two channels from standard national television system committee (NTSC) and cable television (CATV) frequency plan. The channel number (2, 78), (3, 79) and (4, 80) combinations for each 1542 nm, 1550 nm and 1558 nm video signals are taken respectively. Each channel is transmitting separate frequency as shown in Fig. 4.2 within the frequency range 55 MHz to 1000 MHz. The Multiplexed output of all input signals is transmitted via forward input of the bidirectional single mode fiber (SMF) and another backward input is reserved for Raman pumping to achieve Raman amplification.

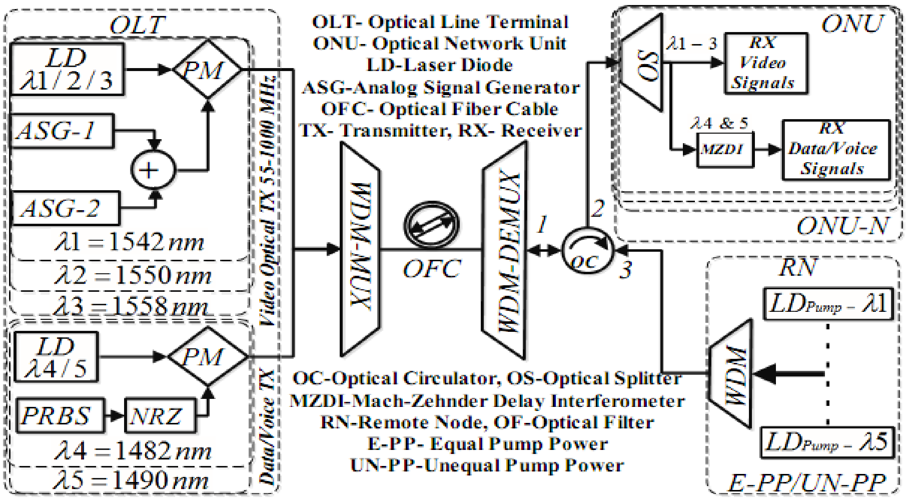


Fig. 4.2 Simulation model of proposed distributed Raman amplified WDM-PON architecture.

A bidirectional single mode fiber (SMF) with core diameter 8.2 micrometer is used for data transmission. An average fiber attenuation of ~0.25-dB/km is taken into consideration. The nominal channel spacing and Raman gain coefficient are 100 GHz and 9.8E-14 m/W respectively. Raman amplification also depends on two equal and unequal pump power (i.e. E-PP and UE-PP) configurations. In both configuration processes, lower wavelength data signals transfer their energy to higher wavelength signals due to stimulated Raman scattering (SRS) property of the fiber.

A splitter/WDM demux is used to transmit these services to different e.g. 32, 64 or 128, etc. users /splits. The video and data/voice signals are Raman-amplified using a pump of wavelengths 1481 nm, 1497 nm, 1513 nm, 1405 nm and 1415 nm respectively. A WDM-mux is used to combine all these pump wavelengths, and the multiplexed output are applied via a remote optical node unit to the bidirectional fiber. The backward pumping configuration is preferred for Raman amplification as nonlinear effects are least in this case and the signal power is smallest throughout the link length. Raman gain is calculated and analyzed per signal before service distribution to the subscribers. At optical network unit (ONU), the received signals are separated into video and data signals using a suitable filter because the phase deviation in the modulator has been identified as a parameter that can affect the transmission. It has already been reported in previous research work that the DPSK modulated signal gets more power (approx. >3-dB) at optical network unit (ONU) terminal when using suitable demodulation techniques [138]. It is also to be noticed that in this technique there is no extra component introduced, such as a semiconductor optical amplifier (SOA) or highly nonlinear fiber or EDFA, besides remote Raman pumps.

4.2.3 Results and Discussion

The launching powers, with and without Raman pump powers are shown in Fig.4.3. It was observed that half power (approx.) of the signal is reduced just after 20 Km fiber span. If we are again increasing the transmission length, the complete signal loss can be observed beyond the 40-50 Km fiber length. At receiver, the Eye diagrams of the pump signal can be observed by using electrical BER visualizer. The increased number of users also reduces the received power for each individual user. Hence if Raman pump is in the off-stage (i.e. without pump), the received power with increased number of users will also reduce the transmission length. Thus,

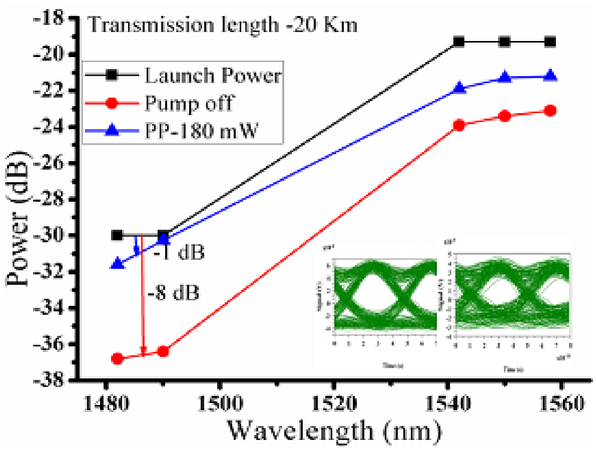


Fig. 4.3 Received power and eye diagram analysis with and without Raman pump.

The higher wavelength signals have higher gain in comparison to lower wavelength data/voice signals as defined in past research work. It is also essential that each signal must have at least 7dB gain enhancement for both pump power configurations to achieve the desired transmission length or number of users or both. If we compare eye height and signal quality of all signals, the higher wavelength signals will always have wider eye opening and better signal quality in comparison to lower wavelength signals. In equal pump power (E-PP) configuration, the 100 mW pump power is taken for each pump wavelength whereas, for unequal pump power (UE-PP) configuration, the pump power decreases with increasing pump wavelength. It can be observed form the plot of Fig. 4.4 (a) that the Raman gain at any fiber length is higher for E-PP than in the UE-PP pumping mode. Raman gain is dominant for shorter fiber length and Raman on-off gain always increases with increasing transmission distance. Raman Gain increases up to the effective length of the fiber and decreases beyond it due to nonlinear effects.

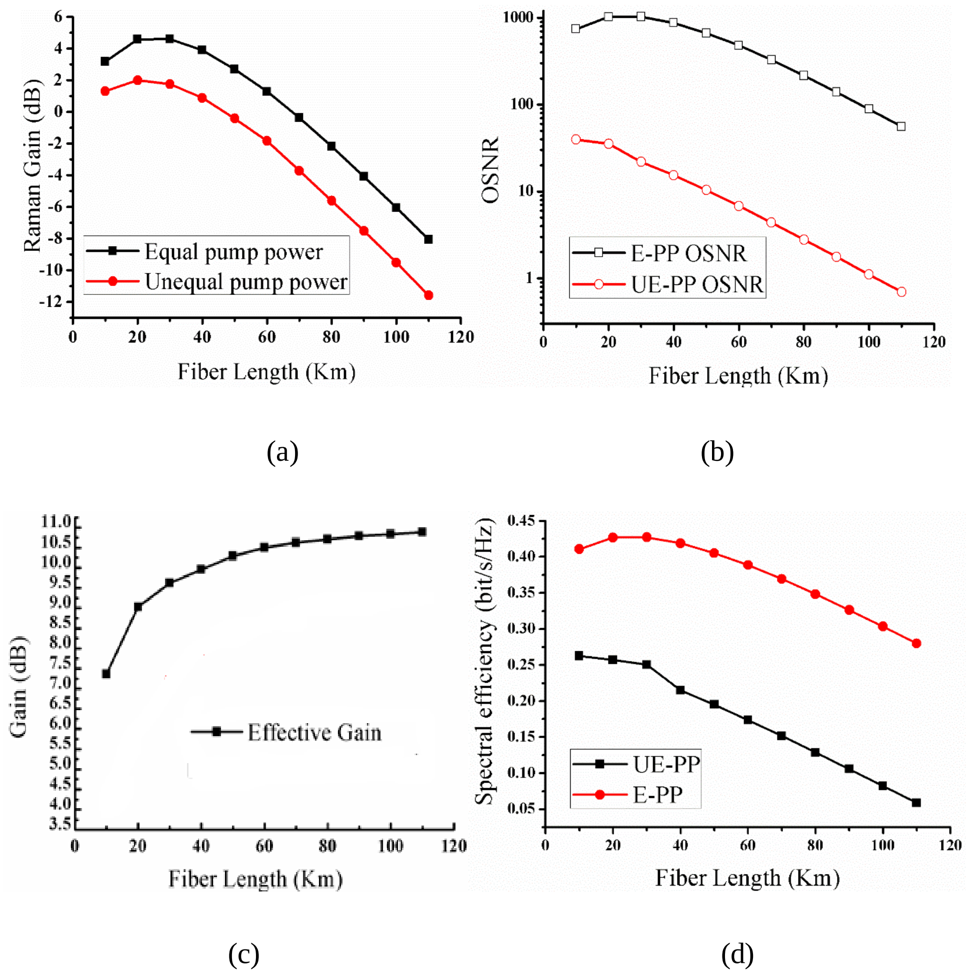


Fig. 4.4 (a) Raman gain, (b) Optical Signal to noise Ratio, (c) Effective Raman gain and (d) spectral efficiency analysis with increasing fiber length.

The Raman on-off gain is calculated in equation 4.6, after observing the received power at fiber end for both on and off stages of Raman pumps. Effective Raman gain is observable from the plot that initially this gain increases and after some fiber length it becomes saturated due to constant Raman gain coefficient and effective area of the fiber. The result analysis for both OSNR and spectral efficiency parameters behaves in the same way as Raman gain with respect to each fiber span. The only difference is that they are oppositely related with the Raman gain at each pump power configuration. This signifies that OSNR, as well as spectral efficiency, is higher and Raman gain is lesser for E-PP case at any fiber span or vice-versa. In each configuration, reach and data transmission rate are dependent on the effective Raman gain and spectral efficiency parameters. The maximum 55 Km reach achieved for 32 users and beyond this length, the received power at the photo-detector is below its acceptable level. Hence no communication can be achieved.

The result analysis of WDM-PON system provides 55 Km transmission reach for 32 users and 0.3 bits/s/Hz higher spectral efficiency with 10 Gbps transmission speed. The network system efficiency is upgraded by increasing the transmission bit rate, distance, and capacity of the system to support a maximum number of users or subscribers. There are many more interesting challenges that remain for the future work. One can use bi-directional Raman pumping configuration for Raman amplification under the effect of temperature variation along the fiber cable. This yields highest system capacity per channel and ultra-long haul transmission distance for advanced optical communication system. Further investigations of non-linear effects, including non-linear phase noise on DPSK systems, are also feasible for longer transmission distance.

4.3 Analysis of Group Velocity Dispersion (GVD)

To overcome the challenges in NGPON1 a new network with ODNs, independent of GPON standard was designed as NGPON2 [147, 78]. Wavelength and Time division multiplexing (WDM-TDM- PON) Network is a primary broad band solution which is selected for NGPON2 [148]. It includes the advantages of both Time division multiplexing (TDM) and WDM (wavelength division multiplexing) Passive Optical Networks. In the network, 40-Gbps downstream and 10-Gbps upstream is achieved by combining XG-PONs via multiple pairs of wavelengths [77, 149]. With careful selection of wavelength band, the designed network can function as TWDM PON that ensures full compatibility with Gigabit-capable PON (GPON), XG-PON and RF-video. The operating wavelengths for TWDM-PON fall in C- (1524 nm~1544 nm) and L + (1596 nm~1603 nm) bands [150-151]. The networks with increased length and higher split ratio were proposed, with the standards for the networks set by ITU-T.G.987.2. The XGPON obeys standards of ITU.T.G.987.2 operates for the maximum length of 25 Km and 128 splitters for with 35 dB maximum optical path loss (OPL) [149]. The performance of the network system can be improved by improving the power budget with the use of erbium doped amplifier, semiconductor amplifier and Raman amplifiers [152-154]. Another technique is power over fiber and tested to offer a complete virtual passive network for 50 Km length and 1:32 split ratio [146].

Takuya T Tsutsumi et [155] al successfully demonstrated 41.3-km-reach and 128-split in an XG-EPON system. However, a phenomenon referred to as group velocity dispersion GVD which leads to the broadening the optical pulses as they propagate through the single mode fiber and thus affecting the bit rate is a considerable issue. Therefore in this chapter, we focus on providing an analytical analysis concerning the GVD-based power penalty to evaluate the maximum allowable bit rate for optical transmission without the need for using any dispersion management techniques (DMTs). A monochromatic optical signal when modulated ideally no longer remains monochromatic and has different frequency components that travel through an optical fiber with different group velocity, resulting in a phenomenon referred as group velocity dispersion or intramodal dispersion. This phenomenon contributes to both material dispersion and waveguide dispersion.

