UNIVERSITI PUTRA MALAYSIA

ABSOLUTE POLAR DUTY CYCLE DIVISION MULTIPLEXING FOR HIGH-SPEED FIBER OPTIC COMMUNICATION SYSTEM

AMIN MALEKMOHAMMADI

ABSOLUTE POLAR DUTY CYCLE DIVISION MULTIPLEXING FOR HIGH-SPEED FIBER OPTIC COMMUNICATION SYSTEM

By

AMIN MALEKMOHAMMADI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of Requirements for the Degree of Doctor of Philosophy

September 2009

DEDICATION

To my parents who have supported me patiently all the time

Thank you.

Abstract of thesis presented to the Senate of University Putra Malaysia in the fulfilment of the requirement for the degree of Doctor of Philosophy

ABSOLUTE POLAR DUTY CYCLE DIVISION MULTIPLEXING FOR HIGH-SPEED FIBER OPTIC COMMUNICATION SYSTEM

By

AMIN MALEKMOHAMMADI

Date: September 2009

Chairman: Dr.-Ing. Ahmad Fauzi Abas

Faculty: Engineering

Multiplexing is one of the fundamental necessities in today's digital communications. It allows multiple users to share the bandwidth of the transmission medium. In this dissertation a new design of the Duty cycle Division Multiplexing (DCDM) family, namely Absolute Polar Duty Cycle Division Multiplexing (AP-DCDM) which is based on the polar signaling and different return to zero (RZ) duty cycles is reported for high speed optical fiber communication systems. Unlike all the other techniques, in AP-DCDM different users share the communication medium to transmit in the same time period and at the same carrier wavelength, but with different duty cycles. The unique duty cycle for each channel helps to regenerate data at the receiver. Two different AP-DCDM designs, namely AP-DCDM with guard band (GB) and AP-DCDM without GB have been successfully demonstrated.

This thesis is presented based on the alternative format which has been approved by University Putra Malaysia's Senate, which is the manuscript-based format. The major difference between this alternative format and the conventional ones is that, this format uses published papers in place of the regular chapters on results and discussion.

The first paper contains a novel concept of decision circuit and Bit-error-rate (BER) estimation method for AP-DCDM which is published in International Review of Electrical Engineering. This journal in indexed by ISI Thomson Scientific. The concepts have significant differences to those used in conventional microwave communication receivers. This is due to the unique characteristics of the multilevel signal produced in AP-DCDM system. The BER estimation method is validated by simulation and compared against bit-to-bit comparison method.

The second paper contains the first design of AP-DCDM (AP-DCDM with guard band) which is published in Optical Fiber Technology journal (OFT) by Elsevier. This journal is indexed by ISI Thomson Scientific with 2008 impact factor of 1.253. It is demonstrated that AP-DCDM system has a clear advantage over conventional RZ-OOK. Complexity and performance comparison against other modulation formats namely Duobinary, Non-Return-to-Zero (NRZ)-OOK and RZ-Differential Quadrature Phase-Shift Keying (RZ-DQPSK) at aggregate speed of 40 Gb/s (2 x 20 Gb/s) are made. It is shown that AP-DCDM has less complexity and the best receiver sensitivity (-32 dBm) and better CD tolerance (±200 ps/nm). In reference to duobinary, AP-DCDM is less complex and has better receiver sensitivity but worse dispersion tolerance

The third paper contains the second design of AP-DCDM (AP-DCDM without guard band) which is published in IET Journal of Optoelectronics by Institution of

Engineering and Technology (IET), previously IEE. This journal is indexed by ISI Thomson Scientific with impact factor of 0.704. The system tolerance to signal impairments is investigated and it shows that the spectral width of the AP-DCDM can be furthered reduced which leads to better dispersion tolerance compared to other modulation techniques.

The fourth paper presents the effect of self-phase-modulation on AP-DCDM system which is accepted for publication in IET Journal of Optoelectronics (with impact factor of 0.704) considering different number of channels, launched power and pre-compensation ratio. It was shown that SPM is a major factor that introduce penalty to the system. Nonetheless, our results indicate that transmission using AP-DCDM should be possible at the launched power of up to tens of dBm, which is consistent with the requirement of high-quality, long distance transmissions.

