MULTI SLOT AMPLITUDE CODING TECHNIQUE FOR HIGH SPEED OPTICAL FIBER COMMUNICATION SYSTEM

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ABSTRACT

The rapid progress of the high speed optical communications system is driven by the exponential growth of users demand on information and services. The trend towards high speed and high capacity transmission system are multiplexing technique such as electrical time division multiplexing (ETDM) and duty cycle division multiplexing (DCDM). Unfortunately, ETDM bit rate is limited by the speed of electronic devices and DCDM suffers from increased spectral width when the number of tributary increased. Therefore, in this research, a new multiplexing technique is proposed, known as Multi Slot Amplitude Coding (MSAC). In this technique, three, four and five tributaries can be achieved with less number of slots compared to DCDM. The performance of 3×10 Gbit/s MSAC is -26 dBm for receiver sensitivity (RS) and 25.5 dB for optical signal-to-noise ratio (OSNR). The improvement of 3.5 dB for RS and 3.7 dB for OSNR are obtained when optimize level spacing is implemented. When compared to DCDM, the spectral width is reduced by around 25%, not less than 55% improvement of chromatic dispersion (CD) tolerance, 0.6 dB better RS, and 1.5 dB better OSNR. The spectral width for 3×10 Gbit/s, 4×10 Gbit/s and 5×10 Gbit/s MSAC is 60 GHz, which indicates improvement of spectral efficiency. Optical spectrum of MSAC has spectral line at 10 GHz to provide an accurate clock frequency at symbol rate. In addition the performance of MSAC technique is simulated under self phase modulation (SPM) effect. The result shows that the maximum launched optical power is +12.79 dBm and +12.62 dBm for 50 km and 80 km standard single mode fiber (SSMF) with 100% compensation of dispersion using dispersion compensation fiber (DCF) at receiver. Moreover, SPM threshold improves around 2.7 dB when adopting the pre and post dispersion compensation method.

ABSTRAK

Kemajuan pesat dalam sistem komunikasi optik kelajuan tinggi didorong oleh pertumbuhan pesat permintaan pengguna kepada maklumat dan perkhidmatan. Haluan menuju sistem penghantaran berkelajuan tinggi dan kapasiti tinggi ialah teknik pemultipleksan seperti pemultipleksan pembahagian masa elektrik (ETDM) dan pemultipleksan pembahagian kitar tugas (DCDM). Malangnya kadar bit ETDM dihadkan oleh kepantasan peranti elektronik dan DCDM mengalami peningkatan lebar spektrum apabila bilangan cabang bertambah. Oleh itu, dalam kajian ini, teknik baru pemultipleksan adalah dicadangkan, yang disebut sebagai pengekodan amplitud pelbagai slot (MSAC). Dalam teknik ini, tiga, empat dan lima cabang dapat dicapai dengan bilangan slot yang rendah berbanding DCDM. Prestasi 3×10 Gbit/s MSAC ialah -26 dBm untuk kepekaan penerima (RS), dan 25.5 dB untuk nisbah isyarat-kepada-hingar (OSNR). Penambahbaikan 3.5 dB untuk RS and 3.7 dB untuk OSNR dicapai apabila jarak aras optimum dilaksanakan. Apabila dibandingkan dengan DCDM, lebar spektrum dikurangkan sekitar 25% dan peningkatan tidak kurang daripada 55% bagi toleransi serakan kromatik (CD), 0.6 dB baik RS, dan 1.5 dB baik OSNR. Lebar jalur 3×10 Gbit/s, 4×10 Gbit/s and 5×10 Gbit/s MSAC ialah 60 GHz, menunjukkan peningkatan kecekapan lebar jalur. Spektrum optik MSAC mempunyai garis spektrum pada 10 GHz untuk memberikan frekuensi pemasa yang tepat. Tambahan pula, prestasi MSAC teknik disimulasi terhadap kesan modulasi swafasa (SPM). Keputusan menunjukkan kuasa lancar optik maksima ialah +12.79 dBm dan +12.62 dBm untuk 50 km dan 80 km gentian optik mod tunggal piawai (SSMF) dengan 100% pampasan penyebaran dengan gentian pemampasan penyebaran (DCF) di penerima. Lebih lagi, ambang SPM meningkat 2.7 dB apabila menggunakan kaedah pampasan penyebaran sebelum dan selepas.

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LIST OF SYMBOLS AND ABBREVIATIONS

A_{eff} - Fiber effective area

$AS2_i$ - *i*-th signal amplitude for slot 2

$AS3_i$ - *i*-th signal amplitude for slot 3

$a_n(t)$ - Symbol function

B_e - Electrical receiver bandwidth

B_o - Optical filter bandwidth

B_n - First null baseband electrical bandwidth

B_{ref} - Optical reference bandwidth

c - Speed of light

d - Slot duration

E - Electrical field

E_p - Energy of a rectangular signal

E_{avg} - Average energy

$E_{Att,Out}(t)$ - Signal output electrical field for x and y polarizations

$E_{In}(t)$ - Signal input electrical field for x and y polarizations

$E_{Mod,out}(t)$ - Modulated optical signal

$E_{Mod,in}(t)$ - Optical input signal

E_{Total} - Total energy

F_o - Optical amplifier noise figure

F_n - Noise figure

f_c - Filter cutoff frequency

f_{cr} - Clock recovery frequency

f_o - Optical carrier frequency

G - Amplifier gain

$G(f)$ - Fourier transform of $g(t)$

$g(t)$ - Rectangular pulse with amplitude 1 and pulse duration be $T_S/3$

$H(f)$ - Filter transfer function

h - Planck's constant

I_d - Dark current

I_{p1} - Photocurrent of incident optical signal of level 1

I_{p2} - Photocurrent of incident optical signal of level 2

k_B - Boltzmann's constant

M - Number of signal level

MI - Modulation index

N - Number of tributary

N_{ASE} - Power spectral density of the ASE

n_2 - Nonlinear refractive index coefficient

P_0 - Optical power of signal level 0

P_1 - Optical power of signal level 1

P_2 - Optical power of signal level 2

P_{eLiSj} - The probability of error for level i (Li) in slot j (Sj)

P_B - Probability of bit error

P_C - Probability of correct symbol

P_E - Probability of symbol error

$\bar{P}_{rec}$ - Average received optical power

P_{in} - Incident optical signal

p_i - Priori probability of symbol $x_i(t)$

Q_{iSj} - *i*-th Q-factor of slot j (Sj)

q - Electron charge

R - Tributary bit rate

R_L - Load resistance

R_T - Aggregate capacity

S - Number of slot

S' - Number of amplitude coded slot

S_{sp} - Spectral density of spontaneous-emission-induced noise

$S_x(f)$ - Power spectral density of $s(t)$

$s(t)$ - Digital signal with random symbol and arbitrary shape

T - Absolute temperature

T_S - Symbol duration

thr_i - *i*-th threshold level

$v(t)$ - Electrical input signal

$X_i(f)$ - Fourier transform of the *i*th signal symbol, $x_i(t)$

$x_i(t)$ - *i*-th MSAC symbol element

Y - Number of unique symbols

Y' - Maximum number of supportable tributary

y_i - The observed output of sampler i

Z - Filter order parameter

Δ - Signal amplitude per level

Δf - WDM channel spacing

α_{Att} - Optical power attenuation

α_{IL} - Insertion loss parameter

β_2 - First group velocity dispersion (GVD) parameters

β_3 - Second group velocity dispersion (GVD) parameters

$\delta(f)$ - Impulse function

λ - Wavelength

μ_{LiSj} - Mean of level i (Li) at sampling point of slot j (Sj),

σ_{LiSj}	-	Standard deviation of level i (Li) at sampling point of slot j (Sj)
σ_{shot}^2	-	Shot noise variance
σ_{sp-sp}^2	-	Spontaneous-spontaneous beat noise variance
σ_{sig-sp}^2	-	Signal-spontaneous beating noise variance
σ_T^2	-	Thermal noise variance
ω_0	-	Reference frequency of the signal
$\Re$	-	Photodiode responsivity
ADC	-	Analog-To-Digital Converter
APDCDM	-	Absolute Polar Duty Cycle Division Multiplexing
ASE	-	Amplified Spontaneous Emission
ATM	-	Asynchronous Transfer Mode
BER	-	Bit Error Rate
CATV	-	Cable Television
CD	-	Chromatic Dispersion
CDR	-	Clock and Data Recovery
CO	-	Central Office
CR	-	Clock Recovery
CW	-	Continuous Wave
DAC	-	Digital-To-Analog Converter
DB	-	Duobinary
DCDM	-	Duty Cycle Division Multiplexing
DCF	-	Dispersion Compensation Fiber
Demux	-	Demultiplexer
DI	-	Delay Interferometer
DPSK	-	Differential Phase Shifted Keying
DQPSK	-	Differential Quadrature Phase Shift Keying
DSL	-	Digital Subscriber Line
DSP	-	Digital Signal Processing
DWDM	-	Dense Wavelength Division Multiplexing
ELS	-	Equal Level Spacing
ETDM	-	Electrical Time Division Multiplexing

FDDI	-	Fiber Distributed Data Interface
FDM	-	Frequency Division Multiplexing
FFT	-	Fourier Transform
FSK	-	Frequency shifted keying
FWM	-	Four Wave Mixing
ICT	-	Information and Communication Technology
IFFT	-	Inverse Fast Fourier Transform
ITU-T	-	International Telecommunication Union – Telecommunication
LAN	-	Local Area Network
LO	-	Local Oscillator
MAN	-	Metropolitan Area Network
MSAC	-	Multi Slot Amplitude Coding
Mux	-	Multiplexer
MZM	-	Mach-Zehnder Modulator
M-ASK	-	M-ary Amplitude Shift Keying
M-PAM	-	M-ary Pulse Amplitude Modulation
NRZ	-	Non Return-to-Zero
OFDM	-	Orthogonal Frequency Division Multiplexing
OLS	-	Optimum Level Spacing
OLT	-	Optical Line Terminal
OOK	-	On-Off-Keying
OSI	-	Open System Interconnection
OSNR	-	Optical To Noise Ratio
OTDM	-	Optical Time Division Multiplexing
OTN	-	Optical Transport Network
PAPR	-	Peak-to-Average Power Ratio
PBS	-	Polarization Beam Splitter
PDF	-	Probability Density Function
PDM	-	Polarization Division Multiplexing
PMD	-	Polarization Mode Dispersion
PolSK	-	Polarization Shifted Keying
PON	-	Passive Optical Network
PPM	-	Pulse Position Modulation

PSD	-	Power Spectral Density
PSK	-	Phase Shifted Keying
QAM	-	Quadrature Amplitude Modulation
RF	-	Radio Frequency
RZ	-	Return-to-Zero
SCM	-	Subcarrier Multiplexing
SBS	-	Stimulated Brillouin Scattering
SDH	-	Synchronous Digital Hierarchy
SE	-	Spectral efficiency
SONET	-	Synchronous Optical Network
SOP	-	States Of Polarization
SP	-	Sampler
SPM	-	Self-Phase Modulation
SRS	-	Stimulated Raman Scattering
SSMF	-	Standard Single Mode Fiber
TD	-	Time Delay
Tr	-	Tributary
ULAF	-	Ultra Large Area Fiber
VCSEL	-	Vertical Cavity Surface Emitting Laser
WDM	-	Wavelength Division Multiplexing
XPM	-	Cross Phase Modulation

CONTRIBUTIONS AND PUBLISHED WORKS

Awards

1. Consolation prize in Research and Innovation Competition 2011 (R&I2011) from 23-24 November 2011 in UTHM.
2. Travel Grant award at 16th European Conference on Networks and Optical Communications (NOC), 2011, Northumbria University, Newcastle upon Tyne, UK,

Journals

1. R. Talib, M. F. L. Abdullah, and M. K. Abdullah. High Speed Electrical Multi Slot Amplitude Coding with Cost Efficient Intensity Modulation and Direct Detection for Optical Communications. *International Journal on Communications Antenna and Propagation (IRECAP).* 2(4): 220-225. June 2012.
2. M. F. L. Abdullah, and R. Talib. Multilevel Signal Analyzer Tool for Optical Communication System. *International Journal of Electrical and Computer Engineering (IJECE).* 2(4): August 2012

Conferences

1. R. Talib, M. F. L. Abdullah, and M. K. Abdullah. Multi Slot Amplitude Coding Performance Improvement with Level Spacing Optimization. *IEEE 4th International Conference on Photonics (ICP)*. Melaka, Malaysia. 28-30 October 2013.
2. R. Talib, M. F. L. Abdullah, and M. K. Abdullah. Probability of Symbol Error of Multi Slot Amplitude Coding (MSAC) technique in Optical Communication System," *IEEE 3rd International Conference on Photonics (ICP)*. Penang, Malaysia. 1-3 October 2012.
3. R. Talib, M. F. L. Abdullah, and M. K. Abdullah. Proof of Concept: Experimental Implementation for Multi Slot Amplitude Coding Technique. *International Conference on Computer and Communication Engineering (ICCCE)*. Kuala Lumpur, Malaysia. 3-5 July 2012.
4. R. Talib, M. F. L. Abdullah, A. Malekmohammadi, and M. K. Abdullah. Multi-slot and Multi-Level Coding Technique over Amplitude-Shift Keying Modulation for Optical Communication Links. *16th European Conference on Networks and Optical Communications (NOC)*. Newcastle upon Tyne, UK. 20-22 July 2011.
5. R. Talib, M. F. L. Abdullah, A. Malekmohammadi, and M. K. Abdullah. A New Multi-slot and Multi-level Coding Technique for High Capacity Communication System. *IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE)*. Port Dickson, Malaysia. 9-11 November 2010

CHAPTER 1

INTRODUCTION

1.1. Background

The tremendous demand for information and communication technology (ICT) is fuelled by the increasing of internet users, amount of time usage and type of services. ICT have become an important resource in this millennium for every country of the world to face the economic challenge. Many countries are trying to spend huge budget every year in order to provide good ICT facilities for their people based on the demand of various community. In the past few years the world have witnessed rapid changes of the internet access technology such as dial up line, digital subscriber line (DSL), Wifi, Cellular broadband and etc. Those technologies have given more opportunity to the people to use the internet much easier than before. At the same time, various services have been created by various communities to expand their business and increase bandwidth space in order to attract new customers. Generally, the services will require the user to spend more time and also require more data capacity in order to get the optimum services. Based on the projections by Cisco, IP Internet traffic will grow to 1.44 zettabyte per year by 2017 internationally, since the global IP traffic currently has an average growth rate of 23% per month from 2012 to 2017 [1]. Figure 1.1 shows the projected forecasts in consumer internet traffic (households, university populations, and internet cafés) globally. More than 50% of the predicted internet traffic is generated by internet video category.