As the waveguide dispersion is fiber dependent and is determined during fiber manufacturing, we mainly focus on material dispersion. In lightwave system, effect of group velocity dispersion on the performance of the receiver can be broadly categorized as below. Firstly, due to pulse broadening the pulse peak power get reduced further reducing the SNR. To obtain the same BER, SNR should remain constant and is possible by increasing the average power at the receiver. This additional power required to obtain desired BER is known as power penalty.Secondly, the broadening of the pulse results in intersymbol interference which degrades the performance of the receiver. To minimize this effect, at the receiver end a decision circuit is so designed that on the application of input signal it corresponds to maintain the transfer function of raised cosine filter. In the practical optical system, the light signal applied do not have perfect rectangular shape, so for analysis and approximations, a bell-shaped Gaussian pulse is preferred over all the pulses. The propagation of optical pulses through single-mode fiber can be mathematically expressed by nonlinear Schrodinger equation (NLSE) as given below [156]

$$i\frac{\partial A}{\partial Z} = -\frac{i\alpha}{2}A + \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - \gamma|A|^2 A \tag{4.13}$$

Where A is the slowly varying electric field pulse envelope, Z is the direction of propagation; t is time, α is constant for loss and γ is nonlinearity coefficient. The dispersive and nonlinear effects in the fiber are related to puls width (T_0) and peak power (P_0) of input pulse.

To study the effect of GVD on optical pulse propagation the medium is assumed to be linear dispersive and nonlinear losses are ignored. Thus the Equation 4.13 can be modified as

$$i\frac{\partial A}{\partial Z} = \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} \tag{4.14}$$

Where Z is the propagation direction, t is the time; A is the electric field envelope, β_2 is group velocity dispersion (GVD) and is defined as Equation (4.15)

$$\beta_2 = \frac{\partial^2 \beta}{\partial \omega^2} \tag{4.15}$$

Equation 4.15 represents the GVD parameter, defined as the second order derivative of the fiber mode propagation constant with respect to the frequency of input signal.

A Gaussian pulse is an incident on the optical fiber can be expressed as [157,158]

$$E(z=0,t) = \sqrt{p_0}\ \exp\left(-\frac{t^2}{2T_0^2}\right) \tag{4.16}$$

Where pulse width T_0 is related to the pulse full width at half maximum by $T_{FWHM} \approx 1.665\ T_0$. The pulse broadening with distance z is expressed as [155]:

$$T(z) = \left[1 + \left(\frac{z}{L_D}\right)^2\right]^{1/2} T_0 \tag{4.17}$$

and, these results to change in the peak power, due to GVD, and can be written as:

$$P(z) = \frac{p_0}{\left[1+\left(\frac{z}{L_D}\right)^2\right]^{1/2}} \tag{4.18}$$

$$L_D = \frac{{T_0}^2}{|\beta_2|} \tag{4.19}$$

Equation (4.19) represents dispersion length; pulse propagates equally to the distance of L_D and pulse get by a factor of $2^{1/2}$.

A 50 Km long communication system operating at 10 Gbps data significantly suffers from GVD. The dicode coding is used to minimize the GVD effects at low frequency; the Fig. 4.5 depicts the spectra of dicode coding [48]. About Equation 3, the dicode coding offers improved performance over conventional NRZ coding in an optical communication system.

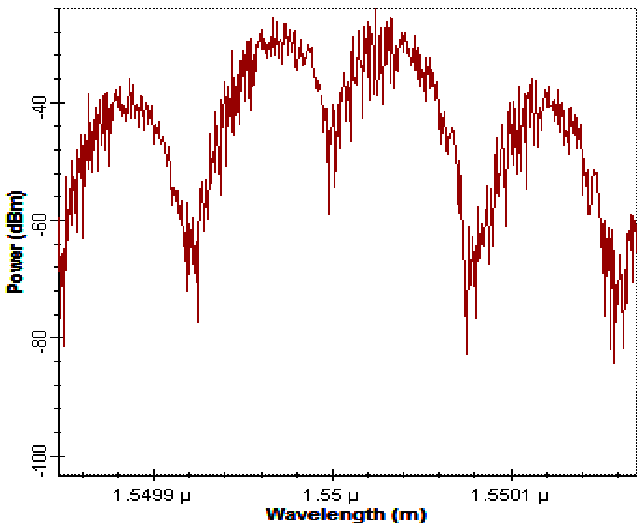


Fig. 4.5 Power spectra of dicode signal.

4.3.1 Network architecture and simulation setup

The architecture shown in Fig. 4.6 is used to analyze the effects of dicode coding on group velocity dispersion (GVD). In the proposed work, we have analyzed and observed the results related to downstream signal only. The simulation work was carried out with a CW laser source operating at wavelength 1550 nm, 1550.8 nm, 1551.60 nm and 1552.40 nm with 0 dBm power. At transmitter end, a (PRBS) generator generates a binary signal at 10 Gbps. The binary signal is converted into electrical pulses by using suitable pulse generator. The optical signals are generated by using lithium niobate modulator as a light source. The modulated optical signals are multiplexed by WDM with insertion loss of 5 dB. The loss due to splitter was of 3.5 Log N, where N is a number of users at the splitter. The losses are compensated by amplifying the signals with erbium-doped fiber amplifier (EDFA). The EDFA offered gain of 20 dB and 4 dB noise figure. Then signal transverses through a fiber of length up to 100 Km with fiber loss of 0.2 dB / Km and dispersion -16.75 Km/nm-ps. During propagation the pulse gets broadened due to GVD, resulting in signal distortion with power loss.

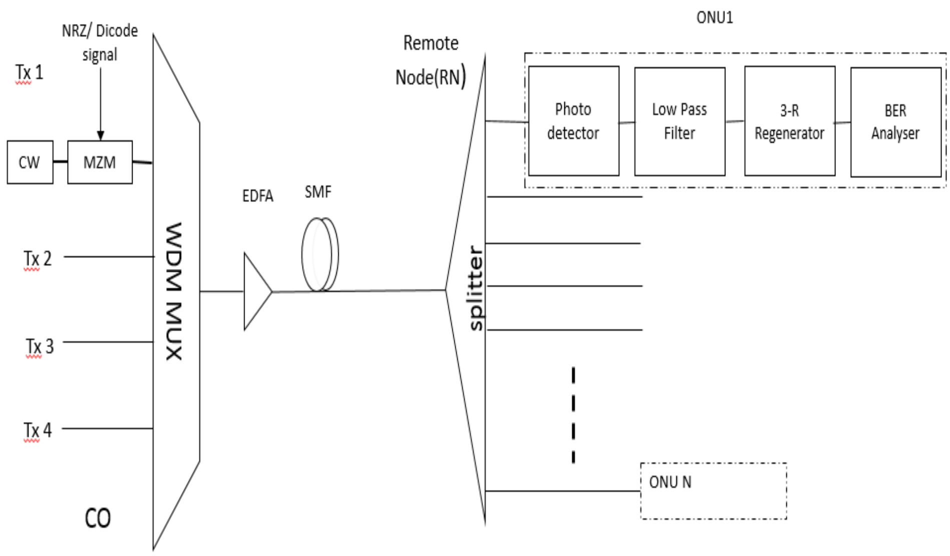


Fig. 4.6 Simulation setup of WDM-TDM-PON.

At the remote end, the signal is split for N users ranging from 2 to 256 users. In the broadcasting mode, all users receive signals of the same wavelength. The setup is used for broadcast mode. At the receiver end signals are filtered using Bessel filters. This optical signal drives the PIN photo detector with a responsivity of 1 A/W and thermal noise density $100e^{-24}$ W/ Hz to generate an electrical signal. The electrical signals are filtered by Low pass filters to remove the noise. A BER analyzer is used to analyze the signal quality in the form of Bit Error Rate and quality factor.

Power Budget: An optical network system requires the estimation of power budget with an approach that sufficient power reaches the receiver, and satisfactory performance is maintained for the entire lifetime of the system. The power budget sets the limit for the losses in the system the losses incurred in the system. The power budget is used to estimate the length of the network. The power budget can be mathematically expressed as below [4]. We estimate the power budget for two access network operating at BER of 10^{-10} including the losses due to various passive components. Maximum allowable system loss can be calculated as:

P_{Max} = output transmitter power – optical receiver sensitivity + Amplifier gain (if used) (4.20)

(I) For NRZ =0-(-31) + 20= 51 dB (4.21)

(II) For Dicode = 0-(-36.5)) +20 dB= 56.5 dB (4.22)

As calculated the power budget in Equation (4.21, 4.22) , a system with dicode coding shows improvement over NRZ coding both for a number of users and length of the system.

4.3.2 Results and Discussion

To explore the feasibility of improving the downstream reach in WDM- TDM PON system, we analyze the results of simulation measuring group velocity dispersion effects on dicode as well as NRZ signal. The effect of GVD on receiver sensitivity, splitter, and the networks reach was also analyzed with the observations and results. Fig. 4.7 shows the RF spectra of dicode in the electrical signal.

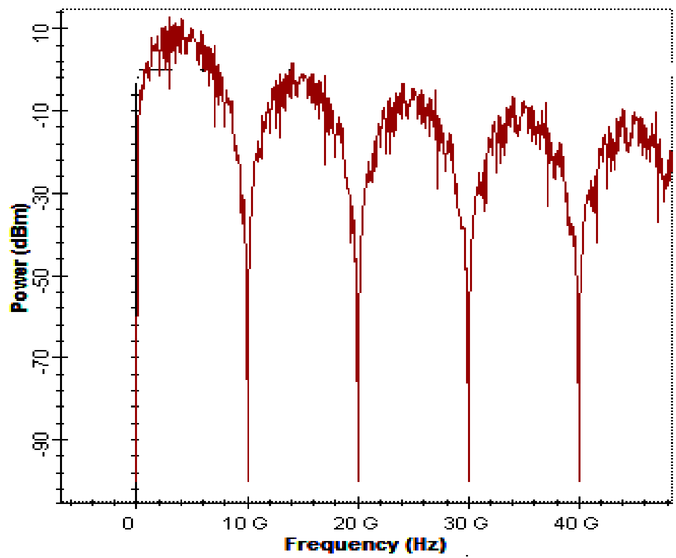


Fig. 4.7 Electrical Dicode signal.

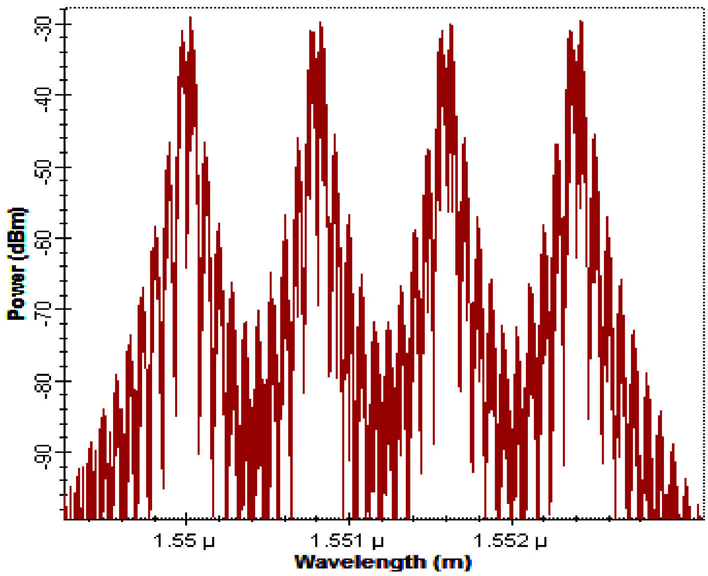


Fig. 4.8 Downstream signal after multiplexer.

The spectra depicts that the zero frequency components power is reduced and the first lobe has the signal bandwith is 10 GHz which is equal to traditional NRZ coding. Fig. 4.8 shows the modulated downstream optical signal with the use of dicode coding in a network for different wavelength passing through the EDFA and optical fiber.

Table 4.5 BER performance with respect to GVD

S. No.	*GVD*	*NRZ BER*	*Dicode BER*	*Remarks*
1	Absent	10^{-36}	10^{-27}	NRZ Perform better
2	Present	10-8	10^{-16}	Dicode perform better

It is well known that GVD is unavoidable in practice and its effects are significant for a system operating at 10 Gbps and above. The results are tabulated in Table 4.5, it can be inferred that dicode coding performs better than NRZ. This development can lead to improvement in the sensitivity of the receiver along with power budget. Fig.4.9 shows the optical power obtained in the two different cases, one back-to-back (0 km) and another for a fiber length of 60 Km. In the case of a back-to-back the receiver sensitivity improvement by 0.7 dB, whereas 5.5 dB improvement was obtained for a fiber length of 60 Km.

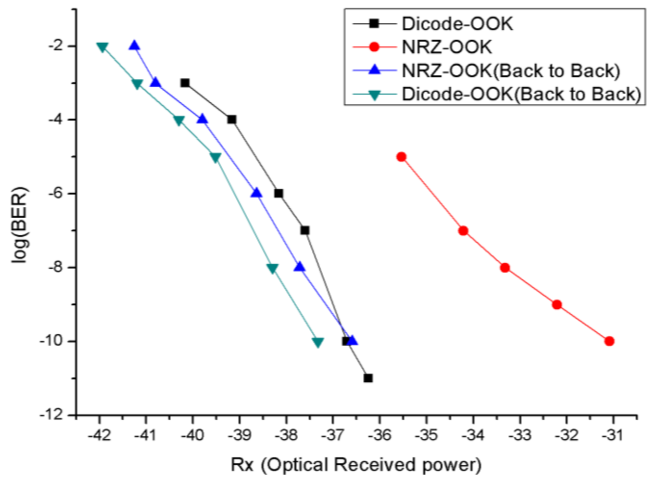


Fig. 4.9 Optical received power.