Finally the fifth paper discusses the performance evaluation of AP-DCDM over Wave length Division Multiplexing (WDM), which is accepted for publication in Optics Communications by Elsevier, which is indexed by ISI Thomson Scientific with 2008 impact factor of 1.552. The narrow optical spectrum on AP-DCDM reduces the inter-channel coherent crosstalk. The possibility of setting channel spacing as narrow as 62.5 GHz for 40 Gbit/s AP-DCDM signal was confirmed. A capacity of 1.28 Tbit/s (32 x 40 Gbit/s) was packed into a 15.5 nm EDFA gain-band with 0.64 bit/s/Hz spectral efficiency by using 10 Gbit/s transmitter and receiver.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMULTIPLEKS PEMBAHAGI KITAR-TUGAS BERKUTUB MUTLAK UNTUK SISTEM KOMUNIKASI FIBER OPTIK BERKELAJUAN TINGGI

Oleh

AMIN MALEKMOHAMMADI

September 2009

Pengerusi: Dr.-Ing. Ahmad Fauzi Abas

Fakulti: Kejuruteraan

Penggandaan adalah salah satu asas yang diperlukan dalam komunikasi digital pada hari ini. Ia membenarkan pengguna yang berganda untuk berkongsi jalur lebar dalam perantaraan siaran. Dalam karangan yang panjang ini, satu rekaan baru dalam keluarga Pemultipleks Pembahagi Kitar Tugas (DCDM), yang diberi nama Pemultipleks Pembahagi Kitar Tugas Berkutub Mutlak (AP-DCDM) yang berdasarkan isyarat polar dan kitar tugas 'return to zero' (RZ) yang berbeza dilaporkan untuk sistem gentian optik berkelajuan tinggi. Tidak seperti teknik-teknik yang lain, dalam AP-DCDM pengguna yang berbeza berkongsi perantaraan komunikasi untuk pemancaran dalam masa dan pengangkut panjang gelombang yang sama, tetapi berbeza kitar tugas. Tugas kitaran yang unik untuk setiap saluran membantu data diperbaharui di bahagian penerima. Dua rekaan AP-DCDM yang berbeza, yang dinamakan AP-DCDM bersama jalur kawalan (GB) dan AP-DCDM tanpa GB telah dibuktikan dengan jayanya.

Tesis ini dipersembahkan berdasarkan format alternatif yang telah disahkan oleh Senat Universiti Putra Malaysia iaitu format manuskrip. Perbezaan utama antara format alternatif dan format terdahulu adalah format ini menggunakan 'Kertas kerja' yang telah dicetak menggantikan bab yang biasa digunakan dalam keputusan dan perbincangan.

'Kertas kerja' yang pertama mengandungi konsep novel litar keputusan dan kaedah anggaran kadar ralat bit (BER) untuk AP-DCDM yang telah dicetak di International Review of Electrical Engineering. Jurnal ini di indeks oleh ISI Thomson Scientific. Konsep-konsep ini mempunyai perbezaan yang penting kepada mereka yang menggunakan komunikasi gelombang mikro penerima yang sedia ada. Ini adalah kerana karakter yang unik dihasilkan oleh isyarat bersusun yang dihasilkan dalam sistem AP-DCDM. Kaedah anggaran kadar ralat bit diperakui oleh kaedah simulasi dan perbandingan antara bit kepada bit.

'Kertas kerja' yang kedua mengandungi rekaan pertama AP-DCDM (AP-DCDM bersama jalur kawalan) dicetak di dalam jurnal Optical Fiber Technology (OFT) oleh Elsevier. 'Jurnal' ini di indeks oleh ISI Thomson Scientific dengan 2008 'impact factor' sebanyak 1.253. Sistem AP-DCDM telah didemonstrasikan bahawa ia mempunyai kebaikan yang nyata berbanding RZ-OOK yang sedia ada. Perbandingan prestasi dan kerumitan terhadap format modulasi yang lain yang dinamakan Duobinary, 'Non-Return-to-Zero' (NRZ)-OOK dan 'RZ-Differential Quadrature Phase-Shift Keying' (RZ-DQPSK) pada jumlah kelajuan 40 Gb/s (2 x 20 Gb/s) telah dibuat. AP-DCDM telah membuktikan ia kurang rumit dan kepekaan penerima yang terbaik (-32 dBm) dan 'CD tolerance' yang bagus (±200 ps/nm). Merujuk kepada 'duobinary', AP-DCDM adalah kurang kompleks dan mempunyai kepekaan penerima yang terbaik tetapi penyelarasan penyebaran kurang baik.