The capabilities of ICT infrastructure must be properly planned for future expansion to support the huge demand of data capacity with reasonable cost and quality. One of the key ICT infrastructures is communication network, to link all internet users all over the world by using fiber optic.

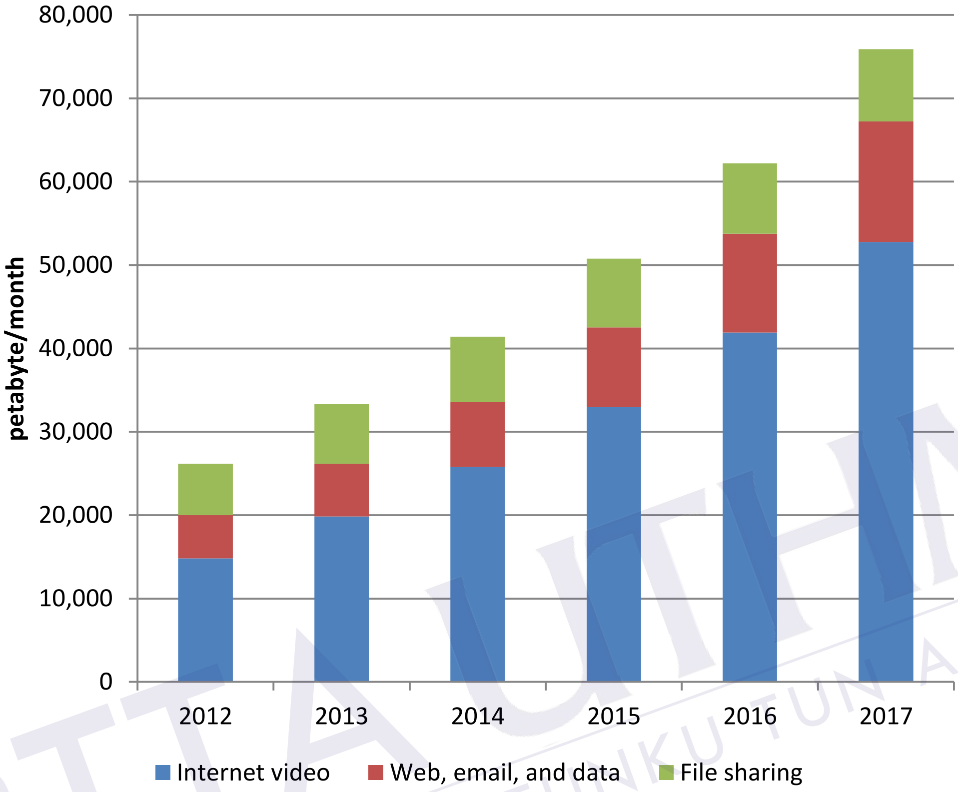

Figure 1.1: Consumer internet traffic forecast [1].

Figure 1.2 shows the structure of typical communication network. The communication network is commonly separated into three categories; access network, metropolitan (metro) network and long-haul network or core network [2]. The metro network covers a region typically, a few kilometres to several tens of kilometres by interconnecting central offices in a region or big cities. However, the long-haul network spans from hundreds to thousands of kilometres to interconnect between different cities or region. The long-haul network known as the core or backbone network is working at high capacity data transmission in order to support all services requested by users which is connected to metro network through access networks. Core network requires devices and facilities with high capabilities to deliver the best performance to the consumers.

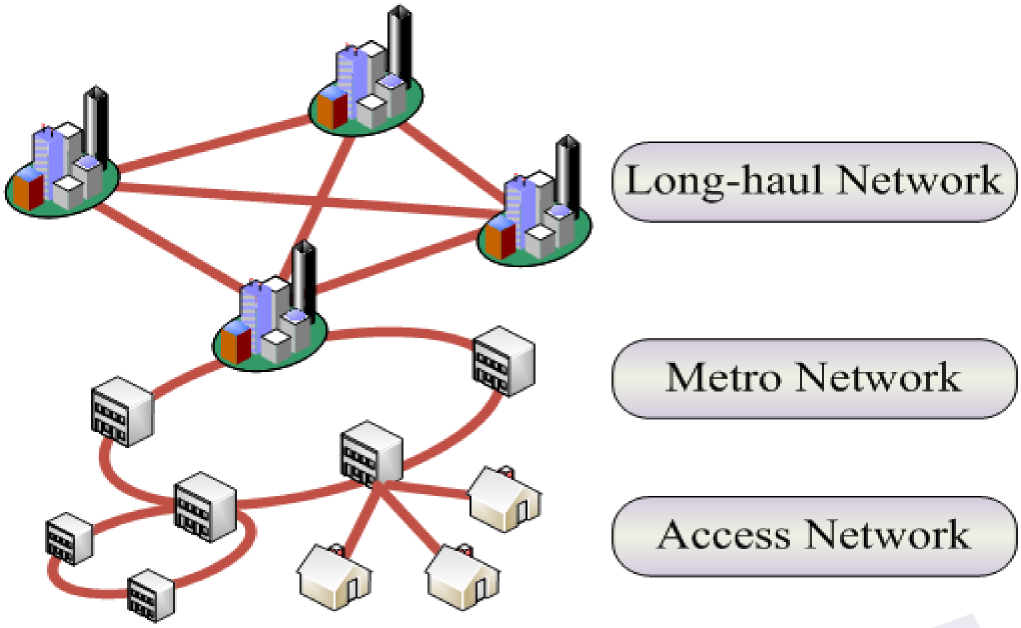

Figure 1.2: Structure of typical communication network [2]

The deployment of optical communication worldwide is based on international standard such as SONET (Synchronous Optical Network), SDH (Synchronous Digital Hierarchy), OTN (Optical Transport Network), ATM (Asynchronous Transfer Mode, FDDI (Fiber Distributed Data Interface), Fibre Channel Standard, Gigabit Ethernet etc [3]. Generally, this standard provides the guide line for the optical society to implement optical communication system using various equipment manufacturers. Therefore, the deployment can be provided more quickly and it would benefit the users and the optical society as well. The evolution of high capacity optical communication can be witnessed by the increasing of the bit rate in SONET/SDH/OTN and Ethernet as shown in Figure 1.3.

Optical communication can be said to be important technology in today's communication network. It is simply because of huge advantages over other types of communication system in terms of high bandwidth or capacity, low attenuation, immunity to electromagnetic interference, less material cost and better security compared to copper cable [2, 4, 5]. The advancement in various technologies such as fibre optic, electronic devices, light sources and etc, have transform optical communication to became more reliable and the only choice to support high capacity data for long haul application.

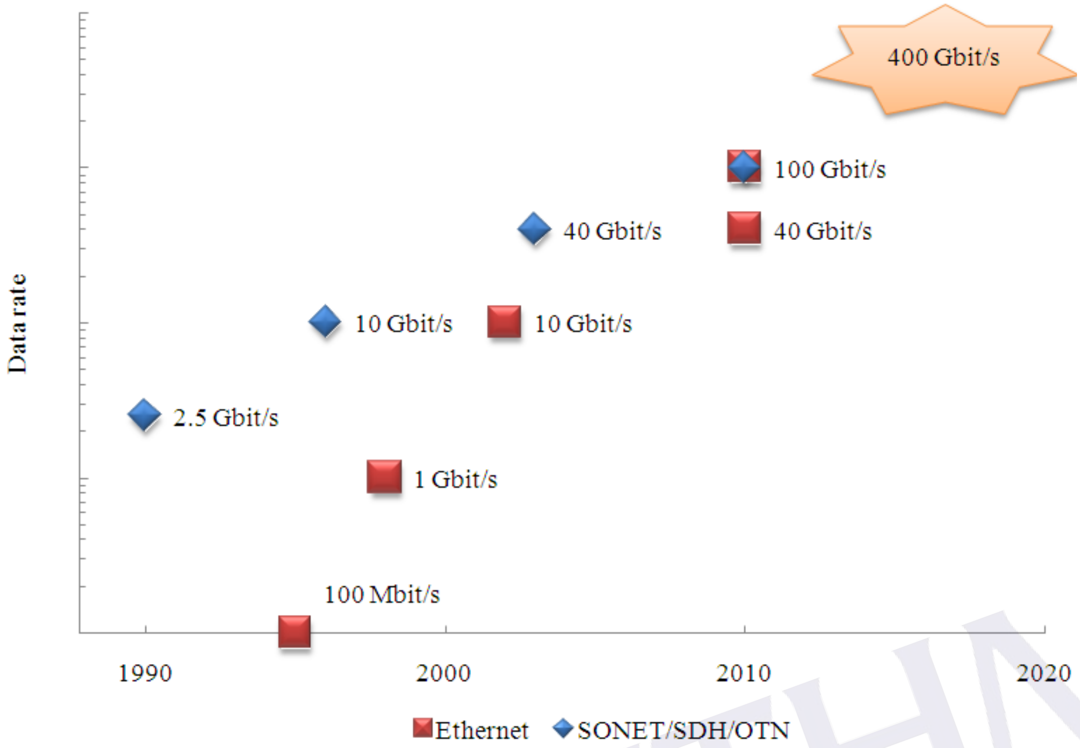

Figure 1.3: Evolution of data rate of SONET/SDH/OTN and Ethernet [6, 7]

In order to utilize the huge bandwidth in fiber optic, generally, multiplexing and modulation are adopted in an optical communication system. Multiplexing is a process of sharing a common channel (fiber optic) by exploiting signal orthogonality, whereas in modulation, data or information (binary) is converted to symbol before transmission. The need for multiplexing is driven by the fact that it is much more economical to increase transmission capacity over a single fiber than it is to transmit at lower rates over multiple fibers, in most applications. Table 1.1 shows several approaches to implement various multiplexing and modulation technique.

In optical communication systems, electrical time division multiplexing (ETDM) plays an important role for high speed and high capacity data transmission. Typically, ETDM is implemented in order to achieve the highest possible per-channel bit rates by multiplexing several low speed channels in electrical domain [2]. The advantages of ETDM are always yielded the lowest cost, footprint, and power consumption per end-to-end networked information bit, once the underlying technologies were sufficiently mature. Due to this advantages, ETDM implementation have always been pushing the limits of high-speed electronic and optoelectronic components, with 100-Gb/s binary transmission systems representing the current limit of electronic multiplexing and demultiplexing capabilities [8-10].

Table 1.1: Multiplexing and modulation technique [8]

Domain	**Multiplexing**	**Modulation**
time	Time division multiplexing (TDM)	Pulse position modulation (PPM)
frequency	Frequency division multiplexing (FDM), and Orthogonal FDM (OFDM)	Frequency shifted keying (FSK)
wavelength	Wavelength division multiplexing (WDM)	
polarization	Polarization division multiplexing (PDM)	Polarization shifted keying (PolSK)
phase		Phase shifted keying (PSK), Quadrature amplitude modulation (QAM)

Typically, this high speed ETDM data stream is modulated using single wavelength. Therefore, high speed ETDM only occupy small portion of fiber optic bandwidth. Hence, another multiplexing known as WDM is adopted to utilize other bandwidth [11]. In WDM, multiple set of high speed ETDM or other technique at different wavelength propagate in similar fiber optic. Note that each WDM channel requires complete set of communication elements (light source, modulator, and photodiode receiver). Therefore with the combination of ETDM and WDM, huge transmission capacity per optical fiber can be achieved [12, 13].

Other types of multiplexing that has been reported is polarization division multiplexing (PDM) [14] and orthogonal frequency division multiplexing (OFDM) [15]. In PDM system, two modulated optical signals are transmitted at the same wavelength with orthogonal states of polarization (SOP). In order to multiplex and demultiplex both SOP, polarization beam splitter (PBS) is required at transmitter and receiver. OFDM is another latest technique in optical system. OFDM belongs to a broader class of multicarrier modulation (MCM) in which the data information is carried over many lower rate subcarriers. In OFDM, modulation and demodulation are efficiently implemented using Inverse Fast Fourier transform (IFFT) and Fast Fourier transform (FFT), respectively. However, for high speed optical system, OFDM requires digital-to-analog converter (DAC) at transmitter and analog-to-digital converter (ADC) at receiver with high speed and high resolution [16].

Most commercial high speed optical system, currently up to 40Gbit/s is based on conventional modulation format such as non return-to-zero (NRZ) and return-to-zero (RZ). Due to capacity demand and to achieve better spectral efficiency for each WDM channel, several advancement modulation format have been studied such as M-ary based on amplitude-shift keying (ASK), phase-shift keying (PSK), quadrature amplitude modulation (QAM) have been reported for high capacity applications [17-31]. Transmission of M-ary ASK can be done using simple intensity modulation and direct detection like binary (NRZ/RZ) but has a relatively large power penalty because the number of signal levels increase significantly with the number of users. High spectral efficiency is also possible with M-ary PSK and QAM, unfortunately, it will increase the complexity of the system at the transmitter and even more at the receiver especially for coherent system.

1.2. Problem statement

In 2007, new multiplexing technique has been proposed to multiplex multiple users per WDM channel, as an alternative to TDM for wireless or optical communication [32, 33] know as Duty Cycle Division Multiplexing (DCDM). DCDM takes advantage of RZ line coding and offers more transitions to simplify the function of clock recovery circuit. In DCDM, each user is identified by its unique duty cycle and signal level[34]. Simulation studies show that DCDM is capable of tolerating more chromatic dispersion (CD) compared to RZ format using simple intensity modulation due to compact spectral width properties [35, 36]. DCDM setup is simple for optical link, therefore, it provides cost efficient for state of the art high data transmission.