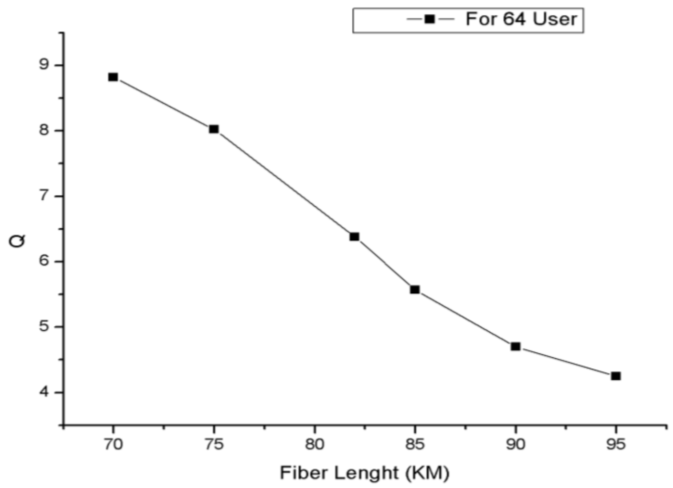


Fig. 4.10 Fiber length vs Q factor.

The length of the fiber was varied in the range from 70 Km to 100 Km to obtain the suitable length matching the value of prescribed quality factor value as 4.10. As represented in Fig. 4.10, the maximum required length is 82 Km. Fig. 4.11 shows the clear eye opening at 82 Km for 64 user, depicts the quality of the signal received at the receiver. The signal can recovered satisfactory at required minimum bit error rate.

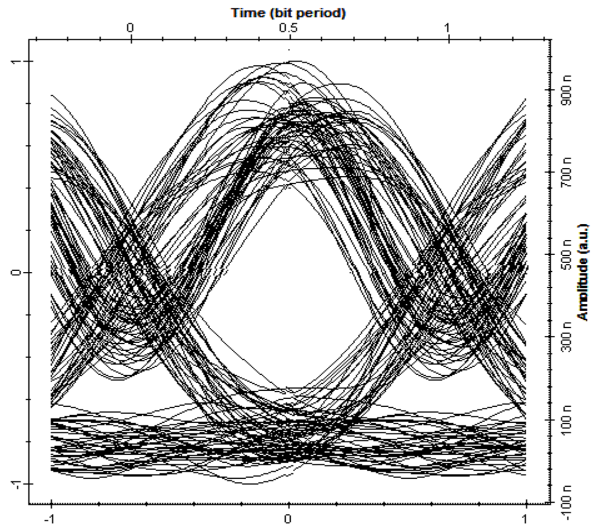


Fig. 4.11 Eye diagram for maximum length for 64 users for 82 KM.

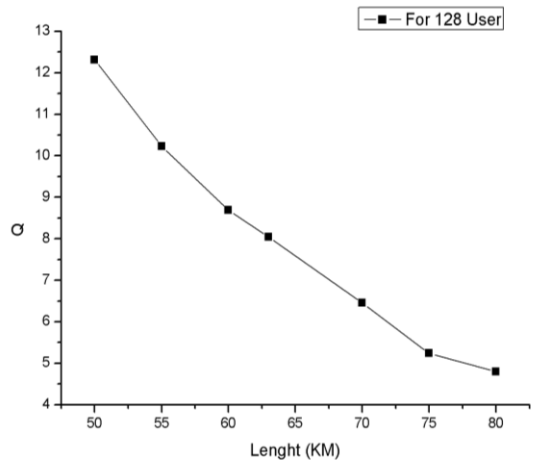


Fig. 4.12 Fiber length vs Q factor for 128 users.

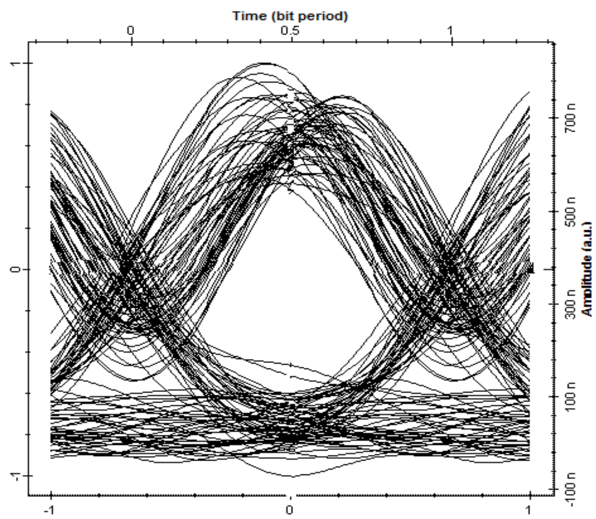


Fig. 4.13 Eye diagram for maximum length for 128 users for 72 KM

The Fig. 4.12 shows that there is considerable improvement in a number of users and length. The number of users extended to 128 and the maximum length that can be achieved is 72 Km as depicted in Fig. 4.12. The Fig. 4.13 is the graphical representation of Quality of signal for 128 users. Here, we have analyzed the effects of dicode coding on group velocity dispersion. The system with Dicode coding is observed to be more tolerant to GVD, and it can have power budget up to 5.5 dB with improved receiver sensitivity by 0.7 dB. Thus the improvement in power budget is helpful to improve the length and number of users in a system. The system showed the best performance for 128 users for length up to 72 Km. Thus a cost effective system can be designed with the parameters obtained.

4.4 Chapter Summary

Here, we have we analyzed the effects of balance duobinary and dicode coding in the presence of nonlinear effects. By simulation, we found that the balance duobinary coding is more affected by stimulus Raman scattering (SRS) by an amount of 0.5 dB as compared to dicode coding. So, dicode coding comparatively provide more tolerance to Raman cross talk in the video Overlay Passive Optical Network (PON). Further in this system 8.3 dB amplification was done by using Raman pump for the data signal to compensate the SRS effect and fiber loss for improving the performance of PON Network. Here we analyzed the spectral efficiency and reach enhancement in next generation passive optical network (NG-PON). The DPSK modulation format mitigates stimulated Raman scattering (SRS) effects in the fiber and boosts channel capacity with multi-giga-bit transmission rate. At 20 km fibre length, a power loss of 8-dB was observed which is compensated to 7-dB with pump power of 180mW. We also analyzed a system at 10 Gbps which has 128 and 32 users for 20 Km and 55 km respectively in permissible BER limit.

The DPSK modulation with interferometry detection technique provides 0.3 (bits/s)/Hz higher spectral efficiency in comparison to other modulation formats. The network system efficiency is upgraded by increasing the transmission bit rate, distance and capacity of the system to support maximum number of users or subscribers. Further investigations of non-linear effects, including non-linear phase noise on DPSK systems, are also feasible for longer transmission distance. This coding has main drawback of complexity of receiver circuits, so in this thesis we mainly focus on intensity modulation. Here, we have analyzed the effects of dicode coding in a passive optical network based on both wavelength and time division multiplexing (WDM-TDM-PON). By numerical analysis, we observed that network using dicode coding is more tolerant to Group Velocity Dispersion (GVD) as compared to traditional NRZ-OOK coding. In the presence of dispersion, dicode coding has improvements of 0.7 dB in receiver sensitivity compared to conventional NRZ coding. It also improved the system power budget up to 5.5 dB. With the observations from analysis and results, use of Dicode coding doubles the number of users and increase the length of the network by 20 percent in respect to NRZ. Thus a cost effective system can be designed with the parameters obtained.

Chapter 5

Design of High Capacity PON using Different Topology

5.1 Introduction

With the Evolution of FTTH networks, the ‘last mile’ bottleneck problem has been broken and due to the exponential growth in the high bandwidth applications, the operators may face new challenges for upcoming bandwidth bottleneck in near future [8]. GPON supports theoretical bandwidth of 2.5 Gbps, however in practice; the effective offered bandwidth per user is limited up to 100 Mbps since it has to be divided among multiple users. The TDM PON is cost effective but it also sacrifices the bandwidth due to high split ratio and provide less security to the applications. Reach is also limited for TDM PON as splitter incorporate higher insertion losses. WDM-PON has emerged as a future proof solution for such high bandwidth applications.

Most of the service operators require highly bandwidth scalable, cost efficient, secured and long distance transmission to serve their users. To resolve the bandwidth, security and reach issue, WDM-PON becomes a most effective solution that transmits multiple wavelengths into the same fiber. Multiplexer multiplexes transmitted wavelengths at the central office and the receiver end demultiplexes by the demultiplexer. By using WDM-PON, high-speed access network services to dedicated business and mobile users can be provided. By providing a dedicated wavelength to each subscriber, service operators can scale the bandwidth requirement cost-effectively that is very essential for today and future services. In this chapter, we discuss about the various solution of WDM-PON.

5.2 2×40 Gbps WDM-PON Long Haul System

In this section, we discuss the transmission of high data rate signal. The high data rate signal limits the length of transmission system due to pulse broadening. This phenomena is known as dispersion. At such high bit rate, transmission of the signal is limited up to few kilometers. So the suitable dispersion compensation techniques can be used together with appropriate line coding. These types of networks can be used for long distance communication. Standard single mode fiber (SSMF) is used in the network, that exhibit chromatic dispersion of the order of 15-17 ps/nm/km at 1550 nm. To compensate the chromatic dispersion, Dispersion-compensated fiber (DCF) [1,159], fiber brag grating [160, 161] and mid-span spectral inversion [108, 162] have been used. Time division multiplexed passive optical network (TDM-PON) and wavelength division multiplexed passive optical network (WDM-PON) are used to provide services in the passive optical network. To achieve large bandwidth and high capacity, WDM is the best technology in an optical communication system that also provides protocol transparency, easy upgradability and high quality of service [163]. The current existing PON network supports the maximum transmission length of 20 km with a data rate of 2.5 Gbps downstream and 1.25 Gbps upstream [163]. 10-Gigabit PON have evolved to support 10 Gbps data rate but not enough to fulfill the increasing future bandwidth demand [164],

In literature, a 40 Gbps or higher PON networks (Next Generation- PON) has been incorporated such as 2.5 Gbps 16 channels and 1.25 Gbps 32 channels [165-166], 4×10 Gbps TDM-PON up to 25 km without any dispersion compensation [35]. 40-Gbps single channel downstream/upstream PON using reduced modulation index [41] for limited reach is also proposed in due to chromatic dispersion. The performance of WDM-PON depends on several factors such as non-linearity, crosstalk, transmission loss, dispersion, etc. Transmission loss and non-linearity can be compensated and reduced by introducing suitable modulation scheme and Erbium-doped fiber amplifier (EDFA) [160]-[163]. To achieve high capacity and long distance, several techniques are used to mitigate dispersion such as DCF, FBG, and dispersion shifted fiber (DSF), etc.

DSF is not a suitable technique for WDM due to infeasibility of installing new fiber cable in the place of existing infrastructure [159]. So, DCF and FBG both are used to compensate dispersion. In WDM-PON, a lot of work on DCF have been done including 40 Gbps & 4×40 Gbps TDM/WDM transmission over 150 and 100 km respectively [167], NRZ & RZ modulation formats of 40 Gbps transmission over 1200 km & 400 km with DCF have also been evaluated [114]. DCF produces non-linearity at a longer distance due to high insertion loss with noise. Therefore, FBG is used with low insertion loss and large bandwidth to mitigate dispersion and crosstalk [158]. Previously, 10 Gbps single-channel transmission over 200 km [168] and 4×10 Gbps WDM channels transmission over 600 km [169] has been demonstrated for FBG. The comparative analysis between DCF and FBG for 4×40 Gbps transmission over 600 km [170] and single channel 40 Gbps over 4000 km have also been analyzed, and the choice of modulation formats such as NRZ, RZ, CSRZ, Duobinary (DB), etc. [158] have been clarified. Here, we have demonstrated an 80 Gbps WDM-PON architecture using 2×40 Gbps WDM channels with NRZ, Dicode-NRZ, Duobinary schemes for FBG post compensation. The modulation schemes are also compared on the basis of their tolerance against the dispersion and transmission length. The modulation schemes are used to enhance the dispersion tolerance, distance, and performance of the system. Different types of modulation schemes such as NRZ, Dicode-NRZ & Duobinary have been discussed in section 3.3. The brief of these schemes is described in the following section.

NRZ is the simplest modulation scheme that can be used in WDM-PON system. Laser source switching is required to get this modulation. The modulation is performed by Mach-Zehnder modulator (MZM) which receives continuous wave (CW) as carrier and modulation signal from electrical filter. During the transmission of bit 1, signal appears at the receiver. While for bit 0, no signal appears [42]. Dicode coded NRZ is modified form of the NRZ level coding, doesn't have zero dc components, thus it is power efficient with more dispersion and nonlinearity tolerance. The overlapping of signals or interference can be mitigated by dicode-NRZ [48]. The binary signal requires differential encoder which converts binary signal into differential signal to get independent correlated signal level.

One logic gate (X-OR) and 1 bit delay is used in Dicode coder. More detail of Dicode generation including power spectra characteristics is given in the section 3.3.5.2 . Receiver complexity, four wave mixing and scattering noise is minimized by Dicode-NRZ scheme. Duobinary code is also similar to Dicode code except its DC component and can be generated by using 1 bit delay and adder. The bandwidth of Duobinary is half as compared to NRZ [118].