‘Kertas kerja’ ketiga mengandungi rekaan AP-DCDM (AP-DCDM tanpa jalur kawalan) yang dicetak dalam IET Jurnal of Optoelectronics oleh Institusi Kejuruteraan dan Teknologi (IET), sebelum ini dikenali sebagai IEE. ‘Jurnal’ ini di indeks oleh Thomson Scientific dalam ‘impact factor’ sebanyak 0.704. Sistem penyelarasan dan kerosakan isyarat telah diselidik dan ia telah menunjukkan lebar spektrum AP-DCDM boleh dikurangkan dan ini memberi penyelarasan penyebaran yang lebih baik berbanding teknik modulasi yang lain.

‘Kertas kerja’ yang keempat menunjukkan kesan ‘self-phase-modulation’ oleh sistem AP-DCDM yang telah diterima untuk dicetak dalam IET Jurnal of Optoelectronics dalam ‘impact factor’ sebanyak 0.704 dengan mengambil kira saluran yang berbeza, kuasa yang dilancarkan dan nisbah pra-ganti rugi. SPM telah dibuktikan sebagai faktor utama yang memperkenalkan sistem denda. Namun, keputusan yang kami diperolehi menunjukkan bahawa siaran yang menggunakan AP-DCDM boleh digunakan pada kuasa pemancar sehingga sepuluh kuasa dBm, sejajar dengan permintaan siaran berkualiti tinggi dan jarak yang panjang.

Akhir sekali, ‘Kertas kerja’ yang kelima membincangkan penilaian prestasi AP-DCDM terhadap ‘Wavelength Division Multiplexing’ (WDM), diterima sementara oleh penerbitan Optics Communications oleh Elsevier, di indeks oleh Thomson Scientific with 2008 ‘impact factor’ sebanyak 1.552. Lebih kecil spektrum optik terhadap AP-DCDM mengurangkan saluran antara koheren ‘crosstalk’. Kebarangkalian penyediaan penjarak siaran sekecil 62.5 GHz untuk isyarat 40 Gbit/s AP-DCDM telah disahkan. Muatan sebanyak 1.28 Tbit/s (32 x 40 Gbit/s) telah dipak dalam ‘gain-band’15.5 nm EDFA dengan ‘spectral efficiency’ 0.64 bit/s/Hz menggunakan 10 Gbit/s pemancar dan penerima.

ACKNOWLEDGEMENTS

First of all, I would like to express my greatest gratitude to ALLAH Almighty, for His help and support during the course of life and the moment of truth. Alhamdulillah

I would like to express my appreciation and sincere gratitude to my supervisor, Dr Ahmed Fauzi Abass and Prof. Dr. Mohamad Khazani Abdullah for their continuous support, encouragement and endless patience towards completing the research. These special thanks also dedicate to supervisory committee member; Dr Makhfudzah bt. Mokhtar and Dr. Mohd. Fadlee A. Rasid, for their invaluable guidance and constructive criticisms throughout the success of this project.

I would like to express my appreciation to my father Prof. Dr. Iraj malekmohammadi, my mother and sister for being there at all times and for their support and encouragement with my research.

I would like to thank to all my colleagues from, Photonic Lab for their support and encouragement. Working with all of you is a good experience that could never be forgotten.