Despite several achievements of DCDM as mentioned above, there are two major weaknesses in this technique. First, N+1 number of signal levels are required in order to multiplex N number of users. Thus, it suffered from increased number of signal levels for additional user. High number of signal level means that more average power is required to achieve similar quality of eye diagram (Q-factor) compared to binary (2 levels). Second, when the number of users increase, slot duration becomes short as number of slots increased as well. As a result, signal bandwidth will increase thus reducing the performance of dispersion tolerance.

Variation version of DCDM, known as absolute polar DCDM (APDCDM) has been introduced in 2008 [37]. APDCDM implements signal inverting for even users before combining all multiplexed users. This approach helps in reducing the increment of multiplexed signal level with reference to the number of users. Thus, the receiver sensitivity improvement are observed as compared to DCDM [37, 38]. In [39-42], narrower spectral width has been achieved as compared to previous report by removing the guard slot but this will reduce symbol transitions which is important for clock recovery. Besides that, APDCDM still suffered from increased number of slots with increasing number of users.

Considering the highlighted weaknesses of DCDM and APDCDM technique as mentioned above, new concept is necessary to search for the best solution. In this research, a new multiplexing technique, known as Multi Slot Amplitude Coding (MSAC) is proposed to further enhance the potential advantages of DCDM. MSAC has better way of utilizing the number of slots and signal levels in order to reduce the signal bandwidth and power penalty, hence improving the system performance. Besides that, the proposed multiplexing has a unique property; like RZ format or DCDM with better clock information thus simplify the function of clock recovery circuit. Multiplexing and demultiplexing for this signal can be performed economically using high speed electronic devices.

1.3. Objectives

The main goal of this research is to develop a new multiplexing technique to provide enhance capability and various important advantages than conventional multiplexing in high speed optical communication system. Based on this technique, multiple tributaries can be multiplexed and propagated efficiently over the same WDM channel. In specific, the objectives of this thesis are:

1. To propose new electrical multiplexing technique known as Multi Slot Amplitude Coding (MSAC) to support multiple tributaries in high speed optical communication system.

2. To evaluate and analyze the performance of MSAC technique in fiber optic in term of receiver sensitivity, OSNR, CD tolerance and spectral width for 3, 4 and 5 tributaries with tributary bit rate of 10 Gbit/s.
3. To further investigate the self-phase modulation effect on MSAC system for 50 km and 80 km SSMF with CDF to compensate the dispersion.

1.4. Scope of study

Figure 1.4 shows the K-Chart for this research represents the study model in order to provide the whole picture of research scope with simplify approach. This chart describes the relation of the main topic in digital communication field and the research work focussing in this thesis. The highlight textbox (pink colour) indicates the direction of this research work in order to achieve the research objectives.

In this research a new multiplexing technique has been proposed known as MSAC. Therefore, the review of conventional transmission techniques in the field of digital communication such as multiplexing, modulation and coding have been done. Note that this research is related to the physical layer issues in the open system interconnection (OSI) 7-layer Reference Model [4]. The purpose of this study is to introduce the novel multiplexing concept for digital communication and evaluate the capability of this technique in a practical optical fiber communication system.

Novel multiplexing concept in MSAC is based on conversion or translation binary data of *N* tributaries to unique symbol. This symbol is defined based on multi amplitude and multi slot structure which is different from conventional multiplexing technique. Therefore, new concept and model of MSAC multiplexer and demultiplexer are developed. The mathematical formulas have been derived to calculate the maximum number of symbol, the maximum number of tributary, aggregate bit rate, signal bandwidth, and spectral efficiency for given number of signal level, number of slot and tributary bit rate.

Since, MSAC has unique symbol sequence with multi amplitude and multi slot, power spectral density (PSD) and bit error rate (BER) formula has significant differences to those used in conventional communication system. Therefore, for theoretical part, a PSD formula and BER formula have been proposed for MSAC technique. The BER formula, derivation is based on Gaussian approximation where from the BER formula, analytical noise model of PIN receiver and optically amplified PIN receiver have been derived and analyzed to plot BER versus received optical power. This analysis provides important information about receiver sensitivity at targeting BER with consideration of noises impairment at receiver. Besides that, the effect of optical amplifier gain, photodiode responsivity, and tributary bit rate are studied.

In this research, numerical simulation has been performed to evaluate the performance of MSAC optical system. Numerical simulation is undoubtedly important to provide more practical analysis which may be too extensive to be considered in the theoretical development. Two commercial software's have been used to prove and implement MSAC technique, which are OptiSystem and MATLAB. OptiSystem has been used as main platform to implement a complete optical communication system. MATLAB is required to implement the new multiplexer, demultiplexer, and BER estimation, which are not available in OptiSystem components library. A practical high speed MSAC optical system setup has been proposed and the performance of this system has been evaluated by including various impairment factors such as noises, attenuation, dispersion, and nonlinearity. The validation of BER estimation has been done with bit-to-bit comparison method using pseudo random binary signal (PRBS) length of 2^{14}-1 bits for each tributary. Besides optical modulation spectra and receiver sensitivity, in this simulation work, chromatic dispersion tolerance, optical to noise ratio (OSNR), spectral width have been studied. Analysis of self-phase modulation (SPM) effect when operating in nonlinear regime is also considered in which the possibility for launching higher optical power for the purpose to extent the transmission distant. In addition, the effect of signal level spacing of MSAC signal is included in this research.

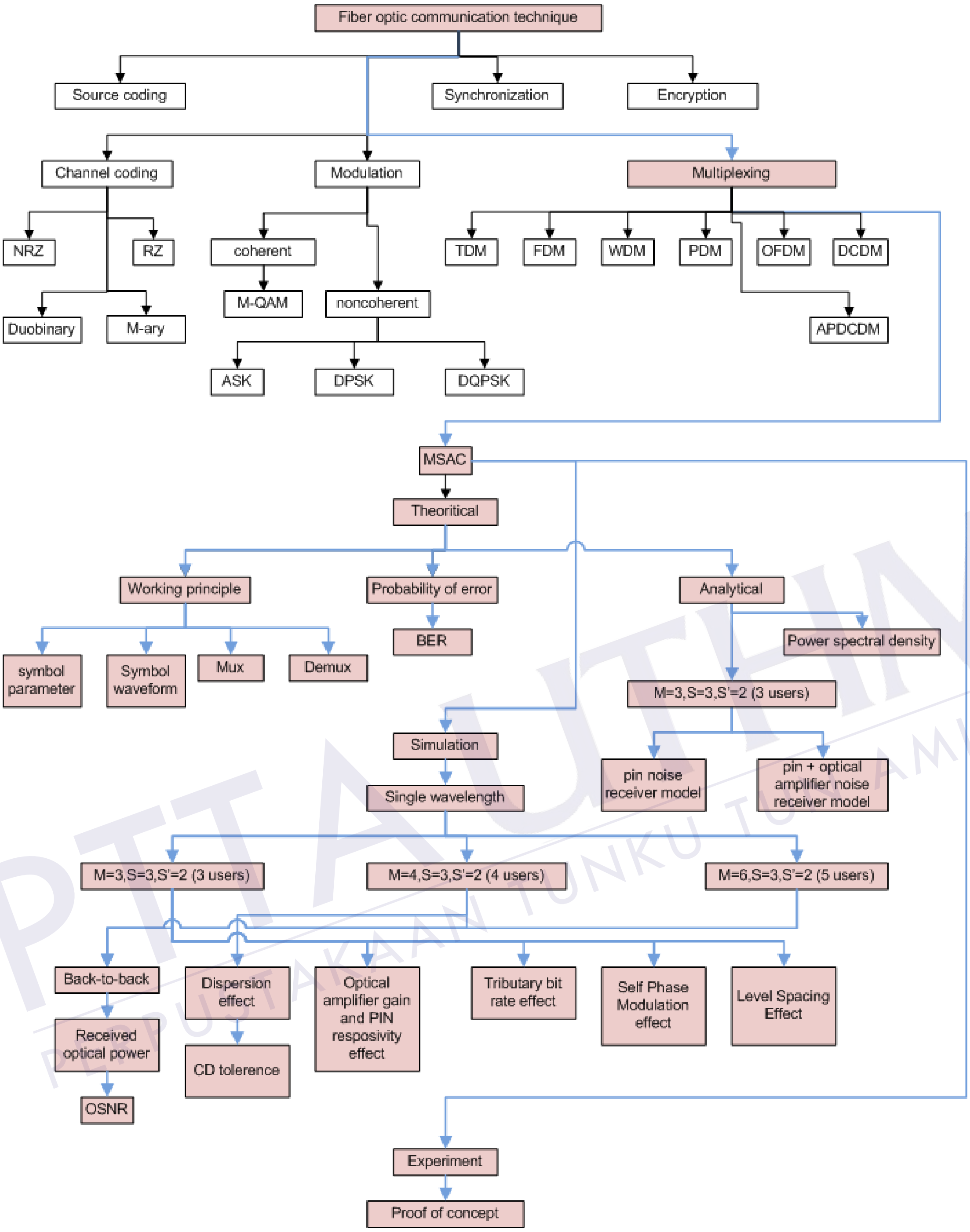

Figure 1.4: Scope of study using K-Chart™

1.5. Thesis Overview

This thesis is significantly dedicated towards the development of new multiplexing technique for optical communication system. This thesis is organized into six chapters. In Chapter 1, a brief and general view of modern fiber optic communication system with various multiplexing and modulation technique is highlighted. Problem statements, objectives and scope of study are also outlined.

Chapter 2 provides the comprehensive review of optical communication system. Communication standards are provided as evident of commercial deployment of optical system. Concept, technical information as well as advantages/disadvantages of current multiplexing and modulation technique are described in detail as these are the main focus in this study. This chapter also address the typical impairments in fiber optic channel, noises, and bit error rate estimation which is important for designing practical optical system.

Chapter 3 presents the basic concept and properties of the proposed technique, MSAC. The general symbol format, the derived mathematical formula related to the parameters (number of signal level, number of slot, tributary bit rate with aggregate capacity, number of tributary, bandwidth, and spectral efficiency), multiplexer, demultiplexer and BER estimation formula are presented.

Based on the proposed technique in Chapter 3, Chapter 4 describes the development of theoretical PSD of MSAC signal. Development PIN receiver noise model and optically amplified PIN receiver model with theoretical performance analysis are discussed in this chapter.

Chapter 5 emphasizes on the numerical simulation of MSAC technique in optical communication system. Performance investigation of MSAC system by considering various aspect of impairment of fiber optic and noises are presented

Finally, Chapter 6 remarks the overall conclusions and research contributions of this thesis and discusses the possibilities for further development of this work.

CHAPTER 2

OPTICAL COMMUNICATION SYSTEM: A REVIEW

2.1. Introduction

The aim of this chapter is to provide up to date review on optical communication system for high capacity and high speed data transmission over a most promising optical fiber channel. Today commercial optical communication system implemented based on international standard. Review on recent international standards is presented in order to understand the current technologies deployment. The state of the art multiplexing and modulation technique in optical communication system are discussed in term of concept, working principle, their advantages and disadvantages. This critical review provides important explanations to support our justification for proposing new multiplexing concept known as MSAC.

Note that, implementation of multiplexing and modulation is actually related to the interaction of completed system which covers transmitter, transmission and receiver. It is expected that MSAC system, like other technique, is affected by various fibre optic impairments such as attenuation, dispersion, and nonlinearity. Due to that, the principle of fibre optic impairments is presented. Besides that, various noises such as shot noise, thermal noise and amplified spontaneous emission (ASE) noise limit the performance of MSAC system is also reviewed. The BER of MSAC is crucial part in optical system characterization, therefore the conventional method to obtain the BER is provided as reference in order to determine the BER of MSAC.

2.2. Review on commercial communication standard

In general, there are many standards that have been established for communication system deployment. The purpose of these standards is to provide guideline for various manufacturer and vendor to interconnect communication equipments for practical realization. This standard consists of specific communication system information to be achieved at that particular time. It is understandable that this standardized work is not rigid, thus revision and new standardization will happen in future due to the growing bandwidth demand and technology advancement.

In communication history, synchronous optical network (SONET) and synchronous digital hierarchy (SDH) are well known and popular standard for high speed communication. SONET is used in North America whereas SDH in other parts of the world. Existing SONET and SDH, actually has same purpose, but due to many differences of opinion and implementation philosophy in digital signal transmission. SDH was standardized by International Telecommunication Union – Telecommunication Sector (ITU-T). This standard provides comprehensive information to implement a digital system by defining the transmission format, speeds, optical interface characteristics, and network configuration. The deployment transmission rates for SONET/SDH is shown in Table 2.1.

Table 2.1: SONET and SDH transmission rates [4]

SONET level	Electrical level	Line rate (Mb/s)	SDH equivalent
OC-1	STS-1	51.84	
OC-3	STS-3	115.52	STM-1
OC-12	STS-12	622.08	STM-4
OC-24	STS-24	1244.16	STM-8
OC-48	STS-48	2488.32	STM-16
OC-96	STS-96	4976.64	STM-32
OC-192	STS-192	9953.28	STM-64
OC-768	STS-768	39,814.32	STM-256

Beside SONET and SDH, ITU-T also establishes other transport standard known as optical transport network (OTN). This standard provides the management of services using multiple, different wavelengths of light over the same fiber optic to cater DWDM. Referring to ITU-T Recommendation G.959.1, three type of bit rate which are 2.5 Gbit/s, 10 Gbit/s and 40 Gbit/s was approved to provide guide line to implement optical system with point-to-point, single and multi channel setup. In this standard, the span distance has been defined as intra-office, short-haul, long-haul, very long-haul and ultra long-haul. Note that, this standard implement NRZ and RZ format as optical modulation format.

Ethernet is another communication technology that has been standardized by IEEE. This technology is popular in local area network (LAN) due to simplicity and cost efficient. Nowadays, Ethernet has become a technology for metro and core network. In order to support the huge capacity demand, 40 Gbit/s and 100 Gbit/s Ethernet technology (40GE and 100GE) have been standardized in IEEE 802.3ba [43].

In summary, as a guide line, this standard describes the specific information to implement optical fiber communication. Note that, in the future, due to increasing bandwidth demand, the evolution of standard is mandatory especially to utilize fiber optic bandwidth, therefore, advancement in optical fiber communication is very important covering various aspect such as fiber optics, electronic, multiplexing, modulation, coding, error correction, digital signal processing, laser, modulator, optical laser, dispersion management, and etc. The progress in optical system therefore gives us motivation to look and understand the limitation of current technology. Therefore, the following review is very important for this research.