5.2.1 Simulation Setup

The proposed 80 Gbps WDM-PON system configuration is depicted in Fig. 5.1. Two 40 Gbps WDM channels with external modulator are used. For this proposed system 1 nm channel spacing is considered. In this set up, each OLT consists of a pseudo random binary sequence (PRBS) generator, electrical pulse generator, continuous wave (CW) laser source and Mach Zender modulator (MZM) as shown in Fig. 5.2.

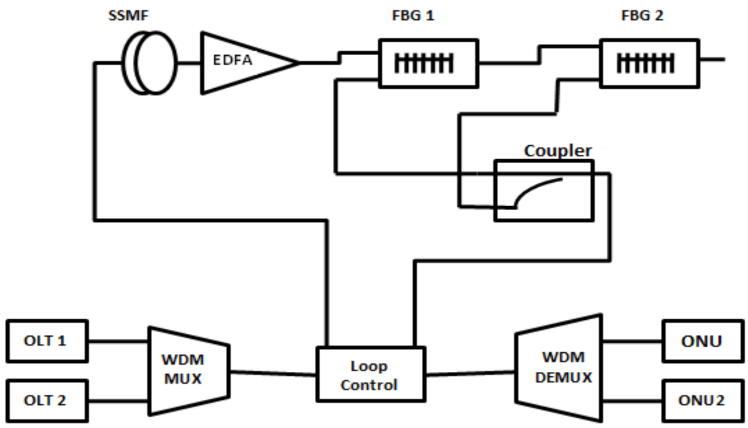
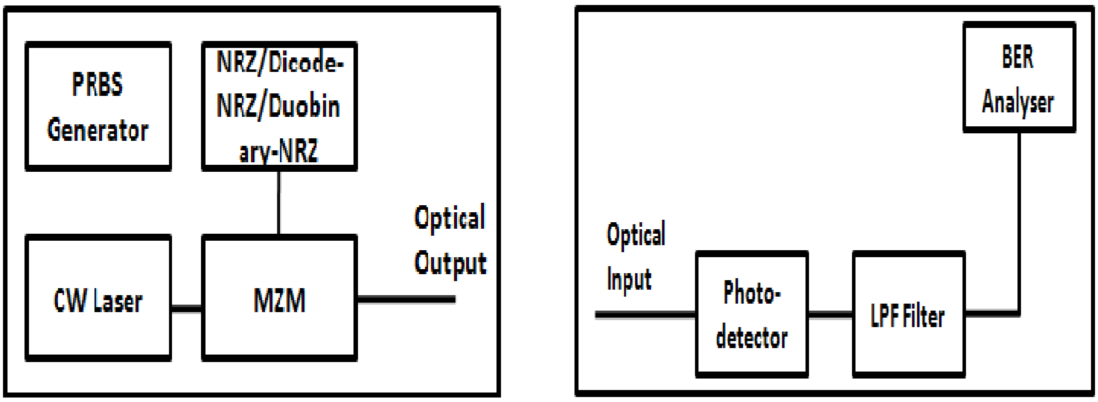


Fig. 5.1 Simulation setup of FBG post compensation.



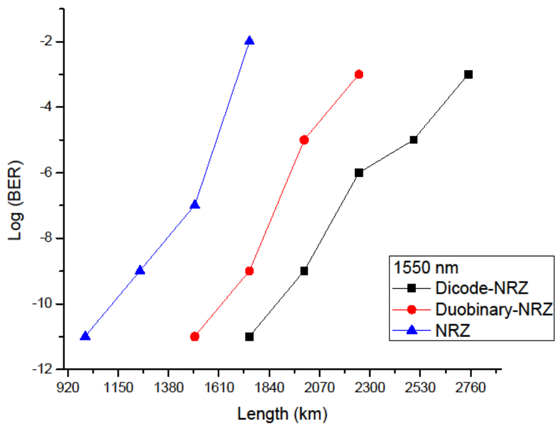
(a) (b)

Fig. 5.2 Block diagram of (a) OLT (b) ONU.

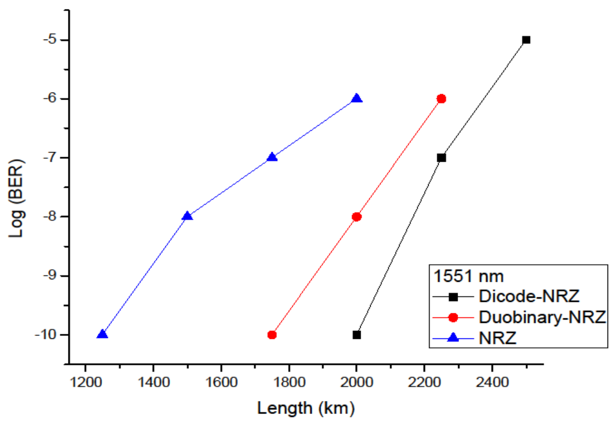
A PRBS with 64-bit stream is carried by each OLT to generate electrical waveforms such as NRZ, Dicode-NRZ, Duobinary schemes. For this, intensities of light sources (CW laser) are externally modulated by MZM modulator and electrical signal is converted in to optical signal. The bandwidth for NRZ and Dicode-NRZ is 2R while for Duobinary bandwidth is R, where R represents the data rate. The input power of laser is kept 0 dBm and both WDM channels are multiplexed and transmitted over SSMF. Fiber spans of 50 km of SSMF with dispersion 17 ps/nm/km and dispersion slope +0.075 ps/nm^2/km is considered for this analyses. EDFA is used for compensating the losses occurring in the fiber. FBGs are also placed at the receiver end (post compensation) to compensate overall link dispersion. The value of dispersion of FBG is negative and equals to -800 ps/nm that cancels the positive dispersion produced by SSMF. At the receiver, demultiplexer is used to separate the channels. At the ONU, PIN photo detector, converts optical signal into electrical signal and low pass filter (LPF) with bandwidth 0.75R and bit error rate (BER) analyzer to measure the performance of the systems as shown in Fig. 5.3. The performance of the signal is measured in terms of Q factor and BER.

5.2.2 Results and Discussion

The various specific characteristics of modulation schemes affect the BER and Q factor with increasing length. The transmission performance of two 40 Gbps WDM channels for two wavelength 1550nm, 1551nm with FBG post compensation using NRZ, Dicode-NRZ, Duobinary scheme for varying lengths are simulated. In Fig. 5.3, the relation between BER and fiber length is evaluated at different length and for different modulation schemes.

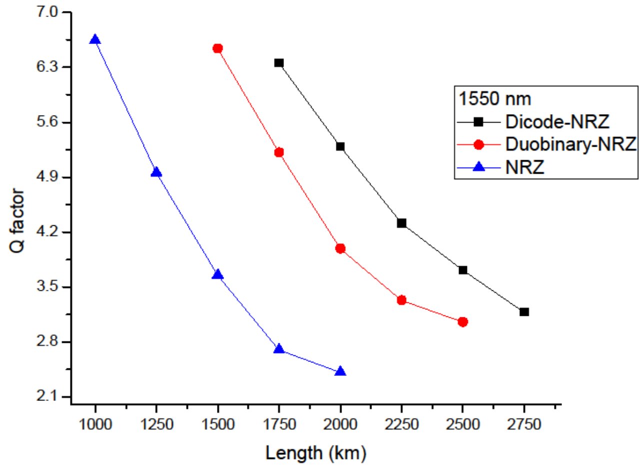


(a)

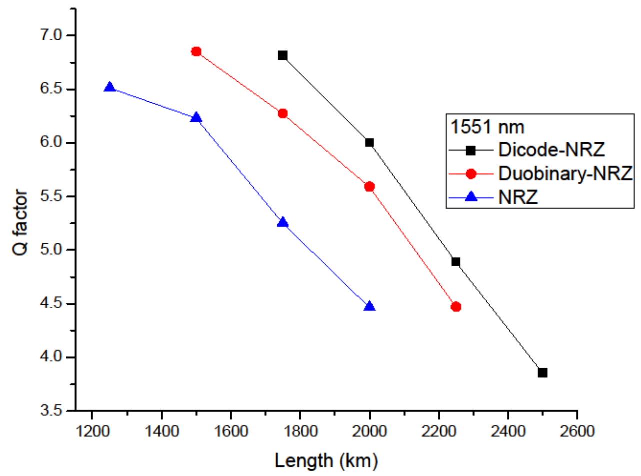


(b)

Fig. 5.3 BER performance (a) 1550 nm & (b) 1551 nm



(a)



(b)

Fig. 5.4 Q factor performance (a) 1550 nm & (b) 1551 nm

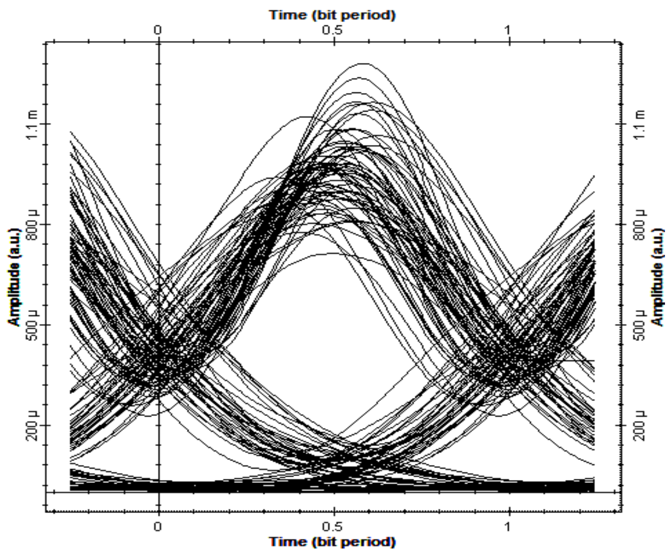


Fig. 5.5 Eye pattern of Dicode-NRZ scheme with FBG for 2000 Km

Relation between Q factor and fiber length is given in Fig 5.4 shows the performance for different coding techniques and find that dicode NRZ can achieve the maximum length for required quality factor. Eye pattern at 2000km at 0 dBm power is shown in Fig. 5.5 which shows clear eye opening. With these observations we conclude that Dicode-NRZ can gives better performance as compared to other schemes. For different PRBS sequence length, we have analysed the receiver sensitivities for Dicode coding and found that as the PRBS sequence length increases, receiver sensitivities improves. For BER of 10^{-9} receiver sensitivities for PRBS sequence 2^7-1 and 2^{10}-1 are found -3.75dBm and -5dBm respectively as shown in Fig 5.6.

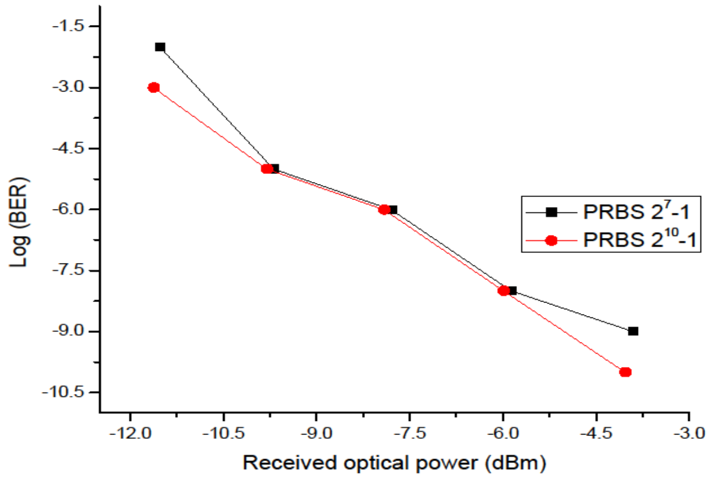


Fig. 5.6 PRBS dependency on dicode NRZ.

The NRZ, Dicode-NRZ and Duobinary schemes with 80 Gbps WDM-PON systems, is analyzed by using two 40 Gbps WDM channels using FBG and evaluated by numerical method. From the investigation and numerical results, Dicode-NRZ is superior compared to the other schemes which increases in length and reduces the system complexity. In future, FBG will mitigate the dispersion in WDM system with increased channels and length.

5.3 Ring based WDM-PON Network

In this section we have designed and analysed a ring-based wavelength-division-multiplexing passive optical network (WDM-PON), which provides fibre-fault protection by using dual ring architecture as well as Rayleigh backscattering (RB) noise mitigation. For protection and restoration against fibre fault, the dual fibre ring is used.

This analysed the characteristics of the downstream signals using 10 Gbps ON–OFF keying (OOK), 10 Gbps dicode-coded NRZ. For the ultra-high speed networks, wavelength division multiplexing (WDM) technique is more efficient than that of the time sharing technique. Use of directly modulated lasers at central office (CO) [171,172] and Reflective Semiconductor Optical Amplifier (RSOA) at the Optical network Unit (ONU) for remodulation and reuse, seeded from the CO [173], is the most desired architecture for future ultra-high speed, high capacity WDM-PONs. However, the Rayleigh Backscattering (RB), which is generated by the downstream signal, is the major issue in the colourless WDM-PONs.