I certify that an Examination Committee has met on to conduct the final examination of **AMIN MALEKMOHAMMADI** on his **DOCTOR OF PHILOSOPHY** thesis entitled "**ABSOLUTE POLAR DUTY CYCLE DIVISION MULTIPLEXING FOR HIGH SPEED FIBER OPTIC COMMUNICATION SYSTEMS**" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

Aznan Jantan, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Borhanuddin Mohd Ali, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Nor Kamariah Nordin, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Kaharuddin Dimyati, PhD
Professor
Faculty of Engineering
Universiti Malaya
(External Examiner)

Bujang Kim Huat
Professor/Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia
Date: June 2009

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Ahmad Fauzi Abas, PhD
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohamad Khazani Abdullah, PhD
Professor
Significant Technologies Sdn. Bhd.
43400 Serdang, Selangor, Malaysia
(Member)

Makhfudzah Mokhtar, PhD
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohd Fadlee A. Rasid, PhD
Head of Department
Faculty of Engineering
Universiti Putra Malaysia
(Member)

HASANAH MOHD GHAZALI, PhD
Professor/Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 16 November 2009

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

AMIN MALEKMOHAMMADI

Date: 10-Jun-2009

TABLE OF CONTENTS

LIST OF ABBREVIATION

Amplitude Modulation	(AM)
Alternate Mark Inversion	(AMI)
Amplitude Modulation- Phase Shift Keying	(AM-PSK)
Absolute Polar Duty Cycle Division Multiplexing	(AP-DCDM)
Amplitude-Shift-Keying	(ASK)
Bit Error Rate	(BER)
Chromatic Dispersion	(CD)
Clock-and-Data-Recovery	(CDR)
Component Iteration Data Flow	(CIDF).
Cross-Phase Modulation	(XPM)
Direct Current	(DC)
Duty Cycle Division Multiplexing	(DCDM)
Dispersion Compensated Fiber	(DCF)
Delay Interferometer	(DI)
Direct Modulation	(DM)
Differential-Phase-Shift-Keying	(DPSK)
Differential Quadrature Phase-Shift Keying	(DQPSK)
Electro Absorption Modulator	(EAM)
Electromagnetic Interference	(EMI)
Frequency Division Multiplexing	(FDM)
Flip-Flop	(FF)
Four Wave Mixing	(FWM)

Guard Band	(GB)
High Electron Mobility Transistors	(HEMT)
Integrated Circuit	(IC)
Intensity Modulation	(IM)
Inter-Symbol-Interference	(ISI)
Laser Diode	(LD)
Low Pass Filter	(LPF)
Multiple Access Interference	(MAI)
Mach-Zehnder Interfromiter	(MZI)
Mach-Zehnder Modulator	(MZM)
Nonlinera Shrodinger	(NLS)
Non-Return to Zero	(NRZ)
Optical Code-Division Multiple Access	(OCDMA)
On-Off Keying	(OOK)
Optical Spectrum Analyzer	(OSA)
Optical Signal to Noise Ratio	(OSNR)
Peak-to-Average Power Ratio	(PAPR)
Polarization Beam Spliter	(PBS)
Polarization Controller	(PC)
Photo Diode	(PD)
Probability of Error	(PE)
Phase Modulators	(PM)
Polarization Mode Dispersion	(PMD)
Polarization Division Multiplexing	(PolDM)
Pulse Position Modulation	(PPM)

Pseudo Random Bit Sequence	(PRBS)
Pulse Width Modulation	(PWM)
Radio Frequency	(RF)
Radio Frequency Interference	(RFI)
Return-to-Zero	(RZ)
Stimulated Brillion Scattering	(SBS)
Spectral Efficiency	(SE)
Signal to Noise Ratio	(SNR)
State of Polarization	(SOP)
Self Phase Modulation	(SPM)
Stimulated Raman Scatering	(SRS)
Standard Single Mode Fiber	(SSMF)
Time Division Multiplexing	(TDM)
Transmitters	(TXs)
Wave Length Division Multiplexing	(WDM)

CHAPTER 1

INTRODUCTION

1.1. Background

The past few years have witnessed rapid transition from analog to digital systems enabling universal processing of all kinds of information, fundamentally without loss of quality. Breakthroughs in digital semiconductor technologies and their enormous ability to scale have enabled the cost effective microchips that are found in any electronic device, from high end internet routers to low-end consumer electronics [1].

Storage of digital information and processing is the need for data transport, using various communication applications, which can be addressed using different communication technologies such as optical communication systems and radio-frequency (RF). Optical communication systems can support high-capacity transmission of Tb/s over thousands of kilometers with very small transmission losses [2], which makes them the ideal technology for high-capacity wire-line networks. Apart from the above major advantages, other considerations sometimes come into play, such as excellent rejection of radio-frequency interference (RFI) [3] and of electromagnetic interference (EMI) [4], eliminating the need for a common ground between a fiber transmitter and receiver and offering a degree of security and privacy.