2.3. Multiplexing technique

Generally, multiplexing technique is used to maximize the usage of the transmission medium or channel. The application of this technique includes increasing the channel capacity or the number of tributary/user. There are several multiplexing techniques which have been deployed in communication; Time Division Multiplexing (TDM), Frequency Division Multiplexing (FDM), subcarrier multiplexed (SCM), Wavelength Division Multiplexing (WDM), Polarization Division Multiplexing (PDM), and Orthogonal frequency division multiplexing (OFDM). The most recent is Duty Cycle Division Multiplexing (DCDM) which has been proposed as an alternative to TDM.

2.3.1. Time Division Multiplexing (TDM)

In the history of communication, TDM has been used since 1950 in the public telephone network. During that time, the main factor for the implementation of TDM is to reduce the cost by utilizing the bandwidth available in a transmission medium which is higher compared to user bandwidth for a single voice. In TDM technique, the users will share the transmission medium based on time slot. This mean, each user will be given specific portion of time to transmit the information. During that portion of time, the user will occupy the medium entirely. In telephone system as an example, the bit rate required by each voice of user is low compared to the maximum bit rate for the transmission medium. Figure 2.1 describes the TDM technique for bits interleave which is simplest version of TDM. In this figure, three channels tributary at R bit rate per channel are multiplexed as single channel data stream at 3R bit rate capacity. Since the incoming bit duration is T_b (=1/R), thus the bit duration of output data stream is $T_b/3$, which is three time smaller than incoming bit duration. Besides bit interleave, 1 byte or frame of data from each channel tributary is selected and arrange in the output data stream. Typically, the actual hardware implementation from incoming data to multiplexed data is determined by the manufacturer. However, the manufacturer must comply with international standard such as SONET/SDH and OTN.

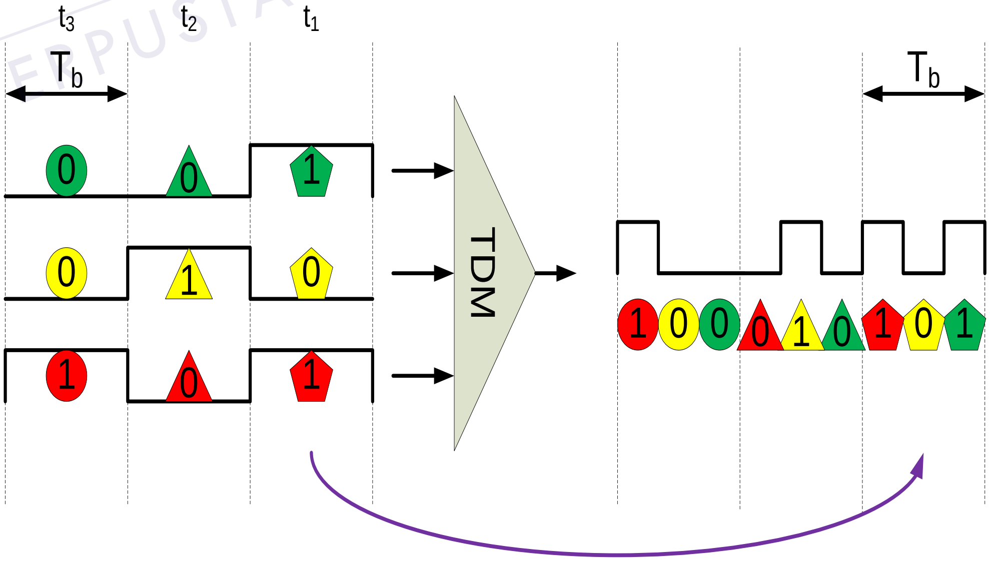

Figure 2.1: TDM technique [2]

The evolution of serial transmission bit rate from 10 Gbit/s to 40 Gbit/s in SONET/SDH and OTN is another milestone in optical fiber system. Even though 40 Gbit/s capacity can be achieved using 4 channels WDM with 10 Gbit/s per channel, but the requirement of simple, quick and economical implementation offered by TDM are an attractive features. Note that, utilizing 40 Gbit/s TDM per channel will reduce network element (transmitter and receiver) effectively, thus management and maintenance effort are much simpler compared to 4 channel WDM [44]. Another version of TDM working on optical domain has been proposed as an alternative to go beyond the limitation of electrical TDM (ETDM), is known as optical TDM (OTDM) [45].

Currently, high speed electronic based ETDM has been reported to support more than 40 Gbit/s serial data using more advance material and state-of-the-art technology [9, 46-48]. Figure 2.2 (a) describes the experimental setup for 107 Gbit/s ETDM optical system as reported in 2006 [9]. In this setup, ETDM was implemented using an electronic 2:1 multiplexer (SHF 408) to produce 107 Gbit/s serial binary (NRZ format) electrical signal as shown in Figure 2.2(b). This multiplexer was fabricated based on silicon-germanium heterojunction bipolar transistor (SiGe HBT) technology and manufactured by SHF Communication Technologies AG, Germany. The bit interval for this signal is corresponding to about 10 ps. Theoretically, ideal NRZ format with 10 ps interval has 100 GHz null electrical bandwidth. However, even though generating serial can be no longer the main limitation, for up to 100 Gbit/s as mentioned above, this serial ETDM signal has to face with other transmission hurdles such as the type of modulation and WDM channel grid issues. Current system, up to 10 Gbit/s, using simple modulation such as on-off-keying (OOK) at 1550 nm, several thousand kilometers can be reached before signal regeneration over standard single mode fiber (SSMF), but this span distance is impossible to be maintained when the serial bit rate continuously increase if similar modulation is used. Therefore, the limitation of the conventional OOK based on NRZ or RZ will be discussed in the next section. Current research direction shows that, high speed serial data have to be converted to low speed symbol rate using multilevel signalling or M-ary in order to propagate at a longer distance compared to OOK.

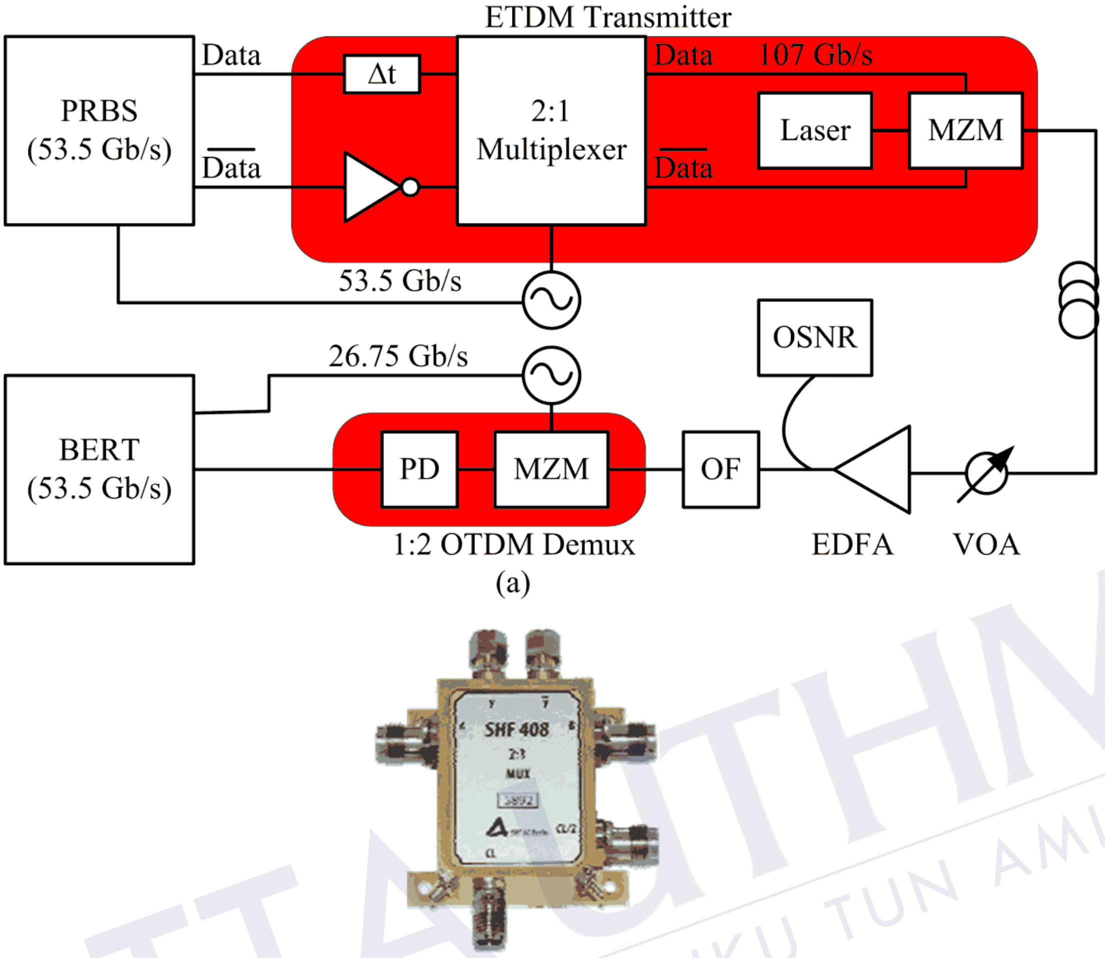

Figure 2.2: (a) 107 Gbit/s ETDM optical system and (b)2:1 Multiplexer SHF 408 [9]

2.3.2. Frequency Division Multiplexing (FDM)

In FDM [49], the spectrum of medium is shared by dividing the spectrum to be sub-band. Figure 2.3 shows the block diagram of FDM principle. In this figure, several typical 3 kHz bandwidth analogue signal of voice are combined in single medium by arranging them in 4 kHz sub-band. For example, in analogue telephone signals, 60 MHz FDM system is capable to accommodate around 10800 channels over coaxial cable. Each sub-band must be well separated in order to prevent interference and the signal can be extracted by band-pass filter at the receiver. However, FDM is unable to compete with digital system based on TDM which is more reliable and more robust to noise. Beside FDM, almost similar concept has been reported especially in optical system, namely subcarrier multiplexing (SCM).

SCM has been reported for video signal distribution in cable television (CATV) [50-55], high speed data transport [56] and fiber-to-the-home (FTTH) of WDM passive optical network (PON) [57] . Since this technique transmits simultaneously several channel with smaller baud rate signal thus reducing impact of CD and M-ary can be adopted for better bandwidth efficiency compared TDM at similar data capacity. Considering hardware issues, microwave devices are more mature to provide stable microwave oscillator and better frequency selectivity of a microwave filter compared to optical devices. This technique is also compatible with advanced modulation format and coherent detection in the RF domain can be implemented easier compared to optical coherent detection.

However, to implement this technique, the number of microwave components increase linearly as number of channels such as microwave oscillator, combiner and filter with different frequency characteristic requirement. Therefore the management of component quality is more challenging during practical implementation. Besides that, nonlinear Mach-Zehnder modulator (MZM) transfer function may induces nonlinear distortions of RF signal in which harmonic is created. This harmonic will interfere with other SCM channel creating intermodulation distortion effect. Moreover, the crosstalk issue associate with chosen channel spacing limits the SCM performance [57].

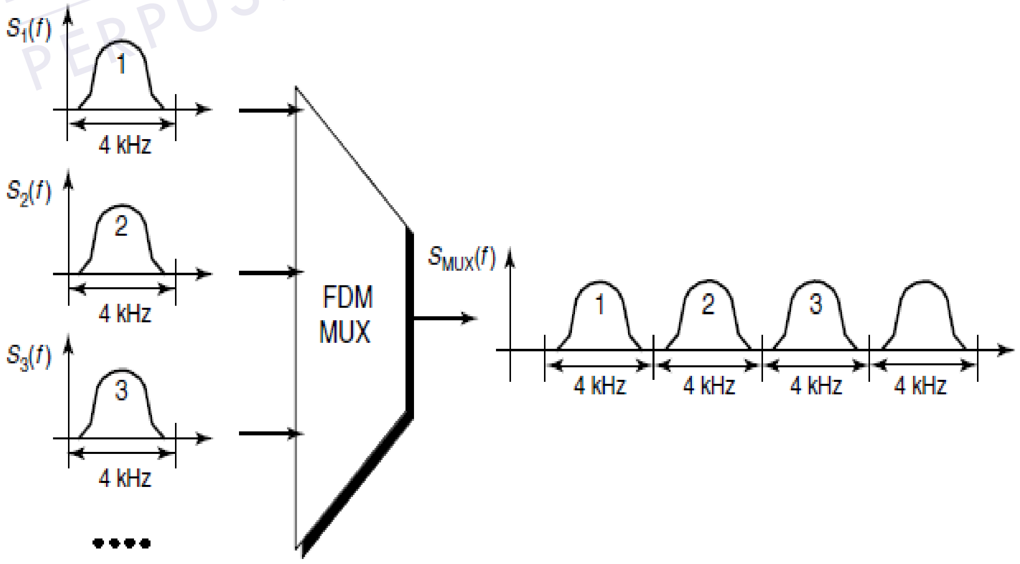

Figure 2.3: FDM principle [49]

2.3.3. Wavelength Division Multiplexing (WDM)

Wavelength Division Multiplexing (WDM) was proposed by DeLange in 1970 [58] as frequency-division multiplexing in optical domain. The popularity of WDM started in the early 1990s because of the limitation of electronic equipment and more complex for high speed equipment realization to utilize fiber optic bandwidth to transport more data. Figure 2.4 shows the principle of WDM system. In this technique, N numbers of optical wavelengths are used as data carrier. These wavelengths are combined into an optical fiber using WDM multiplexer (WDM Mux). At the receiver side, WDM demultiplexer (WDM Demux) separates this wavelength as individual channel. Each optical wavelength is different and typically, channel spacing will determine the gap between those wavelengths so that overlapping optical carrier can be avoided. This technique allows any modulation technique implemented for each wavelength as long as spectral width of signal does not exceed the channel spacing used. Based on this technique, the aggregate capacity per fiber optic is given by $N \times R$, where R is bit rate per channel, and assuming R is similar for all channels.