To mitigate the effect of RB, different techniques have been developed, such as using phase and bias-current dithering, utilizing wavelength-shifting technique, employing advanced modulation formats and double laser bands source, etc. [31, 38-39]. These techniques make network more complex, costly and mainly used in tree based WDM-PON. The effect of RB noise on PON is the major issue, which can be minimized by ring based WDM-PON. In the ring based WDM-PON, RB is generated in opposite direction of upstream signal that reduce the effect of RB noise [174]. Hence the ring based WDM-PON is regarded as one of the important architectures for next-generation PON , the architecture is shown in Fig. 5.7.

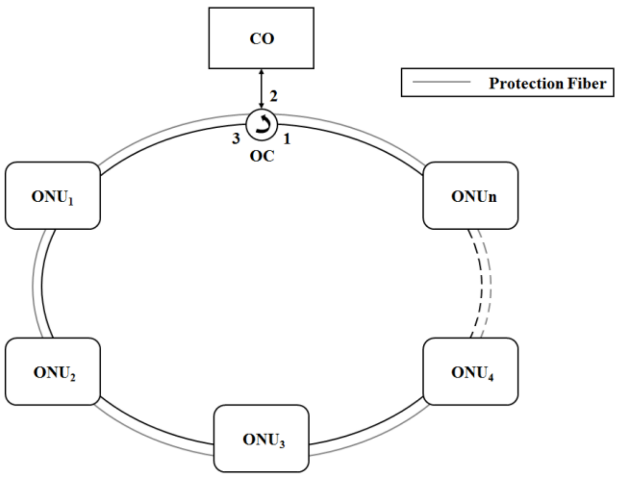


Fig. 5.7 Ring architecture WDM-PON with fibre-fault protection [173].

Next generation WDM-PON must provide higher data rate with high quality of service. If the fault in the fiber has occurred between CO and ONUs, then data traffic cannot reach affected ONU, which leads to loss of data. Hence, Protection management is the major issue in PON access [175, 176]. Fig. 5.7 represents dual ring architecture, which is one of the best solution for the fibre protection [174]. In the system architecture, dual fibre ring architecture has been used for the fibre protection in which each ONU can select its fibre path automatically. In this work, we have compared the system performance for the 10 Gbps downstream On-Off Keying (OOK) with dicode-coded NRZ signal. For upstream characterization 2.5 Gbps OOK has been used. Dicode-coded NRZ as discussed in section 3.3 dicode-coding is one of the simplest dc-balanced correlative level (CL) coding. Dc-balanced CL codes upshift the lower frequency components to upper frequency, which reduces the overlap between signal and interferer spectra.

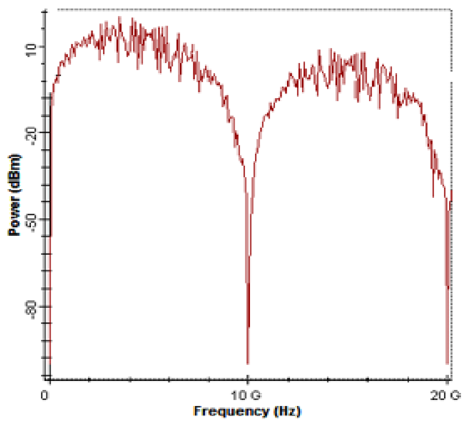


Fig. 5.8 Power Spectra of dicode coded NRZ.

In section 3.3, dicode-coded NRZ is generated as shown in Fig. 3.18. The power spectra of dicode NRZ shown in Fig. 5.8. In order to treat the correlated signal levels independently in the decoding process, the original binary message needs to be differentially coded prior to the CL encoding. The differential encoder consists of two gates and one delay element while dicode coder consists of one gate and a delay element as shown in Fig. 3.18 Due to precoding that we observe in given example that there is 1:1 relation in dicode coded data and original binary data. Hence, 0 is mapped to 1 and -1 and 1 is mapped to 0, that reduces receiver complexity, and imposes no bandwidth redundancy unlike 8bl0b code [40] and Manchester code [177]. From Fig. 5.8, we can see that the dicode-coded NRZ has less baseband components as compared to uncoded NRZ that is major portion of lower frequency component has moved to higher frequency components. Since RB noise affects the dc component of the upstream signal by using dicode-coded signal, we can mitigate the effect of RB noise.

5.3.1 Setup of dual ring WDM-PON

Fig. 5.9 shows the general architecture of the dual ring WDM-PON used in simulation setup. We have used three ONUs, at each ONU where there are three optical circulator, two in clockwise and one in anticlockwise, two FBGs for separation of data signal, and upstream continuous wave (CW) seeding light from multiplexed data stream . The data signal and CW seeding signal received at ONU is separated by filter and passed to receiver and RSOA, respectively. The seeding light is used for generation of upstream signal by remodulating it using RSOA.

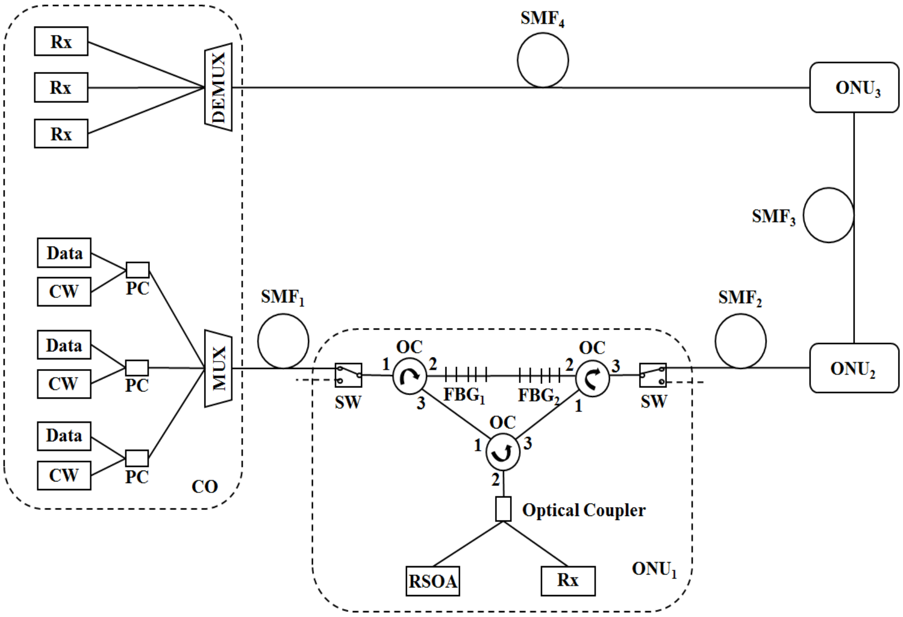


Fig. 5.9 Simulation Setup of dual ring WDM-PON.

In simulation each ONU is placed at 5 km distance from others, that is we have used a 5 Km SMF to connect ONUs with each other and to CO. A CW laser of wavelength 1550.6nm, 1552.6nm, 1554.6nm is used for seeding RSOA and the data is transmitted at 10 Gbps at wavelengths 1512.2nm, 1522.2nm, 1532.2nm for ONU1, ONU2and ONU3, respectively. We have used a PRBS sequence of length 2^7 -1 as data. The upstream signal of 2.5 Gbps is remodulated using OOK at ONU.

5.3.2 Results and Discussion

In the numerical analysis, we are observing the performance of OOK and dicode-coded NRZ modulation and its effect on the system parameters. The input data is modulated with a 2^7-1 PRBS using OOK, and its BER and the Q factor at receiver of all three ONUs are noted as mentioned in the Table 5.1. Now by the same procedure we have analyzed the effect of the dicode -coded NRZ and listed the parameters in Table 1. We can observe from the results that in our level coding techniques, the dicode-coded NRZ is superior. System BER is improved approximately 10 times than that of the OOK. It is also observed that Q factor for dicode-coded NRZ is better than OOK.

To analyze the effect of fiber length on BER and Q factor in optical system we performed simulation using a CO and a single ONU. In which the single CW seeding light with wavelength 1550.6 nm and a data at wavelength 1512.2 nm is used. Here, we are varying the length of the SMF which is connected between CO and ONU to carry out our simulation work. 15 Km, 20 Km, 25 Km and 30 Km SMF fibers have been used to observe the effect.

Table 5.1 BER and Q Factor measurements for NRZ and Dicode at -10dBm

Sr. NO	*User No.*	*NRZ*		*Dicode-Coded NRZ*	
		BER	*Q factor*	*BER*	*Q factor*
1	ONU 1	9.48×10^{-11}	6.39	8.37×10^{-12}	6.72
2	ONU 2	4.66×10^{-8}	5.33	4.55×10^{-9}	5.74
3	ONU 3	1.41×10^{-7}	5.13	2.27×10^{-8}	5.46

The Table 5.2 lists the observation taken from a single ONU configuration at -4dBm power. From Table 2 and Fig. 5.10, we can observe that the dicode-coded NRZ is better than NRZ even at higher distances.

Table 5.2 BER and Q Factor measurements for NRZ and Dicode at -4 dBm

Sr. NO	*Length (Km)*	*NRZ*		*Dicode-Coded NRZ*	
		BER	*Q factor*	*BER*	*Q factor*
1	15	1.02×10^{-36}	12.6	2.00×10^{-40}	13.25
2	20	2.63×10^{-24}	10.1	9.90×10^{-27}	10.63
3	25	4.00×10^{-16}	8.09	8.13×10^{-18}	8.51
4	30	4.30×10^{-11}	6.48	4.94×10^{-12}	6.8

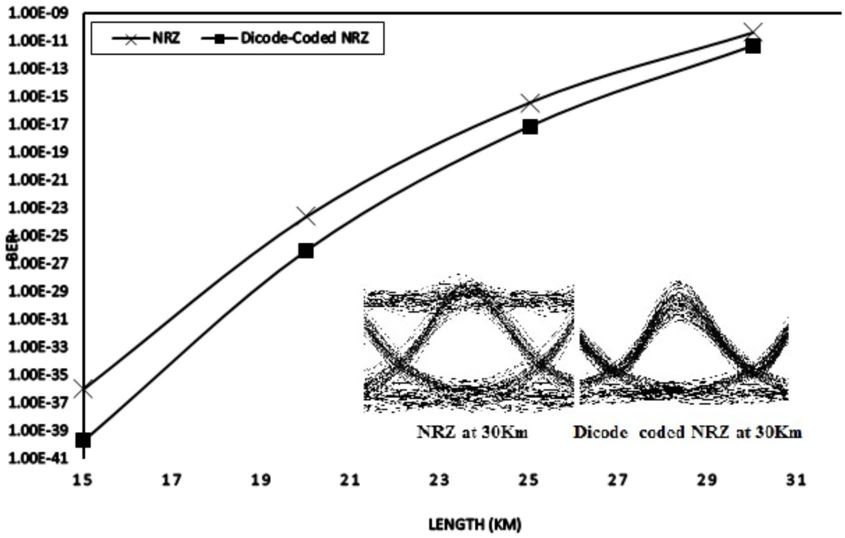


Fig. 5.10 BER performance of NRZ and Dicode-coded NRZ.

In this previous section, we have analyzed and simulated a ring-based WDM-PON providing both RB noise mitigation and fiber-fault protection. We analyzed the characteristics of downstream signal using 10 Gbps OOK and dicode-coded NRZ, and it is observed that there is significant improvement in BER and Q factor while using dicode-coded NRZ. Cost and complexity of receiver at the user side is less as compared to other coding techniques such as DPSK, OFDM.

5.4 Design Hybrid WDM-PON

In this section, we have compared the performance of the hybrid passive optical network (H-PON) for different coding techniques such as Manchester code, and Dicode coded Non-Return to Zero (NRZ). The above stated two codes are employed for comparison since both codes are multilevel codes and suppress the low-frequency component in their spectrum. The better BER performance of Dicode coded NRZ gives us the opportunity to extend the reach of the system. The increase in demand for bandwidth in broadband communication has forced us to analyze our system performance by using data signal along with video signal. Due to this, we need to adopt a cost effective system which can provide high data rates. The hybrid WDM-PON is proposed [13, 178] to support such system. In Manchester coding, the dc component is absent and does not require any external clock signal due to self-clocking which helps to save power [177]. Similarly, Dicode coded NRZ is modified form of the NRZ level coding, have reduced zero dc components. Thus it is also a power efficient with more dispersion tolerance capacity [179, 180].

5.4.1 Hybrid WDM-PON Setup

Simulation setup in Fig. 5.11 depicts the hybrid TDM-WDM-PON. This system is used for doublet services such as data and video transmission. This simulation architecture uses both arrayed waveguide grating for WDM multiplexing and a power splitter for TDM multiplexing. Since the 1X 16 WDM Demux and 1X 8, TDM power splitter is employed hence this hybrid system can provide the service to the 128 users. This hybrid system is capable of using the advantages of both WDM and TDM technology. At the optical line transmitter (OLT), we are transmitting data and video signals simultaneously by modulating with the help of much-Zehnder modulator to get decoded NRZ signal for real-time applications such as video conferencing, virtual classes, telemedicine and many other applications. A 10 Gbps downstream signal is transmitted to 20 km fiber without any repeater and dispersion compensation techniques after 20 Km fiber the signal is separated by arrayed waveguide grating.