As shown in Fig. 1-1 [5-7] the suitability of optical communications for different system can be further analyzed using the three basic criteria namely sensitivity, capacity and implementation issues. A transponder's 'sensitivity' is the minimum optical input signal, usually in dBm needed to operate at the required performance level [8, 9]. This quantity depends on the detector type as well as the receiver circuitry. The 'capacity' of a system measures the amount of data that can be transmitted over the communication medium. Aspects such as power consumptions, reliability, cost and physical dimensions are among the topics that can be included in the 'implementation' issues. Fig. 1-1 indicates the relative importance of the three performance metrics for different communication applications.

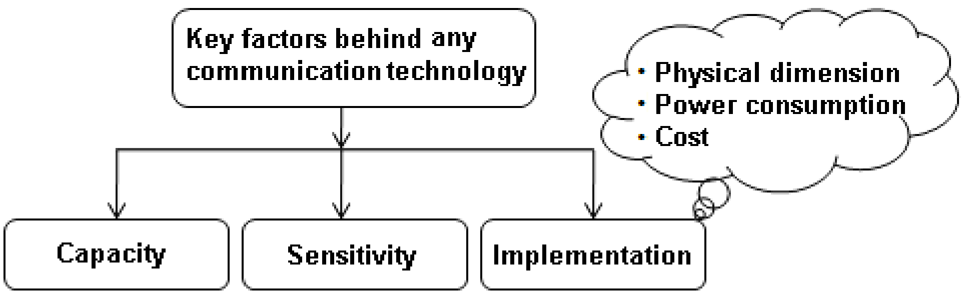

Figure 1-1: Key factors behind the success of any communication technology [5-7]

Today, the emphasis of digital optical communication techniques is on the data rate per-wavelength, signal's robustness to fiber transmission impairments such as polarization mode dispersion (PMD) or chromatic dispersion (CD) is another major concern [10]. As the data rate increases beyond 40 Gb/s, the type of modulation formats, multiplexing techniques and line coding are factors that need to be considered. Parameters such as spectral efficiency and nonlinear effects are also important, which open new challenges to the telecommunication scientists and engineers.

Multiplexing is the combination of information from more than one source, to be transmitted to more than one destination over the same transmission medium [7, 11, 12]. Transmission medium may be a metallic wire pair, a coaxial cable, micro wave radio, a satellite radio or a fiber optic cable. The most advanced multiplexing techniques are found in the capacity-constrained system, such as long-haul fiber optic transport [11, 13]. As shown in Fig. 1-2 there are several ways with which multiplexing can be achieved.

In a Time Division Multiplexing (TDM) system, each channel occupies a time slot, which interleaves with the time slots of other channels. Thus many lower-speed data streams are multiplexed into a higher-speed stream to form the aggregated transmission bit rate [14, 15]. This method was proved to be efficient but is limited to the speed of electronic devices used in multiplexing and demultiplexing. This becomes a bottleneck from exploiting the available transmission bandwidth. Wavelength Division Multiplexing (WDM) [11, 12, 16, 17] is essentially the same as Frequency Division Multiplexing (FDM) [14, 18], which has been used in radio systems for more than a century. WDM is used in the context of optical communication and the term FDM is used widely in radio communication. The idea is to transmit data simultaneously over multiple carrier wavelengths. In WDM, multiplexed signal can be demultiplexed by using optical band pass filter [12]. If the signals leak energy into neighboring frequency the performance is degraded and perfect isolation is no longer possible. This technique suffers from low spectral efficiency due to the wide range of wavelengths used. Moreover, it is limited to the available optical amplifiers band and costly.

With Polarization Division Multiplexing (PolDM) [17, 19, 20] one sends two independent signals on both orthogonal polarizations supported by the single-mode optical fiber. This technique is limited to only two channels and increases the complexity of the receiver by the introduction of the fast polarization controller [19]. In Optical Code Division Multiplexing (OCDM), each user's data is associated with a different code [21], which allows multiple users to efficiently shares the bandwidth. However, the broad spectrum signals used, made the signal less tolerant to some of the transmission line impairments especially the dispersion [22], making it suitable for shorter distances and/or low speed.