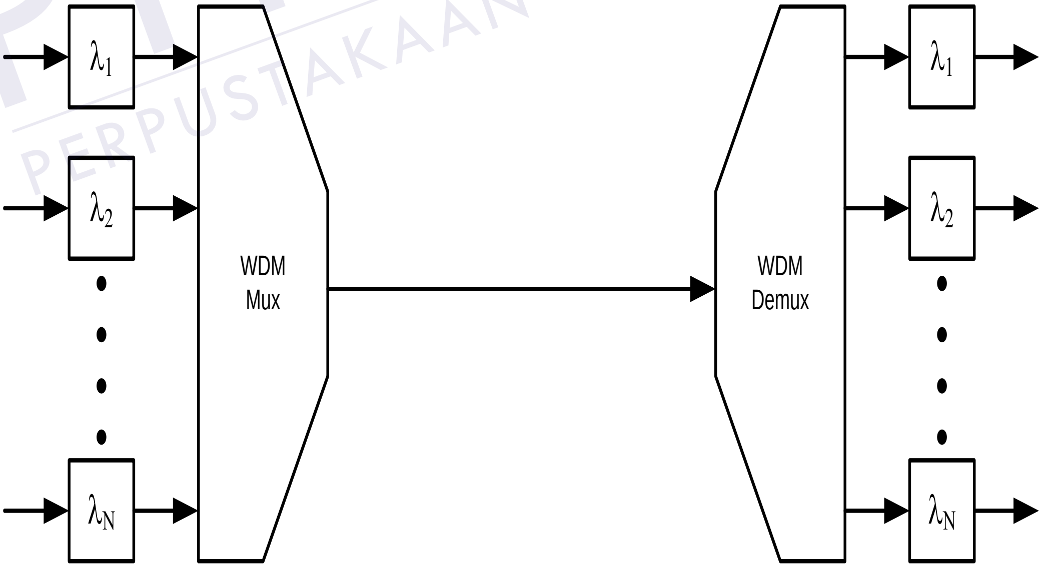

Figure 2.4: WDM principle [2].

Table 2.2 shows the wavelength range of WDM bands. Note that, this range is approximation values and have not yet been standardized. Considering O-band which is 1260 nm to 1360 nm range is equivalent to 14 THz bandwidth. Meanwhile, combination of S-band and C-band in a range of 1460 nm to 1625 nm provides another 15 THz bandwidth. Total available bandwidth per fiber optic in O-, S- and C-band only is around 30THz of the low-loss regions of a standard G.652 single-mode fiber as shown in Figure 2.5.

Table 2.2: WDM bands [59]

Band	Descriptor	Wavelength range (nm)
O-band	Original	1260 to 1360
E-band	Extended	1360 to 1460
S-band	Short	1460 to 1530
C-band	Conventional	1530 to 1565
L-band	Long	1565 to 1625
U-band	Ultra-long	1625 to 1675

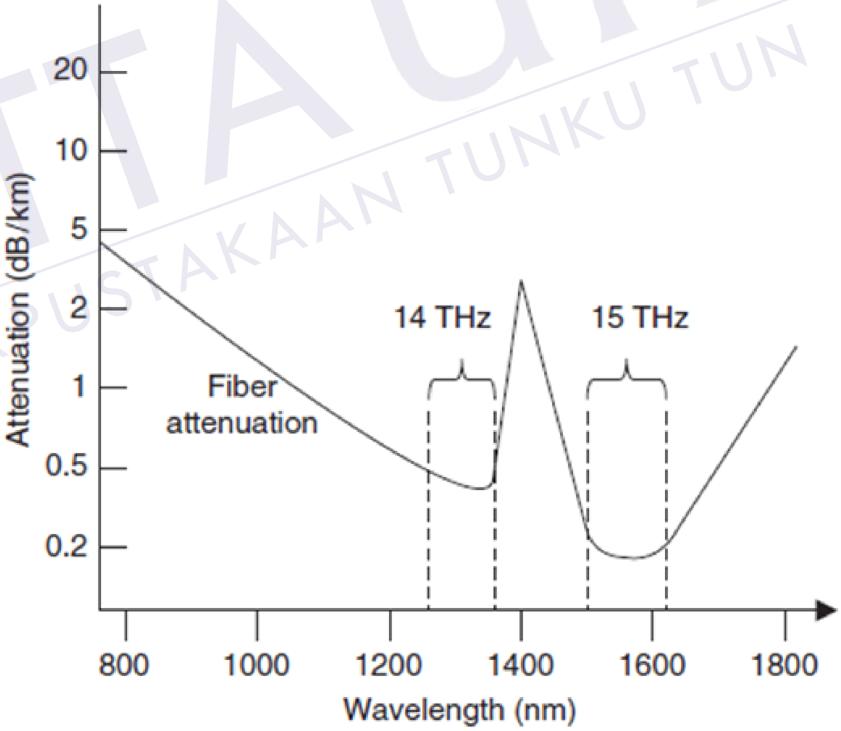

Figure 2.5: Typical silica fiber optic attenuation characteristic [59]

In order to standardized the implementation of available WDM bands above, in 1998, ITU-T released the first specification for WDM known as Recommendation

G.692, Optical Interfaces for Multichannel Systems with Optical Amplifiers [60]. In this standard, channel wavelengths and frequencies have been specified for C-band (1530 nm to 1560 nm) with 50 GHz and 100 GHz channel spacing. In 2002, narrower optical channel spacing has been standardized by ITU-T as Recommendation G.694.1 with 12.5 GHz to 100 GHz channel spacing for C- and L-bands (1530 nm to 1625 nm) [61]. This WDM channel spacing is known as Dense WDM (DWDM). Based on ITU-T standard, the number of channels is about 81 channels for the C-band and about 111 channels for the L-band considering channel spacing of 50 GHz. Besides that, considering low cost requirement for access network and local area network, coarse WDM (CWDM) was standardized by ITU-T Recommendation G.694.2 [62]. This standard specifies the centre wavelength of 18 CWDM channels in O- to L-bands (1270 nm to 1625 nm) with 20 nm channel spacing. This wide spacing is important to give more tolerance in laser source due to wavelength-drift for low cost uncooled laser source.

In the early stage, WDM transmission implementation is based on point-to-point setup as shown in Figure 2.4. After that, the wavelength add/drop multiplexer (ADM) is introduced in WDM system to provide better way to manage the wavelength channel flow for implementing WDM network in which more than two nodes can be linked together with more convenience way because no optical-electrical conversion involved. The purpose of ADM is to add and drop single or several WDM channel from WDM network typically important task in metro and core network. The detail WDM network technology can be found in [11, 63].

Passive optical network (PON) technology is an example of successful WDM implementation in access network to provide high capacity, increased reach and energy saving compared to typical digital subscriber line (DSL) technology [64]. In this technology, the wavelength for the downstream signal and the upstream signal are 1490nm and 1310nm, respectively. A low cost light source that have wide separation in wavelength channel spacing can be used to deliver the triple-play services to end users without affecting the targeted performance. An optical component, known as passive WDM coupler is used to combine both wavelength into a fiber optic at central office (CO) and to separate them in optical line terminal (OLT). PON technology progress indicates that WDM is a better option to be adopted, therefore recent research interest on WDM-PON technology as evident [65-70].

Research studies based on WDM technology for upgrading fiber optic capacity usage by increasing wavelength channel used is tremendous [71-80]. The highest capacity reported so far is 101.7 Tbit/s with 370 WDM channels in C- and L-bands using PDM-128QAM-OFDM at 294 Gbit/s per channel and 25 GHz spacing[13]. 432 WDM channels and 25GHz channel spacing are latest achievable WDM transmission in C- and L-bands using PDM 16-QAM with 171.2 Gbit/s per channel that yield 69.1 Tbit/s capacity [12].

Besides the progress in WDM system, there are several issues need to be considered when dealing with WDM technique. Note that, each WDM channel requires individual components as single channel. Thus the management of component has become more critical compared to TDM system [44]. Nonlinearity effect, such as Four Wave Mixing (FWM) degrades the performance of WDM system seriously when the dispersion-shifted fiber is deployed [81-85]. Others nonlinearity impairment including Stimulated Raman Scattering (SRS) [86, 87] and Cross Phase Modulation (XPM) [88, 89] have been reported as sources of problem in WDM system.

2.3.4. Polarization Division Multiplexing (PDM)

In the inspiration toward the high spectral efficiency of high capacity optical transmission system, polarization of optical signal is a promising key parameter that has been intensively studied as a multiplexing technique. Besides PDM, other acronym has been used such as POLMUX (Polarization Multiplexing) [90] or PolDM (Polarization Division Multiplex) [14].

Note that, electric field orientation or polarization state is a fundamental property of light. This property can be exploited in optical communication as modulation or multiplexing technique similar to time, frequency and wavelength. Polarization shift keying (PolSK) is a modulation technique, in which the state of polarization (SOP) of optical signal is being used to represent a symbol for transmission in free space or fiber optic channel.

In PDM system, two signals are transmitted at the same wavelength with orthogonal SOP. In order to multiplexed and demultiplexed both SOP, polarization beam splitter (PBS) is required at transmitter and receiver. The main drawback of PDM is due to the polarization mode dispersion (PMD) related impairment [90-92].

This impairment reduces the PMD tolerance of the single channel system and furthermore reduces the nonlinear tolerance in the case of WDM transmission, through XPM induced cross polarization modulation. Besides that, the complexity of the system increase with additional optical component such as PBS.

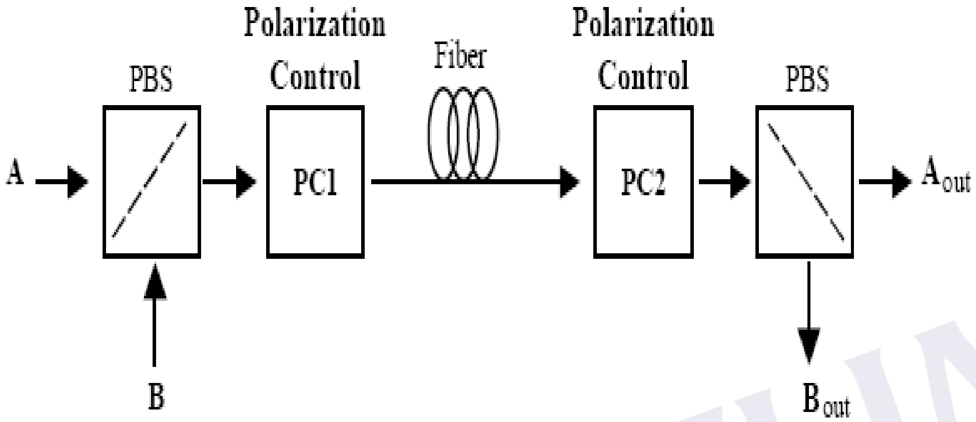

Figure 2.6: PDM technique [91]

2.3.5. Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is another latest technique in optical system. Currently, this technique is widely deployed in broadband wired and radio frequency (RF) based wireless communication. In OFDM, the digital information is converted as multiple lower rate subcarriers. The interest of OFDM in optical system is related with the advancement of digital signal processing (DSP) technology. DSP technology is required for efficiently implementing inverse fast Fourier transform (IFFT) and fast Fourier transform (FFT). OFDM requires digital-to-analog converter (DAC) at transmitter and analog-to-digital converter (ADC) at receiver. Figure 2.7 shows the coherent optical OFDM (CO-OFDM) system. Generally, OFDM has two fundamental advantages which are; robust to channel dispersion, and ease of phase and channel estimation in a time-varying environment. However, OFDM also has its intrinsic disadvantages, such as high peak-to-average power ratio (PAPR) and sensitivity to frequency and phase noise[93]. On top of that, the operation speed of electronic devices such as DAC/ADC and modulator drivers limits the channel line rate [94].

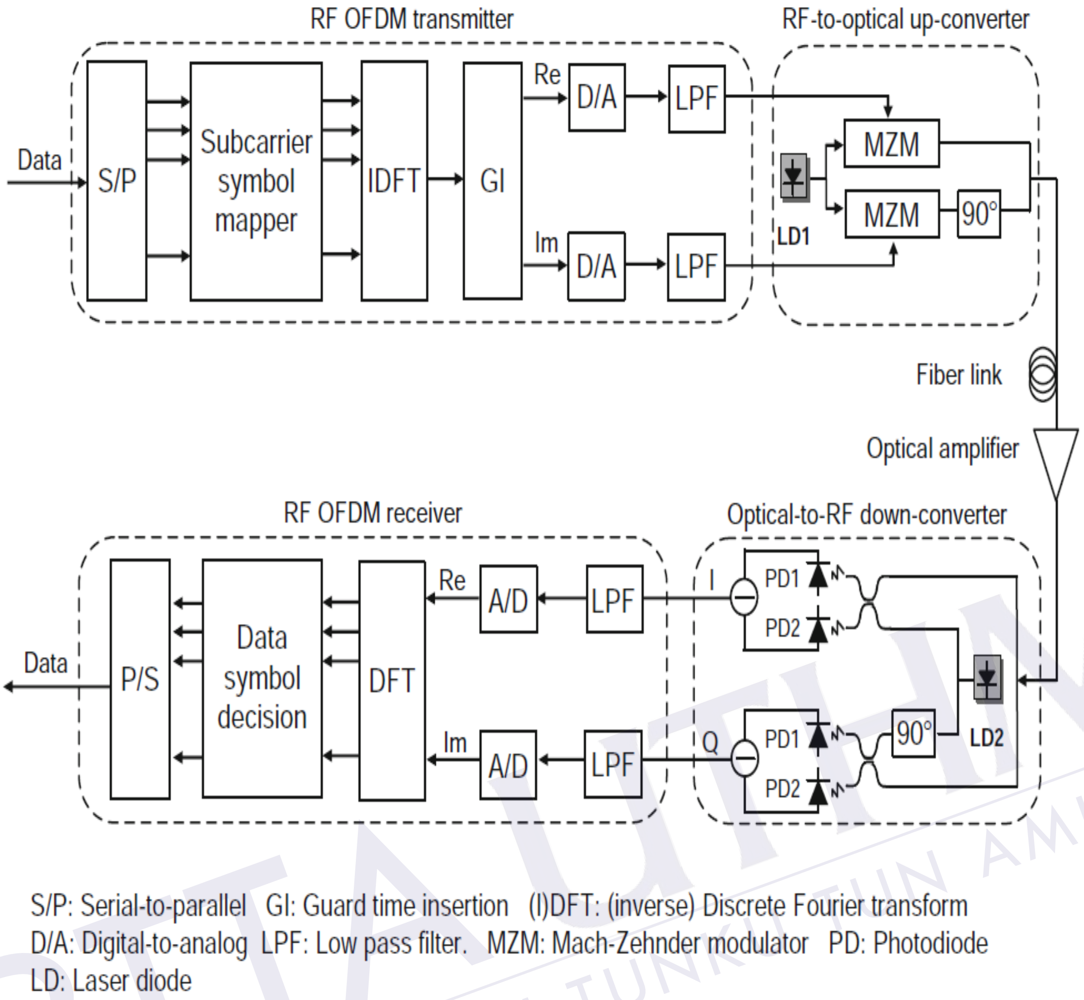

Figure 2.7: CO-OFDM system [93]

2.3.6. Duty Cycle Division Multiplexing (DCDM)

DCDM is a new multiplexing technique that has been proposed in 2007 as an alternative to TDM by Abdullah [33]. In this technique, several user or tributary are multiplexed as a symbol by exploiting RZ signal properties. In order to generate unique symbol for all possible data from each user, RZ conversion are applied with the predefined duty cycle for each user before the signal is combined together. This technique assumes that the data from each user are synchronized and identical amplitude with NRZ line code. The duty cycle of RZ conversion is based on the time duration over symbol duration, T_s. The duty cycle for i^{th} user is given by

$$Tdc_i = \frac{i \times T_S}{n+1} \tag{2. 1}$$

REFERENCES

[1] Cisco Visual Networking Index: Forecast and Methodology 2012–2017 (White Paper). 2013.