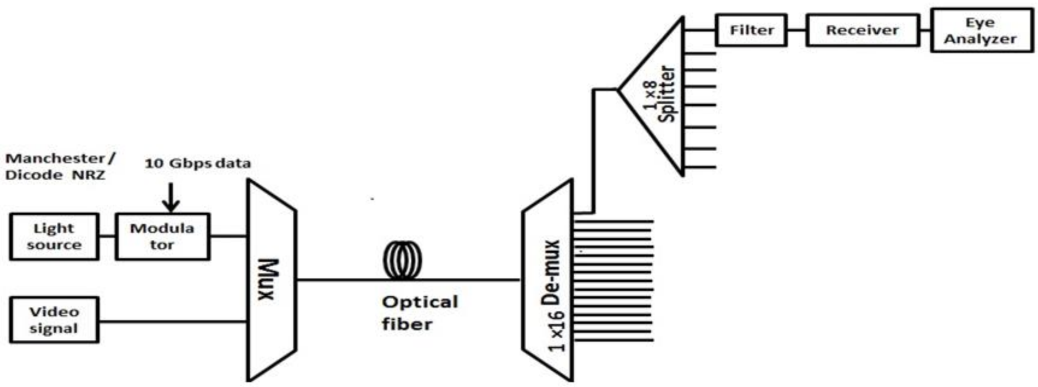


Fig. 5.11 Simulation Setup of HPON.

These different wavelength signals are applied to power splitter to increases the capacity of the system in terms of the users. So in this case, 8 users are sharing the same wavelength, and total number of effective users is 128. At the optical networking unit (ONU), Bessel's filter is used to suppress the unwanted noise and the filtered output is detected by PIN diode. This received signal is analyzed with the help of BER / Eye analyzer to measure the bit error rate and Q factor.

5.4.2 Results and Discussion

The present work gives the simulation results of hybrid PON system for data and video services for different modulationon formats such as Manchester and Dicode-coded NRZ signal. The BER and Q factor for different distance for different level coding has been compared to observe possible transmission distance for optical network.

Table 5.3 BER and Q Factor measurement for Manchester coding

S. No	*Length(Km)*	*Q Factor*	*BER*
1	5	6.65	$2.62*10^{-11}$
2	10	5.9	$1.04*10^{-9}$
3	15	5.5	$2.74*10^{-7}$
4	20	4.12	$1.74*10^{-5}$

Table 5.4 BER and Q factor measurement of Dicode-coded NRZ

S. No	*Length (km)*	*Q Factor*	*BER*
1	10	8.29	$3.92*10^{-17}$
2	20	7.63	$8.70*10-^{15}$
3	30	6.67	$1.59*10^{-11}$
4	40	5.89	$1.76*10^{-9}$

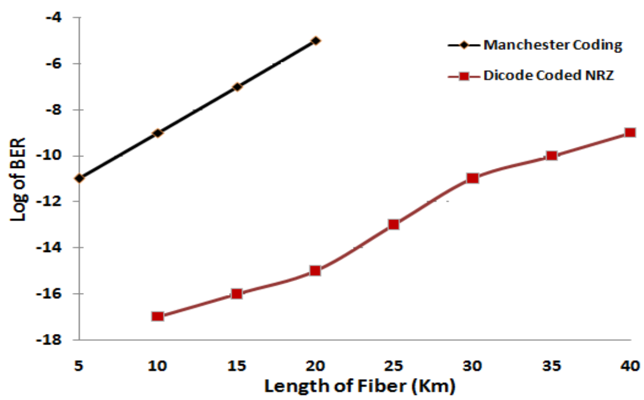


Fig. 5.12 BER Performance of Manchester and Dicode coded NRZ.

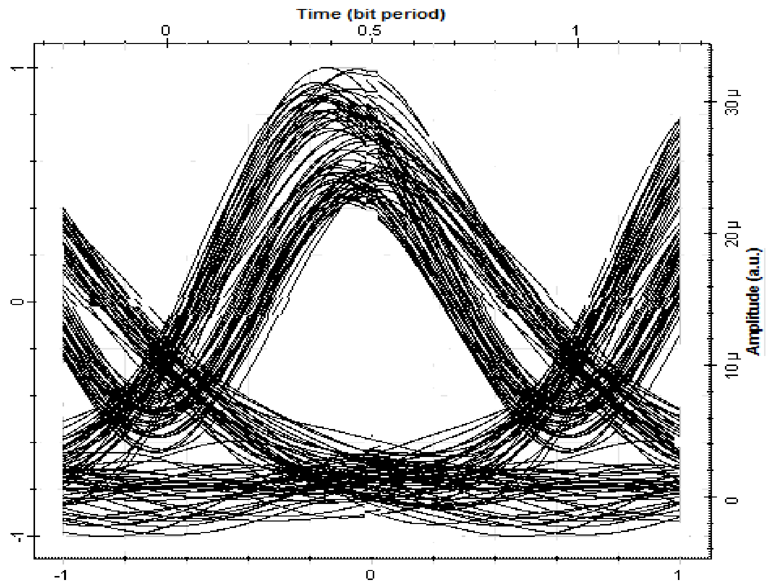


Fig. 5.13 Eye diagram at 40 km for Dicode-coded NRZ.

For Manchester coding Bit error rate and Q factor is measured by varying different length of fiber i.e. 5, 10, 15, 20 Km. We observed the permissible values of BER & Q factor at 10 Km length as shown in Table 5. 3. Similarly Table 5.4 indicates the value of Q factor and BER for Dicode coded NRZ for different length of fiber & works satisfactory up to 40 Km. Fig. 5.12 shows the graphical representation how the BER vary with length of fiber with different level coding. Fig. 5.13 shows the eye diagram of Dicode coded NRZ at 40 Km, which gives clear eye opening and good quality of signal transmission. In the above section, the performance of hybrid passive optical network with 128 users is observed with different level coding. The simulation results shows that for fixed input power of 10 dBm and data rate 10 Gbps, Dicode coded NRZ maximizes the transmission distance up to 40 km without any repeater and dispersion compensation.

5.5 Chapter Summary

The effects of reshaped spectra of different schemes such as NRZ (Non return to zero), Dicode-NRZ and Duobinary on Wavelength division multiplexing have been analyzed for two wavelength 1550 & 1551 nm with the system capacity of 80 Gbps. For a system with the capacity of 80 Gbps is achieved by wavelength division multiplexing of two 40 Gbps channels and fixed fiber length of 50 km/span. Dispersion is mitigated by fiber Bragg grating (FBG) with post compensation and nonlinear effects are reduced using Dicode. We evaluated the performance of three schemes in terms of bit error rate (BER) and Q factor. Numerical simulation results show that Dicode-NRZ provides better tolerance towards dispersion and nonlinearities compared to others and can transmit signal up to 2000 km. We have analyzed a ring-based wavelength-division-multiplexing passive optical network (WDM-PON) which provides Rayleigh backscattering (RB) noise mitigation as well as fiber-fault protection. For protection and restoration against fiber fault, the dual fiber ring is used. Here, we discussed and analyzed the characteristics of the downstream signals using 10 Gbps ON–OFF keying (OOK), 10 Gbps dicode-coded NRZ.

It is observed that there is significant improvement in BER and Q factor while using dicode-coded NRZ. Cost and complexity of receiver at the user side is less as compared to other coding techniques such as DPSK, OFDM. In the above section, the performance of the hybrid wavelength division multiplexing passive optical network (H-PON) is observed for different coding techniques such as Manchester code and Dicode coded Non Return to Zero (NRZ). The above stated two codes are employed for comparison since both suppress the low frequency component in their spectrum. The simulation results shows bit Error rates of 8.7×10^{-15} for fixed input power of 10 dBm, data rate 10 Gbps, Dicode coded NRZ maximizes the transmission distance up to 20 km without any repeater and dispersion compensation. Mean the better BER performance of Dicode coded NRZ gives us opportunity to extend the reach of the system up to 40 KM.

Chapter 6

Enhancement of Links Performance by Incorporating EDFA and Dicode coding

6.1 Introduction

The everyday evolution and updates in technologies, the triple play, and other related services have a quench of higher bandwidth [10]. The wavelength division multiplexing (WDM) based network offers high transmission capabilities as several wavelengths can be transmitted through a single fiber [181]. In a conventional system, the transmitted wavelengths are multiplexed at the central office (CO) and are separated at the remote node (RN) with the help of arrayed waveguide grating [37]. WDM-PON is one of the most promising solutions for the next-generation broad-band access network to meet out the bandwidth requirement. PON uses point to multipoint architecture, which is considered as the best economic approach for fiber to the home solutions. The performance reaches a limit due to inter-symbol interference, reflection noise, spectral efficiency, dispersion, nonlinearity and Raman cross-talk [182, 183].

The cost of infrastructure and equipment are among major challenges in WDM-PON deployment. The laser source for each wavelength used at the optical line terminal is the main contributor of the costly set up [28, 57]. The challenge of high cost for set up can be controlled by Flexible hybrid PON, which can be implemented with the existing system [87]. It can be designed by using WDM then TDM, hence by utilizing the advantages of both, the set of wavelengths are shared by various optical network units (ONUs) at the same time instead of dedicated wavelength as in WDM-PON [183]. It offers low cost, sharing of single wavelength by multiple users with a limited channel bandwidth per user [183], which is compensated by using the high bit rate signal. The multiple wavelengths in same fiber can lead to an increase in the concentration of a low-frequency component at Remote Node (RN), thus limiting the power budget of the system due to noise, affecting the low frequency the most [151].

A dicode coding is a spectral reshaped spectrum which has reduced low-frequency spectra that are least affected in comparison to other coding systems, offering improved power budget in such type of networks [151]. The feasibility of hybrid PON with a different number of users is verified by reports of R. S Kaler et al. [13]. A system at 1.25 Gbps data rate hybrid WDM- PON system with triple play services i.e. data, voice and video for 128 users for different modulation schemes such as NRZ, RZ (return to zero) and Manchester was analysed by his team. The results express that NRZ scheme is suitable for transmitting information to all ONUs for up to 28 Km without using any repeater in the link. R. S. Penze et al. [146] proposed a PON extender using the power over fiber techniques which helps to eliminate the batteries at the remote node.

A set up with 32 split and 50 Km reach for XGPON/ GPON system is analysed with PON extender. A 10 G– EPON system is proposed by T. Tsutsumi et al. [155], the link budget of the access network is increased by using semiconductor optical amplifier (SOA). The setup is reported to be functional upto 41.5 Km length for 128 users together with N:1 optical subscriber unit (OSU) protection to improve reliability against OSU failure. Dicode coding in WDM-PON architecture is proposed by Q. Guo et al. [184] with aided improvement in the reach of the network as compared to NRZ coding. The proposed architecture is costly due to the allocation of dedicated wavelength to each user and increases the capacity of each user. It is the waste of bandwidth due to the lack of flexibility [87].

In this chapter, we propose a flexible Hybrid (WDM-TDM) PON using dicode coding that utilizes traffic rate of 40 Gbps as a downstream for 128 users up to 83 KM without using dispersion compensation techniques. The system depicts an improvement in the receiver sensitivity with dicode coding, which helps in increasing the number of users.

6.2 Importance of flexible PON

In WDM-PON network, multiple wavelengths are transmitted from the transmitter into the same fiber. At the remote node, these wavelengths are demultiplexed, separated and provided to the end users. Normally, a set of multiple 10Gbps signals is used i.e. each user is getting an individual 10Gbps wavelength. However in practice, below 1Gbps data rates are required by each user. Therefore in WDM technology, most of the bandwidth is wasted. By using flexible PON architecture, the utilization of bandwidth can be increased. For this, rather than using pure WDM technology, a combination of

WDM and TDM must be utilized. TDM PON enables the sharing of one 10Gbps signal to the multiple users and therefore increases the bandwidth utilization.

6.3 Hybrid WDM-PON with Dicode Coded None Return to Zero (NRZ)

The performance of the system is a function of characteristics of the modulation schemes employed [185]. The numerous significant applications and developments inspired us to study the different Line codes. These line codes are selected by some dominant consideration like timing, dc content, power Spectrum, performance monitoring as well as transparency. In this work, the property of line coding with reduced dc content in the power spectrum has been deployed . The power spectrum should be such that the maximum energy is contained in a small bandwidth to achieve high transmission efficiency [185].

Dicode is a special spectrum reshaping technique to reduce the low-frequency dc component compared with the conventional NRZ coding which will improve noise performance as well as nonlinearity. It is correlative coding which has the advantage to permit some amount of interference at the receiver end to reproduce the original message. The block diagram of dicode encoder is discussed and shown in Fig. 3.18. The effect of spectra on the system performance due to channel impairments such as dispersion is analyzed. The bandwidth required for the critical spectral content at the receiver end is determined by the waveform spectra.

Hybrid WDM-PON: - The Equipment cost is the main obstacle regarding WDM- PON technology (Need to have one laser at the OLT for each wavelength) [82]. Hybrid PON is the compromise of the WDM-PON and time division multiplexing (TDM-PON) network & use the current existing TDM system [45]. Efficiency of these network resources is enhanced by this architecture [87].