[2] R. Ramaswami and K. N. Sivarajan. OpticaI Networks: A Practical Perspective. 2nd ed. San Francisco: Morgan Kaufmann. 2002.

[3] M. Bass and E. W. V. Stryland. Fiber optics handbook: Fiber, devices, and systems for optical communications. New York: McGraw-hill. 2002.

[4] G. Keiser. Opitical Communications Essentials. New York: McGraw-Hill. 2003

[5] G. P. Agrawal. Fiber-Optic Communication Systems. 3rd ed. New York: John Wiley & Sons. 2002.

[6] J. Sinsky and P. Winzer. 100-Gb/s optical communications. *Microwave Magazine, IEEE*. 2009. 10(2): 44-57.

[7] C. Cole. Beyond 100G client optics. *IEEE Communications Magazine*. 2012. 50(2): s58-s66.

[8] P. J. Winzer and R.-J. Essiambre. Advanced optical modulation formats. in: I. P. Kaminow, T. Li, and A. E. Willner. *Optical Fiber Telecommunications V B : Systems and Networks*. Amsterdam: Elsevier. 2008.

[9] P. J. Winzer, G. Raybon, C. R. Doerr, M. Duelk, and C. Dorrer. 107-Gb/s optical signal generation using electronic time-division multiplexing. *Lightwave Technology, Journal of*. 2006. 24(8): 3107-3113.

[10] E. Lach and K. Schuh. Recent Advances in Ultrahigh Bit Rate ETDM Transmission Systems. *Lightwave Technology, Journal of*. 2006. 24(12): 4455-4467.

[11] B. Mukherjee. Optical WDM Networks. New York: Springer. 2006.

[12] A. Sano, H. Masuda, T. Kobayashi, M. Fujiwara, K. Horikoshi, E. Yoshida, Y. Miyamoto, M. Matsui, M. Mizoguchi, H. Yamazaki, Y. Sakamaki, and H.

Ishii. Ultra-High Capacity WDM Transmission Using Spectrally-Efficient PDM 16-QAM Modulation and C- and Extended L-Band Wideband Optical Amplification. *Lightwave Technology, Journal of*. 2011. 29(4): 578-586.

[13] Q. Dayou, H. Ming-Fang, E. Ip, H. Yue-Kai, S. Yin, H. Junqiang, and W. Ting. High Capacity/Spectral Efficiency 101.7-Tb/s WDM Transmission Using PDM-128QAM-OFDM Over 165-km SSMF Within C- and L-Bands. *Lightwave Technology, Journal of*. 2012. 30(10): 1540-1548.

[14] S. Hinz, D. Sandel, F. Wuest, and R. Noe. PMD tolerance of polarization division multiplex transmission using return-to-zero coding. *Opt. Express*. 2001. 9(3): 136-140.

[15] A. J. Lowery, D. Liang Bangyuan, and J. Armstrong. Performance of Optical OFDM in Ultralong-Haul WDM Lightwave Systems. *Lightwave Technology, Journal of*. 2007. 25(1): 131-138.

[16] A. Barbieri, G. Colavolpe, T. Foggi, E. Forestieri, and G. Prati. OFDM versus Single-Carrier Transmission for 100 Gbps Optical Communication. *Journal of Lightwave Technology* 2010. 28(17): 2537-2551.

[17] G. Li. Recent advances in coherent optical communication. *Advances in Optics and Photonics*. 2009. 1(2): 279-307.

[18] D. v. d. Borne, S. L. Jansen, E. Gottwald, E. D. Schmidt, G. D. Khoe, and H. d. Waardt. DQPSK modulation for robust optical transmission. *Optical Fiber Communication Conference (OFC)*. San Diego, California. Feb. 2008.

[19] S. Walklin and J. Conradi. Multilevel Signaling for Increasing the Reach of 10 Gb/s Lightwave Systems. *Journal of Lightwave Technology*. 1999. 17(11): 2235-2248.

[20] J. M. Kahn and K.-P. Ho. Spectral efficiency limits and modulation/detection techniques for DWDM systems. *Quantum Electronics*. Mar. 2004. 10(2): 259 - 272

[21] A. F. Abas, A. Hidayat, D. Sandel, B. Milivojevic, and R. Noe. 100 km fiber span in 292 km, 2.38 Tb/s (16 ×160 Gb/s) WDM DQPSK polarization division multiplex transmission experiment without Raman amplification. *Optical Fiber Technology*. 2007. 13(46-50.

[22] L. Christen, I. Fazal, O. F. Yilmaz, X. Wu, S. Nuccio, A. E. Willner, C. Langrock, and M. M. Fejer. Tunable 105-ns Optical Delay for 80-Gbit/s RZ-DQPSK, 40-Gbit/s RZ-DPSK, and 40-Gbit/s RZ-OOK Signals using

Wavelength Conversion and Chromatic Dispersion. *Conference on Optical Fiber communication/National Fiber Optic Engineers Conference, OFC/NFOEC* 2008.

[23] H. Song, A. Adamiecki, P. J. Winzer, C. Woodworth, S. Corteselli, and G. Raybon. Multiplexing and DQPSK Precoding of 10.7-Gb/s Client Signals to 107 Gb/s Using an FPGA. *Conference on Optical Fiber communication/National Fiber Optic Engineers Conference, OFC/NFOEC* San Diego, CA. 2008.

[24] N. Kikuchi. Intersymbol Interference (ISI) Suppression Technique for Optical Binary and Multilevel Signal Generation. *Journal of Lightwave Technology*. Aug. 2007. 25(8): 2060 - 2068.

[25] A. H. Gnauck, G. Charlet, P. Tran, P. J. Winzer, C. R. Doerr, J. C. Centanni, E. C. Burrows, T. Kawanishi, T. Sakamoto, and K. Higuma. 25.6-Tb/s WDM Transmission of Polarization-Multiplexed RZ-DQPSK Signals. *Journal Of Lightwave Technology*. Jan. 2008. 26(1): 79-84.

[26] N. Kikuchi and S. Sasaki. Highly Sensitive Optical Multilevel Transmission of Arbitrary Quadrature-Amplitude Modulation (QAM) Signals With Direct Detection. *Journal of Lightwave Technology*. Jan. 2010. 28(1): 123-130.

[27] Y. Mori, C. Zhang, K. Igarashi, K. Katoh, and K. Kikuchi. Unrepeated 200-km transmission of 40-Gbit/s 16-QAM signals using digital coherent receiver. *Optics Express*. Feb. 2009. 17(3): 1435-1441.

[28] A. P. T. Lau and J. M. Kahn. 16-QAM Signal Design and Detection in Presence of Nonlinear Phase Noise. *Digest of the IEEE LEOS Summer Topical Meetings, 2007*. Portland, OR. Jul. 2007.

[29] D. Annika, A.-D. Majed Omar, and R. Werner. Optimization of Cost Efficient Multilevel-ASK Modulation Formats under the Constraint of Chromatic Dispersion. *Optical Fiber Communication Conference*. 2010.

[30] K. Szczerba, P. Westbergh, J. Karout, J. Gustavsson, Å. Haglund, M. Karlsson, P. Andrekson, E. Agrell, and A. Larsson. 30 Gbps 4-PAM transmission over 200 m of MMF using an 850 nm VCSEL. *Opt. Express*. 2011. 19(26): 203-208.

[31] H. G. Batshon, I. B. Djordjevic, and B. V. Vasic. An Improved Technique for Suppression of Intrachannel Four-Wave Mixing in 40-Gb/s Optical

Transmission Systems. *IEEE Photonics Technology Letters*. 2007. 19(2): 67-69.

[32] M. K. Abdullah, M. F. Abdalla, A. F. Abas, and G. Amouzad. Duty-cycle Division Multiplexing (DCDM): A Novel and Economical Optical Multiplexing and Electrical Demultiplexing technique for High Speed Fiber Optics Networks. *IFIP International Conference on Wireless and Optical Communications Networks (WOCN)*. Singapore. 2007.

[33] M. K. Abdullah, G. A. Mahdiraji, and M. F. Elhag. A new duty cycle based digital multiplexing technique. *IEEE International Conference on Telecommunications and Malaysia International Conference on Communications. ICT-MICC* Penang. 2007.

[34] G. A. Mahdiraji, M. K. Abdullah, M. Mokhtar, A. Malekmohammadi, and A. F. Abas. Duty-cycle-division-multiplexing: Bit error rate estimation and performance evaluation *Journal Optical Review* 2009. 16(4): 422-425

[35] G. A. Mahdiraji, A. Malekmohammadi, A. F. Abas, M. Mokhtar, and M. K. Abdullah. A novel economical duty cycle division multiplexing with electrical multiplexer and demultiplexer for optical communication systems. *International Journal of Information and Communication Technology* 2009. 2(1-2): 31 - 40

[36] G. A. Mahdiraji, M. K. Abdullah, A. M. Mohammadi, A. F. Abas, M. Mokhtar, and E. Zahedi. Duty-cycle division multiplexing (DCDM). *Optics & Laser Technology*. 2010. 42(2): 289-295.

[37] A. Malekmohammadi, G. A. Mahdiraji, A. F. Abas, M. K. Abdullah, M. Mokhtar, M. Fadlee, and A. Rasid. Performance analysis on transmission of multilevel optical pulses using Absolute Polar Duty Cycle Division multiplexing. *Electronic Design, 2008. ICED 2008. International Conference on*. 2008.

[38] A. Malekmohammadi, G. A. Mahdiraji, A. F. Abas, M. K. Abdullah, M. Mokhtar, and M. F. A. Rasid. Realization of high capacity transmission in fiber optic communication systems using Absolute Polar Duty Cycle Division Multiplexing (AP-DCDM) technique. *Optical Fiber Technology*. 2009. 15(4): 337-343.

[39] A. Malekmohammadi, G. A. Mahdiraji, A. F. Abas, M. K. Abdullah, M. Mokhtar, and M. F. A. Rasid. Effect of self-phase-modulation on dispersion

compensated absolute polar duty cycle division multiplexing transmission. *Optoelectronics, IET*. 2009. 3(5): 207-214.

[40] A. Malekmohammadi, M. H. Al-Mansoori, G. A. Mahdiraji, A. F. Abas, and M. K. Abdullah. Performance enhancement of Absolute Polar Duty Cycle Division Multiplexing with Dual-Drive Mach-Zehnder-Modulator in 40 Gbit/s optical fiber communication systems. *Optics Communications*. 2010. 283(16): 3145-3148.

[41] A. Malekmohammadi, A. F. Abas, M. K. Abdullah, G. A. Mahdiraji, M. Mokhtar, and M. F. A. Rasid. Absolute polar duty cycle division multiplexing over wavelength division multiplexing system. *Optics Communications*. 2009. 282(21): 4233-4241.

[42] A. Malekmohammadi, M. K. Abdullah, G. A. Mahdiraji, A. F. Abas, M. Mokhtar, M. F. A. Rasid, and S. M. Basir. Analysis of return-to-zero-on-off-keying over absolute polar duty cycle division multiplexing in dispersive transmission medium. *Optoelectronics, IET*. 2009. 3(4): 197-206.

[43] *IEEE 802.3ba Part 3: Carrier Sense Multiple Access with Collision Detection (CSMA/CD) Access Method and Physical Layer Specifications*. 2010.

[44] Y. Miyamoto, M. Yoneyama, T. Otsuji, K. Yonenaga, and N. Shimizu. 40-Gbit/s TDM transmission technologies based on ultra-high-speed ICs. *Solid-State Circuits, IEEE Journal of*. 1999. 34(9): 1246-1253.

[45] M. Hitoshi, K. Masatoshi, T. Hiromi, and F. Kozo. EA-Modulator-Based Optical Time Division Multiplexing/Demultiplexing Techniques for 160-Gb/s Optical Signal Transmission. *Selected Topics in Quantum Electronics, IEEE Journal of*. 2007. 13(1): 70-78.

[46] C. Schubert, R. H. Derksen, M. Moller, R. Ludwig, C. J. Weiske, J. Lutz, S. Ferber, A. Kirstadter, G. Lehmann, and C. Schmidt-Langhorst. Integrated 100-Gb/s ETDM Receiver. *Lightwave Technology, Journal of*. 2007. 25(1): 122-130.

[47] R. Ludwig, C. Schubert, B. Huettl, C. Schmidt-Langhorst, R. H. Derksen, and M. Moller. 100 Gb/s ETDM Receivers. *The 20th Annual Meeting of the IEEE Lasers and Electro-Optics Society, 2007. LEOS 2007*. 2007.

[48] P. van der Wagt, T. Broekaert, S. Yinger, S. Zheng, N. Srivastava, J. Rogers, J. Sanders, R. Thiagarajah, R. Coccioli, E. Arnold, and K. Nary. 50Gb/s 3.3V

logic ICs in InP-HBT technology. *Symposium on VLSI Circuits, Digest of Technical Papers.* Year. 326-329.

[49] S. Bregni. Synchronization of Digital Telecommunications Networks. Chichester: John Wiley. 2002.

[50] T. E. Darcie. Subcarrier multiplexing for lightwave networks and video distribution systems. *IEEE Journal on Selected Areas in Communications*. 1990. 8(7): 1240-1248.

[51] T. E. Darcie, P. P. Iannone, B. L. Kasper, J. R. Talman, C. A. Burrus, Jr., and T. A. Baker, Sr. Wide-band lightwave distribution system using subcarrier multiplexing. *Lightwave Technology, Journal of*. 1989. 7(6): 997-1005.

[52] R. Gross and R. Olshansky. Performance evaluation of digital and analogue video distribution systems using coherent subcarrier multiplexing. *Electronics Letters*. 1989. 25(25): 1699-1701.

[53] A. A. M. Saleh. Fundamental limit on number of channels in subcarrier-multiplexed lightwave CATV system. *Electronics Letters*. 1989. 25(12): 776-777.

[54] R. Olshansky and V. A. Lanzisera. 60-channel FM video subcarrier multiplexed optical communication system. *Electronics Letters*. 1987. 23(22): 1196-1198.

[55] T. E. Darcie, M. E. Dixon, B. L. Kasper, and C. A. Burrus. Lightwave system using microwave subcarrier multiplexing. *Electronics Letters*. 1986. 22(15): 774-775.

[56] R. Hui, B. Zhu, R. Huang, C. T. Allen, K. R. Demarest, and D. Richards. Subcarrier Multiplexing for High-Speed Optical Transmission. *Journal Of Lightwave Technology* 2002. 20(3): 417-.

[57] K. Kim, J. Lee, and J. Jeong. Performance limitations of subcarrier multiplexed WDM signal transmissions using QAM modulation. *Journal of Lightwave Technology*. 2009. 27(18): 4105-4111.

[58] O. E. DeLange. Wide-band optical communication systems: Part II—Frequency-division multiplexing. *Proceedings of the IEEE*. 1970. 58(10): 1683 - 1690.

[59] G. Keiser. FTTX Concepts and Applications. Hoboken, New Jersey: John Wiley & Sons. 2006.

[60] ITU-T. *Optical interfaces for multichannel systems with optical amplifiers*. Recommendation G.692. 1998.

[61] ITU-T. *Dense Wavelength Division Multiplexing (DWDM)*. Recommendation G.694.1. 2002.

[62] ITU-T. *Coarse Wavelength Division Multiplexing (CWDM)*. Recommendation G.694.2. 2002.

[63] B. Mukherjee. WDM Optical Communication Networks: Progress and Challenges. *IEEE Journal Selected Areas in Comm*. 2000. 18(10): 1810-1824.

[64] G. Kramer, M. De Andrade, R. Roy, and P. Chowdhury. Evolution of Optical Access Networks: Architectures and Capacity Upgrades. *Proceedings of the IEEE*. 2012. 100(5): 1188-1196.

[65] J. i. Kani, F. Bourgart, A. Cui, A. Rafel, M. Campbell, R. Davey, and S. Rodrigues. Next-generation PON-part I: Technology roadmap and general requirements. *Communications Magazine, IEEE*. 2009. 47(11): 43-49.

[66] B. Skubic, C. Jiajia, J. Ahmed, L. Wosinska, and B. Mukherjee. A comparison of dynamic bandwidth allocation for EPON, GPON, and next-generation TDM PON. *Communications Magazine, IEEE*. 2009. 47(3): S40-S48.

[67] A. Chowdhury, C. Hung-Chang, H. Ming-Fang, Y. Jianjun, and C. Gee-Kung. Rayleigh Backscattering Noise-Eliminated 115-km Long-Reach Bidirectional Centralized WDM-PON With 10-Gb/s DPSK Downstream and Remodulated 2.5-Gb/s OCS-SCM Upstream Signal. *Photonics Technology Letters, IEEE*. 2008. 20(24): 2081-2083.

[68] Y. Jianjun, H. Ming-Fang, Q. Dayou, C. Lin, and C. Gee-Kung. Centralized Lightwave WDM-PON Employing 16-QAM Intensity Modulated OFDM Downstream and OOK Modulated Upstream Signals. *Photonics Technology Letters, IEEE*. 2008. 20(18): 1545-1547.

[69] K. M. Choi, S. M. Lee, M. H. Kim, and C. H. Lee. An Efficient Evolution Method From TDM-PON to Next-Generation PON. *Photonics Technology Letters, IEEE*. 2007. 19(9): 647-649.

[70] O. Akanbi, Y. Jianjun, and C. Gee-Kung. A new scheme for bidirectional WDM-PON using upstream and downstream channels generated by optical

carrier suppression and separation technique. *Photonics Technology Letters, IEEE*. 2006. 18(2): 340-342.

[71] S. Bigo, A. Bertaina, M. W. Chbat, S. Gurib, J. Da Loura, J.-C. Jacquinot, J. Hervo, P. Bousselet, S. Borne, D. Bayart, L. Gasca, and J.-L. Beylat. 320-Gb/s (32×10 Gb/s WDM) transmission over 500 km of conventional single-mode fiber with 125-km amplifier spacing. *Photonics Technology Letters, IEEE*. 1998. 10(7): 1045 - 1047.

[72] H. Suzuki, J. I. Kani, H. Masuda, N. Takachio, K. Iwatsuki, Y. Tada, and M. Sumida. 1-Tb/s (100 x 10 Gb/s) super-dense WDM transmission with 25-GHz channel spacing in the zero-dispersion region employing distributed Raman amplification technology. *Photonics Technology Letters, IEEE*. 2000. 12(7): 903-905.

[73] Y. Inada, H. Sugahara, K. Fukuchi, T. Ogata, and Y. Aoki. 32 × 40-Gb/s dense WDM transmission over 3000 km using "double-hybrid" fiber configuration. *Photonics Technology Letters, IEEE*. 2002. 14(9): 1366 - 1368.

[74] Y. Miyamoto, H. Masuda, A. Hirano, S. Kuwahara, Y. Kisaka, H. Kawakami, M. Tomizawa, Y. Tada, and S. Aozasa. S-band WDM coherent transmission of 40x43-Gbit/s CS-RZ DPSK signals over 400 km DSF using hybrid GS-TDFAs/Raman amplifiers. *Electronics Letters*. 2002. 38(24): 1569-1570.

[75] T. Ohara, H. Takara, T. Yamamoto, H. Masuda, T. Morioka, M. Abe, and H. Takahashi. Over-1000-channel ultradense WDM transmission with supercontinuum multicarrier source. *Lightwave Technology, Journal of*. 2006. 24(6): 2311-2317.

[76] A. H. Gnauck, G. Charlet, P. Tran, P. J. Winzer, C. R. Doerr, J. C. Centanni, E. C. Burrows, T. Kawanishi, T. Sakamoto, and K. Higuma. 25.6-Tb/s WDM Transmission of Polarization-Multiplexed RZ-DQPSK Signals. *Journal Of Lightwave Technology*. 2008. 26(1): 79-84.

[77] Y. Jianjun, D. Ze, C. Hung-Chang, S. Yufeng, and C. Nan. 7-Tb/s (7x1.284Tb/s/ch) Signal Transmission Over 320 km Using PDM-64QAM Modulation. *Photonics Technology Letters, IEEE*. 2012. 24(4): 264-266.

[78] C. Jin-Xing, C. R. Davidson, A. Lucero, Z. Hongbin, D. G. Foursa, O. V. Sinkin, W. W. Patterson, A. N. Pilipetskii, G. Mohs, and N. S. Bergano. 20

Tbit/s Transmission Over 6860 km With Sub-Nyquist Channel Spacing. *Lightwave Technology, Journal of*. 2012. 30(4): 651-657.

[79] C. Jin-Xing, C. Yi, C. R. Davidson, D. G. Foursa, A. Lucero, O. Sinkin, W. Patterson, A. Pilipetskii, G. Mohs, and N. S. Bergano. Transmission of 96x100-Gb/s Bandwidth-Constrained PDM-RZ-QPSK Channels With 300% Spectral Efficiency Over 10610 km and 400% Spectral Efficiency Over 4370 km. *Lightwave Technology, Journal of*. 2011. 29(4): 491-498.

[80] Z. Xiang, L. E. Nelson, P. Magill, R. Isaac, Z. Benyuan, D. W. Peckham, P. I. Borel, and K. Carlson. PDM-Nyquist-32QAM for 450-Gb/s Per-Channel WDM Transmission on the 50 GHz ITU-T Grid. *Lightwave Technology, Journal of*. 2012. 30(4): 553-559.

[81] D. Marcuse, A. R. Chraplyvy, and R. W. Tkach. Effect of fiber nonlinearity on long-distance transmission. *Lightwave Technology, Journal of*. 1991. 9(1): 121-128.

[82] E. Mateo, L. Zhu, and G. Li. Impact of XPM and FWM on the digital implementation of impairment compensation for WDM transmission using backward propagation. *Opt. Express*. 2008. 16(20): 16124-16137.

[83] R. Randhawa, J. S. Sohal, and R. S. Kaler. Optimum algorithm for WDM channel allocation for reducing four-wave mixing effects. *Optik - International Journal for Light and Electron Optics*. 2009. 120(17): 898-904.

[84] S. Ten, K. M. Ennser, J. M. Grochocinski, S. P. Burtsev, and V. L. da Silva. Comparison of four-wave mixing and cross phase modulation penalties in dense WDM systems. *Optical Fiber Communication Conference and the International Conference on Integrated Optics and Optical Fiber Communication (OFC/IOOC)*. 1999.

[85] S. Betti, M. Giaconi, and M. Nardini. Effect of four-wave mixing on WDM optical systems: a statistical analysis. *Photonics Technology Letters, IEEE*. 2003. 15(8): 1079-1081.

[86] A. R. Chraplyvy and P. S. Henry. Performance degradation due to stimulated Raman scattering in wavelength-division-multiplexed optical-fibre systems. *Electronics Letters*. 1983. 19(16): 641-643.

[87] S. Bigo, S. Gauchard, A. Bertaina, and J. P. Hamaide. Experimental investigation of stimulated Raman scattering limitation on WDM

transmission over various types of fiber infrastructures. *Photonics Technology Letters, IEEE*. 1999. 11(6): 671-673.

[88] D. Marcuse, A. R. Chraplyvy, and R. W. Tkach. Dependence of cross-phase modulation on channel number in fiber WDM systems. *Lightwave Technology, Journal of*. 1994. 12(5): 885-890.

[89] H. Rongqing, K. R. Demarest, and C. T. Allen. Cross-phase modulation in multispan WDM optical fiber systems. *Lightwave Technology, Journal of*. 1999. 17(6): 1018-1026.

[90] D. van den Borne, N. E. Hecker-Denschlag, G. D. Khoe, and H. de Waardt. PMD-induced transmission penalties in polarization-multiplexed transmission. *Lightwave Technology, Journal of*. 2005. 23(12): 4004-4015.

[91] L. Nelson and H. Kogelnik. Coherent crosstalk impairments in polarization multiplexed transmission due to polarization mode dispersion. *Opt. Express*. 2000. 7(10): 350-361.

[92] D. van den Borne, S. L. Jansen, E. Gottwald, P. M. Krummrich, G. D. Khoe, and H. de Waardt. 1.6-b/s/Hz Spectrally Efficient Transmission Over 1700 km of SSMF Using 40 x 85.6-Gb/s POLMUX-RZ-DQPSK. *Lightwave Technology, Journal of*. 2007. 25(1): 222-232.

[93] W. Shieh and I. Djordjevic. OFDM for Optical Communications. Burlington, MA: Academic Press. 2010.

[94] A. Sano, E. Yamada, H. Masuda, E. Yamazaki, T. Kobayashi, E. Yoshida, Y. Miyamoto, R. Kudo, K. Ishihara, and Y. Takatori. No-Guard-Interval Coherent Optical OFDM for 100-Gb/s Long-Haul WDM Transmission. *Lightwave Technology, Journal of*. 2009. 27(16): 3705-3713.

[95] G. A. Mahdiraji. *Performance Analysis of Duty-Cycle Division Multiplexing for Optical Fiber Communication Systems*. Universiti Putra Malaysia; 2009

[96] A. Malekmohammadi. *Absolute Polar Duty Cycle Division Multiplexing for High-Speed Fiber Optic Communication System*. Universiti Putra Malaysia; 2009

[97] E. Sackinger. Broadband Circuits for Optical Fiber Communication. 1st ed. New Jersey: John Wiley & Sons. 2005.

[98] M. I. Hayee and A. E. Willner. NRZ versus RZ in 10-40-Gb/s dispersion-managed WDM transmission systems. *Photonics Technology Letters, IEEE*. 1999. 11(8): 991-993.

[99] D. Breuer and K. Petermann. Comparison of NRZ- and RZ-modulation format for 40-Gb/s TDM standard-fiber systems. *Photonics Technology Letters*. 1997. 9(3): 398 - 400

[100] C. Caspar, H.-M. Foisel, A. Gladisch, N. Hanik, F. Kuppers, R. Ludwig, A. Mattheus, W. Pieper, B. Strebel, and H. G. Weber. RZ versus NRZ modulation format for dispersion compensated SMF-based 10-Gb/s transmission with more than 100-km amplifier spacing. *Photonics Technology Letters*. 1999. 11(4): :481 - 483

[101] R. Ludwig, U. Feiste, E. Dietrich, H. G. Weber, D. Breuer, M. Martin, and F. Küppers. Experimental comparison of 40 Gbit/s RZ and NRZ transmission over standard singlemode fibre. *Electronics Letters*. 1999. 35(25): 2216-2218.