Hybrid WDM-TDM-PON classify mainly are two types [87]:-

- Broadcast and select (B&S) PON architecture
- A wavelength splitting (WS) PON

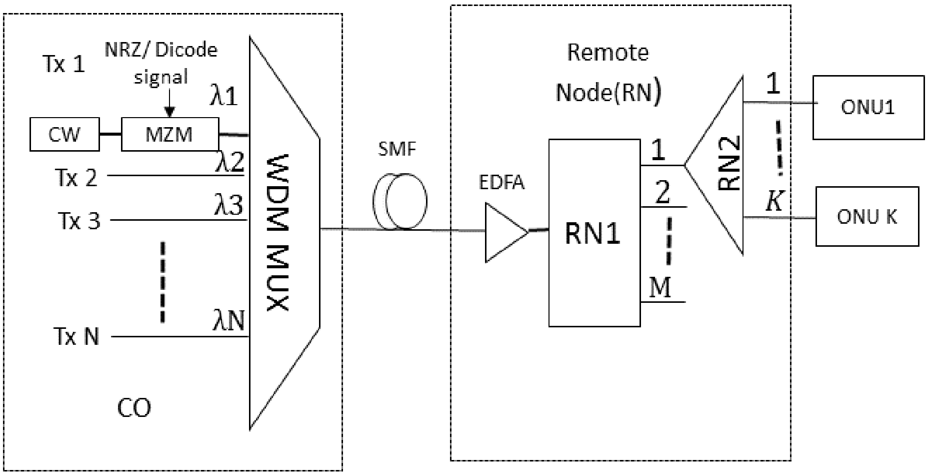


Fig. 6.1 Flexible hybrid PON.

In Fig. 6.1, if at RN1, the splitter is used, then it is broadcast and select (B&S) PON architecture.

Limitation:-

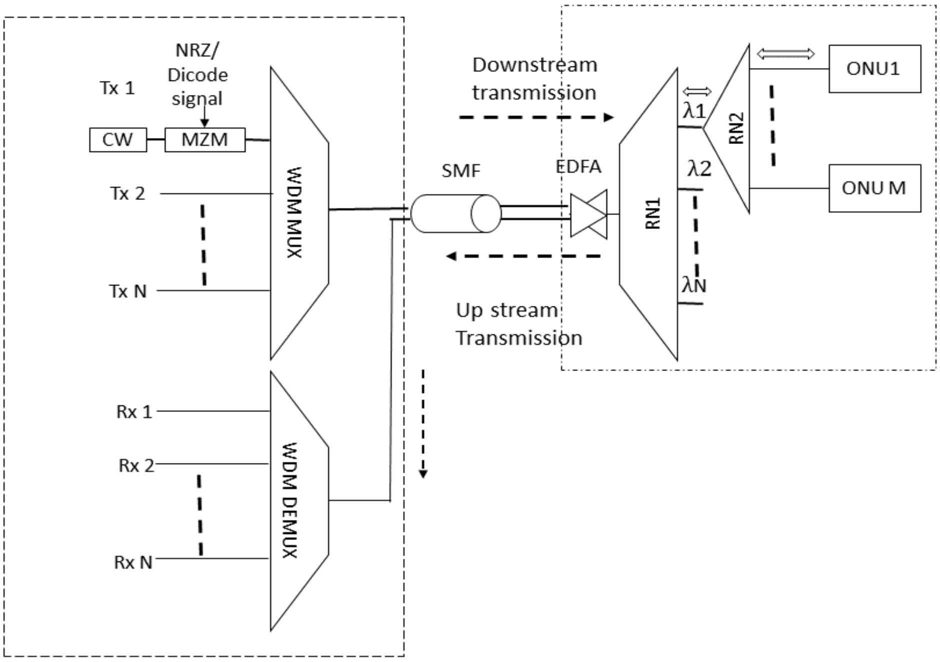
- It has severe security issues and provides no data isolation.
- It has poor power budget and therefore restricts the overall reach.

RN1 as an AWG or WDM, it is a wavelength splitting (WS) PON

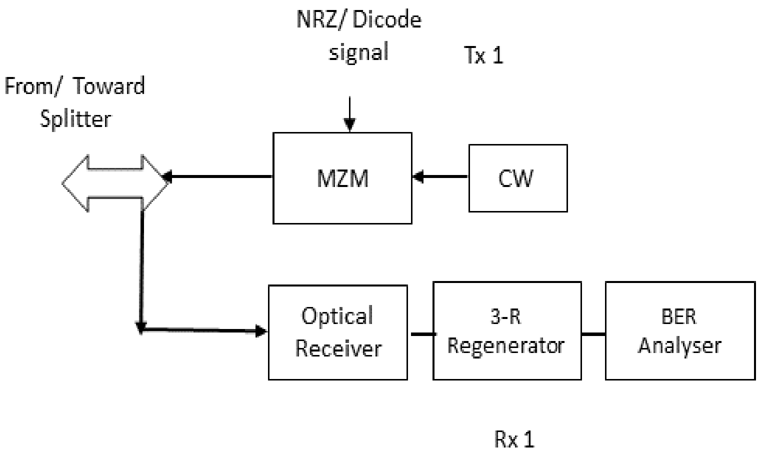
- Significantly improves the data security and the power budget, it reduces the overall flexibility available in a B&S-PON.

Now we consider a setup with RN1 as a WDM and RN2 as a splitter so it can provide moderate security as well as flexibility.

6.3.1 Flexible Hybrid PON Setup: A flexible hybrid PON is the cost-effective approach that can be used to fulfill the future bandwidth demand of subscriber with low cost. In our work, N is considered 4 and M are variable from 16 to 256 as shown in Fig. 6.2.



(a)



(b)

Fig. 6.2 (a) A flexible hybrid PON system (b) Optical network unit (ONU).

The block diagram of flexible hybrid PON is depicted in Fig 6.2 (a), in which, the central office consists of an optical source, modulator, electrical signal generator and a Mux/ Demux unit. A continuous wave (CW) laser of 0 dBm power, 10 MHz line width generates four frequencies at 193.1 THz, 193.2 THz, 193.3 THz and 193.4 THz with 100 GHz spacing light pulse as a downstream transmission. A PRBS generator generated a 10 Gbps binary data sequence and converted into electrical signal by using NRZ / dicode signal. This signal is converted into optical signal by a push-pull operation of Lithium Niobate ($LiNbO_3$) Mach-Zehnder Intensity Modulator (MZM) having an extinction ratio of up to 30 dB. These modulated signals are multiplexed by 4×1 WDM multiplexer and transmitted through the optical fiber. Attenuation and dispersion losses of fiber are assumed to be 0.2 dB and 16.75 ps / nm-km respectively. At the other end of the remote node, an erbium-doped fiber amplifier (EDFA), a 1×4 Demux (RN1) and power splitters (RN2) are used. EDFA of 6 dB Noise figure and 22 dB gain, amplifies the received optical signal, however it is the main source of amplified spontaneous emission (ASE) noise, and this ASE noise is affected by the power spectra of the signal. These amplified signals get demultiplexed and further split at RN1 and RN2 respectively. The splitting ratio of RN2 can be varied from 1×2 to 1×256.

Splitting loss of the splitter depends on $3.5\log_2 M$. RN1 and RN2 can be employed for two-way, i.e., splitter- splitter / Demux- splitter to achieve the flexibility of the system [6] as per bandwidth requirement. The Splitter – Splitter combination reduces power and available bandwidth for each user. It also reduces the total fiber length. In our work, we are using the combination of RN to meet the future demand for bandwidth and a large number of users. As shown in Fig 6.2 (b) Optical Network Unit (ONU), received optical signal is converted into electrical signal by using PIN Photodetector having a responsivity of 1 A/W and dark current 10 nA. This electrical signal is filtered by low pass filter (LPF) to reduce noise. The performance of received signal is analyzed by Bit Error Rate (BER) Analyzer.

Upstream transmission is also possible for the proposed architecture by using 198.1 THz, 198.2 THz, 198.3 THz, 198.4 THz frequency band. The signal coming from Remote Node is amplified by EDFA and enters into circulator via bidirectional optical fiber and directed to the OLT demux. Here all upstream signals are separated and received by the respective receiver.

6.3.2 Results and Discussion

a) On/Off Extinction Analysis: - The impact of the high extinction ratio (ER) on the performance of the Hybrid PON system as shown in Fig. 6.2 for Dicode coded NRZ is presented below.

Table 6.1 Extinction ratio analysis

S. No.	*Extinction ratio(dB)*	*Dicode (Q)*
1	5	2.32
2	10	2.67
3	15	4.1
4	20	5.52
5	25	5.97
6	30	6.26

Table 6.1 shows that moving towards the higher extinction ratio (ER), performance improves regarding Quality factor (Q) and Bit Error rate. At 30 dB extinction ratio achieved Quality factor is 6.26 for 128 users at 67 KM fiber length.

b) Effects of thermal power density (receiver sensitivity):-

Receiver is responsible for performance of system as change in minimum receiver sensitivity causes change in required power budget. Thus, we analysed the effect of coding in the presence of highly sensitivity detector.

Table 6.2 Effects in the presence of thermal power density.

S. No.	*Thermal Power density (W/ Hz) at Receiver*	*Dicode (Q)*	*NRZ (Q)*
1	100×10^{-23}	3.23	3.22
2	100×10^{-24}	6.39	6.25
3	100×10^{-25}	8.82	6.20
4	100×10^{-26}	9.71	6.31
5	100×10^{-27}	9.92	6.31

Table 6.2 shows that when thermal power density is reduced, receiver sensitivity improves. Dicode shows significant improvements in system performance, but there is no significant change in the case of NRZ coding. The value of Thermal Power density at photodetector is 100×10^{-24} W/Hz for our work.

c) Effects of Group velocity dispersion (GVD):-

Table 6.3 GVD Analysis at 10 Gbps data rate.

S. No.	*GVD*	*NRZ (Q)*	*Dicode (Q)*	*Remarks*
1.	Absent	23.38	22.20	NRZ performs better
2.	Present	6.22	9.66	Dicode performs better

It is shown in Table 6.3 that when we consider GVD effects in Single mode optical fiber with length of 67 KM, dicode will perform better than NRZ. In the absence of GVD, NRZ will perform better than Dicode. But as we know that GVD effects cannot be negligible in standard single mode fiber for practical communication system, it follow that dicode is the best choice in case of high data rate system at 10 Gbps and above. A flexible hybrid PON system is designed as shown in Fig. 6.2, considering the 30 dB extinction ratio and 100×10^{-24} W/Hz thermal Power density.

The performance of the system is observed at the different lengths and number of users by using different coding viz. NRZ and Dicode. For designing of a system, it is important to have required power budget so it is ensured that enough power will reach to the receiver to maintain reliable performance during the entire lifetime of the system. Fig. 6.3 shows the BER vs optical received power at 10 Gbps for NRZ and dicode for with and without fiber. We can mathematically express the power budget and losses due to various components used in passive optical access network as,

Available Optical power Budget

= Input power – Optical receiver sensitivity + amplifier gain (if used) (2)

Minimum Receiver sensitivity can be obtained by Fig. 6.3 for NRZ and dicode is respectively -32.60 dBm and -36.20 dBm.

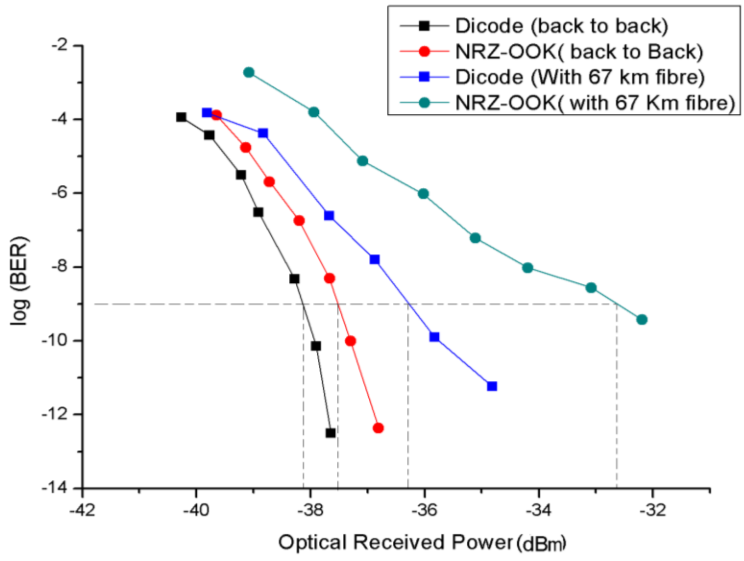


Fig. 6.3 Optical received power vs BER

For NRZ

= 0-(-32.60) + 22 dB = 54.60 dB

For Dicode

= 0-(-36.20)) +22 dB= 58.20 dB

The available optical power budget is calculated for NRZ and dicode is 54.60 dB and 58.20 dB respectively.

As shown in Table 6.4, NRZ only satisfies the power budget for 64 users at 67 KM, and for other, it's not suitable, but dicode will perform satisfactorily in all the three case. Fig. 6.3 shows that the received optical power obtained for BER @ 10^{-9} in the NRZ and Dicode coding in the back-to-back (0 km) is -37.50 dBm and -38.20 dBm respectively. Hence dicode provides 0.7 dBm of improvement in receiver sensitivity. At 67 Km fiber length, received optical power at BER 10^{-9} is -32.60 and -36.20 dBm respectively, for NRZ and dicode. So dicode provides 3.6 dB improvements in power budget as compared to NRZ coding. This improvement in power budget could be used to increase the number of users.