[102] R. A. Griffin, R. G. Walker, R. I. Johnstone, R. Harris, N. M. B. Perney, N. D. Whitbread, T. Widdowson, and P. Harper. Integrated 10 Gb/s chirped return-to-zero transmitter using GaAs-AlGaAs modulators. *Optical Fiber Communication Conference and Exhibit, 2001. OFC 2001*. 2001.

[103] H. Suche, A. Greiner, W. Qiu, R. Wessel, and W. Sohler. Integrated optical Ti:Er:LiNbO$_3$ soliton source. *Quantum Electronics, IEEE Journal of*. 1997. 33(10): 1642-1646.

[104] N. M. Froberg, G. Raybon, U. Koren, B. I. Miller, M. G. Young, M. Chien, G. T. Harvey, A. Gnauck, and A. M. Johnson. Generation of 2.5 Gbit/s soliton data stream with an integrated laser-modulator transmitter. *Electronics Letters*. 1994. 30(22): 1880-1881.

[105] J. J. Veselka, S. K. Korotky, P. V. Mamyshev, A. H. Gnauck, G. Raybon, and N. M. Froberg. A soliton transmitter using a CW laser and an NRZ driven Mach-Zehnder modulator. *Photonics Technology Letters, IEEE*. 1996. 8(7): 950-952.

[106] B. Schwanke and K. Nellis. ELECTRONIC PRODUCTS:NRZ-to-RZ data conversion using high-speed OR/AND; Fast Gbit/s gates provide straightforward solutions. Inphi. Westlake Village, CA 2009.

[107] K. S. Cheng and J. Conradi. Reduction of pulse-to-pulse interaction using alternative RZ formats in 40-Gb/s systems. *Photonics Technology Letters, IEEE*. 2002. 14(1): 98-100.

[108] A. Lender. Correlative Digital Communication Techniques. *Communication Technology, IEEE Transactions on*. 1964. 12(4): 128-135.

[109] P. J. Winzer and R. J. Essiambre. Advanced Modulation Formats for High-Capacity Optical Transport Networks. *Lightwave Technology, Journal of*. 2006. 24(12): 4711-4728.

[110] A. Tan and E. Pincemin. Performance Comparison of Duobinary Formats for 40-Gb/s and Mixed 10/40-Gb/s Long-Haul WDM Transmission on SSMF and LEAF Fibers. *Lightwave Technology, Journal of*. 2009. 27(4): 396-408.

[111] P. J. Winzer. Optical Transmitters, Receivers, and Noise. in: *Wiley Encyclopedia of Telecommunications*: John Wiley & Sons, Inc. 2003.

[112] A. H. Gnauck and P. J. Winzer. Optical Phase-Shift-Keyed Transmission. *Journal Of Lightwave Technology*. 2005. 23(1): 115-130.

[113] K. Hoon and P. J. Winzer. Robustness to laser frequency offset in direct-detection DPSK and DQPSK systems. *Lightwave Technology, Journal of*. 2003. 21(9): 1887-1891.

[114] G. Kramer, A. Ashikhmin, A. J. van Wijngaarden, and W. Xing. Spectral efficiency of coded phase-shift keying for fiber-optic communication. *Lightwave Technology, Journal of*. 2003. 21(10): 2438-2445.

[115] N. Avlonitis, E. M. Yeatman, M. Jones, and A. Hadjifotiou. Multilevel amplitude shift keying in dispersion uncompensated optical systems. *Optoelectronics, IEE Proceedings* -. 2006. 153(3): 101-108.

[116] J. E. Cunningham, D. Beckman, X. Zheng, D. Huang, T. Sze, and A. V.Krishnamoorthy. PAM-4 Signaling over VCSELs with 0.13µm CMOS Chip Technology. *OSA*. 2006. 14(25): 12028-12038.

[117] R. Rodes, M. Mueller, B. Li, J. Estaran, J. B. Jensen, T. Gruendl, M. Ortsiefer, C. Neumeyr, J. Rosskopf, K. J. Larsen, M. Amann, and I. T. Monroy. High-Speed 1550 nm VCSEL Data Transmission Link Employing 25 GBd 4-PAM Modulation and Hard Decision Forward Error Correction. *Journal of Lightwave Technology*. 2013. 31(4): 689-695.

[118] Y. Mori, C. Zhang, K. Igarashi, K. Katoh, and K. Kikuchi. Unrepeated 200-km transmission of 40-Gbit/s 16-QAM signals using digital coherent receiver. *Optics Express*. 2009. 17(3): 1435-1441.

[119] P. J. Winzer, A. H. Gnauck, C. R. Doerr, M. Magarini, and L. L. Buhl. Spectrally Efficient Long-Haul Optical Networking Using 112-Gb/s

Polarization-Multiplexed 16-QAM. *Journal of Lightwave Technology*. 2010. 28(4): 547-556.

[120] A. H. Gnauck, P. J. Winzer, A. Konczykowska, F. Jorge, J. Dupuy, M. Riet, G. Charlet, B. Zhu, and D. W. Peckham. Generation and Transmission of 21.4-Gbaud PDM 64-QAM Using a Novel High-Power DAC Driving a Single I/Q Modulator. *Lightwave Technology, Journal of*. 2012. 30(4): 532-536.

[121] G. Raybon, A. L. Adamiecki, S. Randel, C. Schmidt, P. J. Winzer, A. Konczykowska, F. Jorge, J. Dupuy, L. L. Buhl, S. Chandrasekhar, L. Xiang, A. H. Gnauck, C. Scholz, and R. Delbue. All-ETDM 80-Gbaud (640-Gb/s) PDM 16-QAM Generation and Coherent Detection. *IEEE Photonics Technology Letters*. 2012. 24(15): 1328-1330.

[122] D. A. Fishman and J. A. Nagel. Degradations due to stimulated Brillouin scattering in multigigabit intensity-modulated fiber-optic systems. *Lightwave Technology, Journal of*. 1993. 11(11): 1721-1728.

[123] R. G. Smith. Optical Power Handling Capacity of Low Loss Optical Fibers as Determined by Stimulated Raman and Brillouin Scattering. *Appl. Opt.* 1972. 11(11): 2489-2494.

[124] X. P. Mao, R. W. Tkach, A. R. Chraplyvy, R. M. Jopson, and R. M. Derosier. Stimulated Brillouin threshold dependence on fiber type and uniformity. *IEEE Photonics Technology Letters*. 1992. 4(1): 66-69.

[125] T. Hirooka, K. Osawa, M. Okazaki, M. Nakazawa, and H. Murai. Stimulated Brillouin Scattering in Ultrahigh-Speed In-Phase RZ and CS-RZ OTDM Transmission. *IEEE Photonics Technology Letters*. 2008. 20(20): 1694-1696.

[126] J. Toulouse. Optical nonlinearities in fibers: review, recent examples, and systems applications. *Journal of Lightwave Technology*. 2005. 23(11): 3625-3641.

[127] L. E. Adams, G. Nykolak, T. Tanbun-Ek, A. J. Stentz, A. M. Sergent, P. F. Sciortino Jr, and L. Eskildsen. SBS suppression using a multichannel tunable laser with data-encoding capability. *Fiber and Integrated Optics*. 1998. 17(4): 311-316.

[128] A. Sano, Y. Miyamoto, T. Kataoka, H. Kawakami, and K. Hagimoto. 10 Gbit/s, 300 km repeaterless transmission with SBS suppression by the use of the RZ format. *Electronics Letters*. 1994. 30(20): 1694-1695.

[129] Y. Miyamoto, T. Kataoka, A. Sano, K. Hagimoto, K. Aida, and Y. Kobayashi. 10 Gbit/s, 280 km nonrepeatered transmission with suppression of modulation instability. *Electronics Letters*. 1994. 30(10): 797-798.

[130] T. Sakamoto, T. Matsui, K. Shiraki, and T. Kurashima. SBS Suppressed Fiber With Hole-Assisted Structure. *Journal of Lightwave Technology*. 2009. 27(20): 4401-4406.

[131] A. M. Hill, D. Cotter, and J. V. Wright. Nonlinear crosstalk due to stimulated Raman scattering in a two-channel wavelength-division-multiplexed system. *Electronics Letters*. 1984. 20(6): 247-249.

[132] D. Cotter and A. M. Hill. Stimulated Raman crosstalk in optical transmission: effects of group velocity dispersion. *Electronics Letters*. 1984. 20(4): 185-187.

[133] G. P. Agrawal. Nonlinear Fiber Optics. 4th ed. London: Academic Press. 2007.

[134] D. Breuer, H. J. Ehrke, F. Kuppers, R. Ludwig, K. Petermann, H. G. Weber, and K. Weich. Unrepeated 40-Gb/s RZ single-channel transmission at 1.55mm using various fiber types. *IEEE Photonics Technology Letters*. 1998. 10(6): 822-824.

[135] W. C. Kwong and G. C. Yang. Allocation of unequal-spaced channels in WDM lightwave systems. *Electronics Letters*. 1995. 31(11): 898-899.

[136] W. C. Kwong and Y. Gun-Chang. An algebraic approach to the unequal-spaced channel-allocation problem in WDM lightwave systems. *Communications, IEEE Transactions on*. 1997. 45(3): 352-359.

[137] A. Bogoni and L. Poti. Effective channel allocation to reduce inband FWM crosstalk in DWDM transmission systems. *Selected Topics in Quantum Electronics, IEEE Journal of*. 2004. 10(2): 387-392.

[138] R. C. Steele, G. R. Walker, and N. G. Walker. Sensitivity of optically preamplified receivers with optical filtering. *Photonics Technology Letters, IEEE*. 1991. 3(6): 545-547.

[139] M. C. Jeruchim, P. Balaban, and K. S. Shanmugan. Simulation of Communication Systems: Modeling, Methodology, and Techniques. 2nd ed. New York: Kluwer Academic. 2002.

[140] F. Xiong. Digital Modulation Techniques. 2nd ed. Norwood: Artech House. 2006.

[141] B. Razavi. Design of integrated circuit for optical communications. Boston: McGraw-Hill. 2003.

[142] H. Ming-ta and G. Sobelman. Architectures for multi-gigabit wire-linked clock and data recovery. *IEEE Circuits and Systems Magazine*. 2008. 8(4): 45-57.

[143] P. A. Humblet and M. Azizoglu. On the bit error rate of lightwave systems with optical amplifiers. *Lightwave Technology, Journal of*. 1991. 9(11): 1576-1582.

[144] J. G. Proakis and M. Salehi. Digital Communications. 5th ed. New York: McGraw Hill. 2008.

[145] S. G. Wilson. Digital Modulation and Coding. Englewood Cliffs, New Jersey: Prentice-Hall. 1996.

[146] R. Laming, M. N. Zervas, and D. N. Payne. Erbium-doped fiber amplifier with 54 dB gain and 3.1 dB noise figures. *Photonics Technology Letters, IEEE*. 1992. 4(12): 1345-1347.

[147] Y. Miyamoto and S. Suzuki. Advanced optical modulation and multiplexing technologies for high-capacity OTN based on 100 Gb/s channel and beyond. *Communications Magazine, IEEE*. 2010. 48(3): S65-S72.

[148] ITU-T. *Optical transport network physical layer interfaces*. Recommendation G.959.1. 2009.

[149] G. Amouzad Mahdiraji and A. F. Abas. Improving the performance of electrical duty-cycle division multiplexing with optimum signal level spacing. *Optics Communications*. 2012. 285(7): 1819-1824.

[150] Y. Zhou, C. Gan, and L. Zhu. Self-healing ring-based WDM-PON. *Optics Communications*. 2010. 283(9): 1732-1736.

[151] K. Tanizawa and A. Hirose. Performance Analysis of Steepest Descent-Based Feedback Control of Tunable-Dispersion Compensator for Adaptive Dispersion Compensation in All-Optical Dynamic-Routing Networks. *Lightwave Technology, Journal of*. 2007. 25(4): 1086-1094.

[152] V. Roncin, S. Lobo, N. Minh, N. t, L. Bramerie, A. O'Hare, M. Joindot, and J. C. Simon. Patterning Effects in All-Optical Clock Recovery: Novel Analysis Using a Clock Remodulation Technique. *Selected Topics in Quantum Electronics, IEEE Journal of*. 2010. 16(5): 1495-1502.

[153] R. Poboril, J. Latal, P. Koudelka, J. Vitasek, P. Siska, J. Skapa, and V. Vasinek. A Concept of a Hybrid WDM/TDM Topology Using the Fabry-Perot Laser in the Optiwave Simulation Environment. *Advances In Electrical And Electronic Engineering*. 2011. 9(4): 167-178.

[154] T.-C. Liang and S. Hsu. The L-band EDFA of high clamped gain and low noise figure implemented using fiber Bragg grating and double-pass method. *Optics Communications*. 2008. 281(5): 1134-1139.

[155] A. K. Kodi and A. Louri. Multidimensional and Reconfigurable Optical Interconnects for High-Performance Computing (HPC) Systems. *Lightwave Technology, Journal of*. 2009. 27(21): 4634-4641.

[156] X. Haiyun, W. Chao, S. Blais, and Y. Jianping. Ultrafast and Precise Interrogation of Fiber Bragg Grating Sensor Based on Wavelength-to-Time Mapping Incorporating Higher Order Dispersion. *Lightwave Technology, Journal of*. 2010. 28(3): 254-261.

[157] N. Gryspolakis and L. R. Chen. Response of fibre optic parametric amplifiers to channel add/drop in agile all-photonic networks. *Optics Communications*. 2007. 278(1): 168-174.

[158] O. Boukari, L. Hassine, H. Bouchriha, and M. Ketata. Study of dynamic chirp in direct modulated DFB laser for C-OFDR application. *Optics Communications*. 2010. 283(10): 2214-2223.

[159] P. P. Baveja, D. N. Maywar, and G. P. Agrawal. Optimization of All-Optical 2R Regenerators Operating at 40 Gb/s: Role of Dispersion. *Lightwave Technology, Journal of*. 2009. 27(17): 3831-3836.

[160] OptiSystem Component Library: Optical Communication System Design Software Version 9. OptiWave 2010.