Table 6.4 Power Budget Analysis

	64 user at 67 Km	*128 user at 67 km*	*64 user at 77Km*
Min Launch Power (dBm)	0	0	0
MZM insertion loss	5	5	5
SSMF Attenuation (dB)	13.4 (0.2dB/km over 67km of SMF)		15.4 dB (0.2dB/km over 77km of SMF)
Coupler/Mux/ Demux(dB)	(5+5)	(5+5)	(5+5)
Optical Splitter(dB)	21	24.5	21
Other loss(dB)	5	5	5
Total System loss	54.4 dB	57.9	56.4
NRZ (power budget)	(54.6-54.4) = 0.2 dB	-ve	-ve
Dicode (Power Budget)	(58.20-54.4) = 3.80 dB	(58.20-57.9)= 0.30 dB	(58.20-56.4) = 1.80dB

Power penalty analysis:-

Power penalty for dicode is (-36.20 – (-38.20)) = 2 dB @ 10^{-9}

For NRZ is (-32.60-(-37.5)) = 4.90 dB @ 10^{-9}

Dicode's power penalty due to fiber is less than NRZ by 2.9 dB. Fig. 6.4 shows the performance of the system when varying the fiber length for 64 users. It is found that up to 67 KM length both coding provides good quality of signal but after that NRZ signal degrades severely and dicode provides good quality of signal up to 77 KM after that signal starts to degrade.

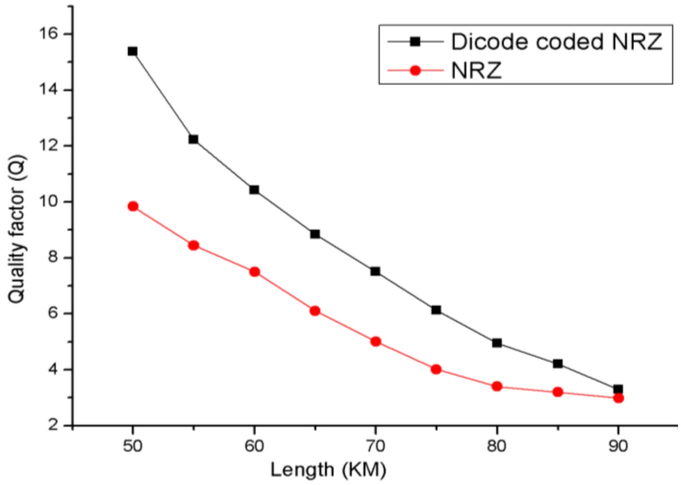


Fig. 6.4 Length v/s Q at 10 Gbps data rate.

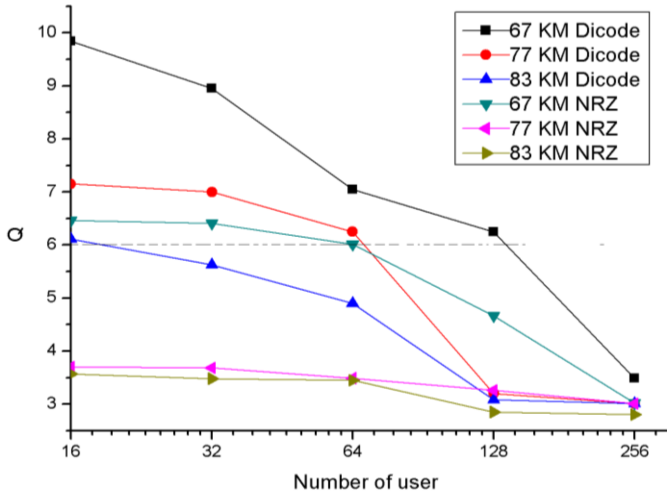


Fig. 6.5 Q factor analysis with length and number of users.

Quality factor of the system with varying number of users at fixed fiber length is evaluated in Fig. 6.4 and the minimum required Q for system can be found for different coding schemes. As analyzed in Fig. 6.5, minimum required Q can achieved for NRZ at 67 KM up to 64 user and further increasing the length of system shows the low quality of signal irrespective of a number of the user. In the case of dicode, it gives the quality of signal at 67 KM up to 128 user, 77 KM up to 64 user and 83 KM for 16 users. Fig. 6.6 shows the maximum number of user at fiber length 67 KM and more. Possible maximum number of users at 67 km is 64 for NRZ and 67 KM, 77 KM and 83KM as 128, 64 and 16 users respectively for dicode.

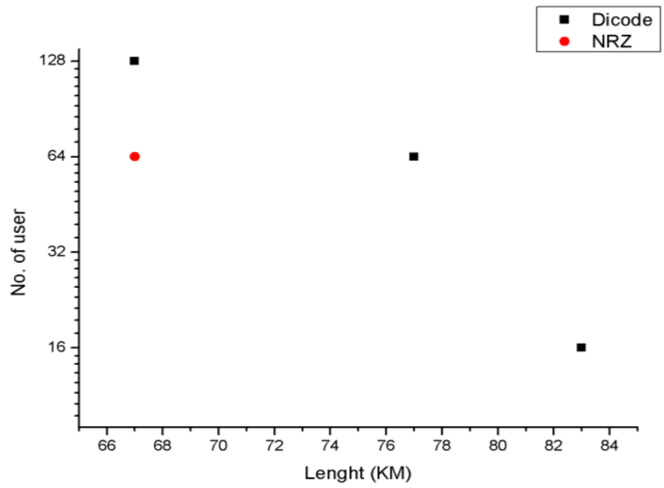
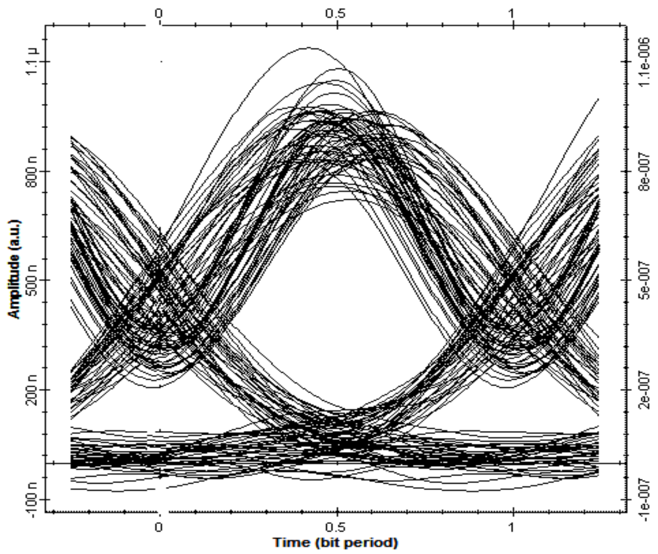


Fig. 6.6 Length vs maximum No. of Users.

Fig. 6.7 gives the comparative graphical analysis for received signal. Further good eye opening as depicted in Fig. 6.7 (a) and Fig. 6.8 (b) ensure the quality of signal achievable for 64 users at 77 Km and 128 users at 67 km respectively for dicode coding.



(a)

Fig. 6.7 Eye diagram for 64 users at 77 Km Dicode coding.

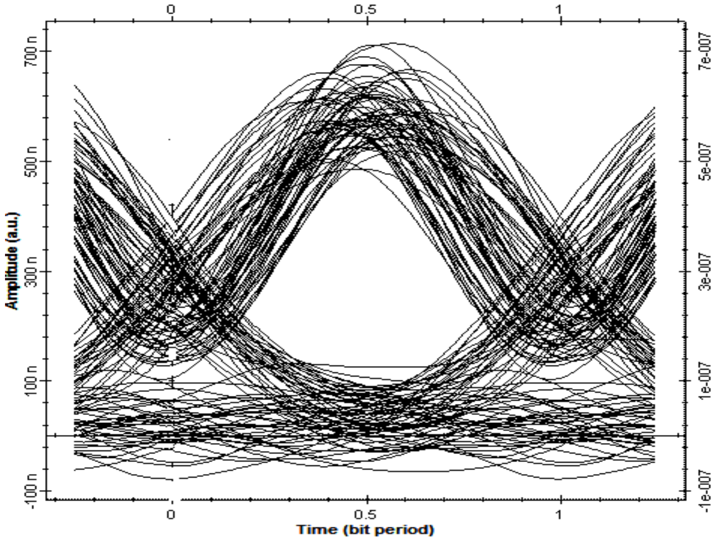


Fig. 6.8 Eye diagram for 128 user at 67 KM for dicode.

ASE, thermal and shot noise in EDFA and PIN detector will affect NRZ signal due to presence of dc and low frequency spectra as compare to dicode coding. Therefore the use of dicode coding results in an improvement of 3.6 dB power budget which aids to improve the length of fiber and number of the users.

6.3.3 Chapter Summery

In this work, we have analyzed the performance of flexible hybrid WDM-PONs with NRZ and dicode coding with 128×4 user at 67 KM. Further, we have also calculated the BER, Q factor and received optical power to observe the improvements in receiver sensitivity and power penalty as 0.7 dB and 2.9 dB respectively for the dicode. Hence, extra power budget of 3.6 dB for the dicode can increase the length up to 77 Km for 64 users or double the number of user at 67 Km compared to conventional NRZ coding. The possible increase in number of users helps to minimize the cost per user of the system.

Chapter 7

Conclusion and Future trends

We have discussed the background of optical fiber communication and passive optical networks in detail in chapter 2. We have also studied the merits and demerits of various PON generations like APON, BPON, GPON, next generation PON etc. Maturity, cost and power consumption of PONs also have been studied and observed the requirements to improve the network performance and various channel impairments like dispersion, attenuation, nonlinearity, etc. Chapter 3 described the different line coding such as NRZ, RZ, Manchester, DPSK, with their characteristics to make them suitable for the different applications and developments. To transmit the information signal into the fiber channel, different optical modulation schemes including OOK and DPSK have been studied.

Moreover, different modulations formats such as NRZ-OOK, RZ-OOK, DPSK, dicode, and duobinary have studied in detail. We found that dicode coding is more resilient to dispersion and nonlinearity as compared to other coding and therefore we utilized it for different designs described in upcoming chapters. Chapter 4 deals with the Raman crosstalk. Here, we investigated its effect on multilevel coding and observed that stimulus Raman scattering is more dominant in Duobinary than the dicode coding and the dicode coding gain is found to be 0.5 dB approximately. Raman scattering and fiber losses are compensated by amplifying the downstream data signal through remote Raman pump.

Also, The DPSK modulated distributed Raman amplifier in WDM passive optical network system is designed and analyzed parametrically. WDM-PON system provided the 55 Km transmission reach for upto 32 user and 0.3 bits/s/Hz higher spectral efficiency with 10 Gbps transmission speed. The network system efficiency is upgraded by increasing the transmission bit rate, distance and capacity of the system to support maximum number of users or subscribers. There are many more interesting challenges that remain for the future work. One can use bi-directional Raman pumping configuration for Raman amplification under the effect of temperature variation along the fiber cable. Here, we also analyzed the effects of dicode coding on GVD. Dicode coding was found to be more tolerant to GVD and observed the power budget and receiver sensitivity improvement of up to 5.5 dB and 0.7 dB respectively. The improved power budget can be used to increase the fiber length or a number of users. The system showed the best performance for up to 128 users, and 72 Km reach. Thus a cost effective system can be designed with these obtained parameters. High bandwidth WDM-PON system and ring WDM-PON has been designed in chapter 5. We designed a high bit rate system using FBG that supports long haul networks. We compared the performance at 80Gbps using NRZ, Dicode-NRZ and Duobinary schemes and found Dicode-NRZ is more tolerant to dispersion, which can be used to increase fiber length and reduce system complexity.

A ring-based WDM-PON is also designed which provide RB noise mitigation as well as fiber-fault protection. Here, we analyzed the characteristics of downstream signal using 10 Gbps OOK and dicode-coded NRZ and found a significant improvement in BER and Q factor using dicode-coded NRZ. The performance of the hybrid passive optical network with 128 users was also observed for different level coding. For 10 dBm input power and 40km fiber distance, transmission using dicoded coded NRZ are achieved successfully without any repeater and dispersion compensation. In Chapter 6, the performance of flexible hybrid WDM-PONs with NRZ and dicode coding has been analyzed for 128×4 user and 67 km fiber reach. We observed the improvements in receiver sensitivity and a power penalty of 0.7 dB and 2.9 dB respectively for the dicode coding. Therefore total power budget up to 3.6dB is improved that can be used to further increase the length or users.

The increment in the number of supported users for the same system reduced effective cost per user. Designed system can be used to provide flexibility and future bandwidth demands. In near future we would like to extend our work by implementing the proposed line coding in wireless network integrated with optical networks. We will also design some new line coding by integrating some existing ones to improve the performance of passive optical network further. We would also like to focus on energy efficiency of the network, which will definitely reduce the emission of carbon foot print to design the environmental friendly network. Also, identified line coding will guarantee to support maximum users for the long run within the available energy resources.

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Profile Summary

Mukesh Kr Gupta received the Bachelor of Engineering degree in Electronics and Communication Engineering from University of Rajasthan, Jaipur (Year: 2006) and Master of Technology in Microwave & optical Communication from Delhi Technological University (Formerly Delhi College of Engineering), New Delhi (Year: 2012). He is pursuing Ph.D. degree from MNIT Jaipur. He is an active member of Society of Photo-Optical Instrumentation Engineers (SPIE) and the Optical Society of America (OSA). His current research includes optical communication, optoelectronics devices and high speed Gigabit Passive Optical Networks (PONs).