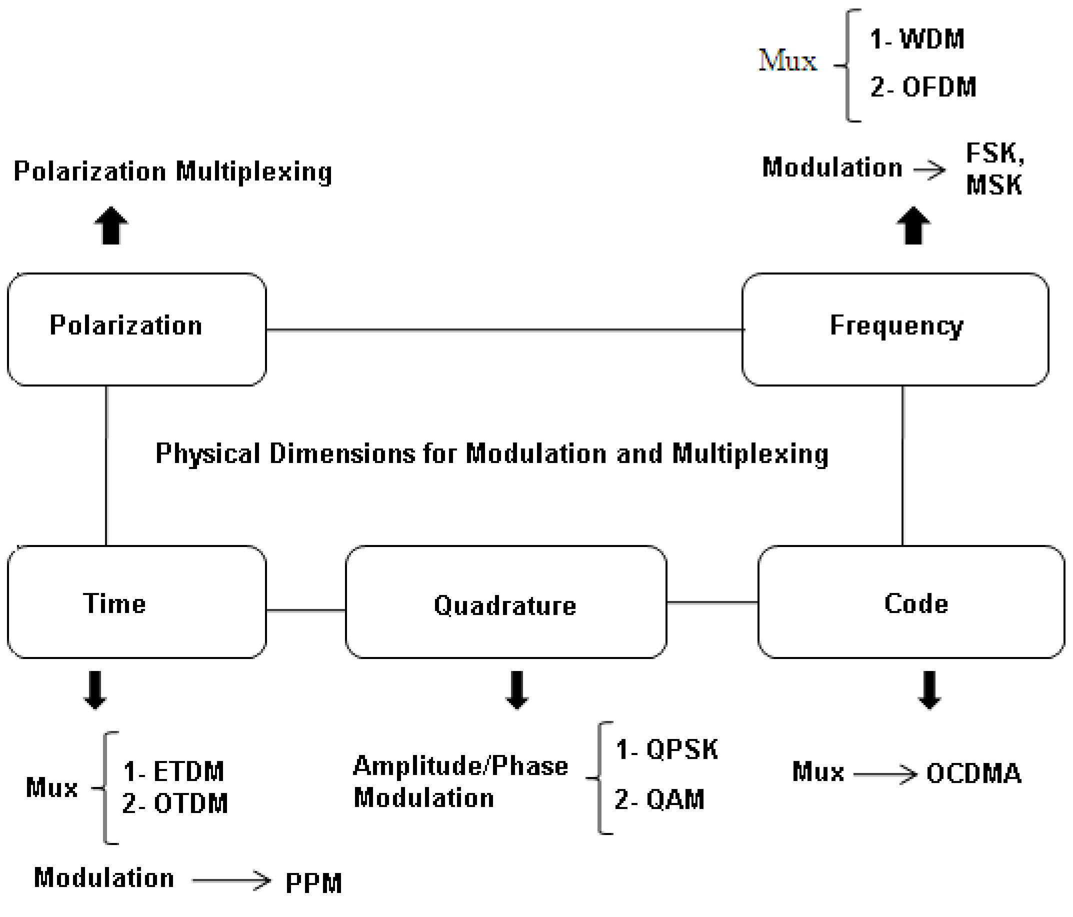

Figure 1-2: Physical dimensions that can be used for modulation and multiplexing in optical communications [2, 6, 7, 23-25].

For long-haul transport systems, which are the most capacity-constrained, dense WDM is required. To improve the WDM transmission performance, various techniques have been proposed, which include the implementation of advanced modulation formats and multiplexing techniques, new types of fiber, and advanced dispersion and loss management. Among these techniques, the use of advanced modulation formats has been demonstrated as an effective solution [5, 6, 26]. Some of the advanced modulation formats are not only useful because they are spectrally efficient but also because they have other features such as high tolerance to chromatic dispersion (CD).

Modulation denotes the method by which digital information is imprinted onto an optical carrier [5, 7], and in its most general sense also includes coding to prevent transmission errors from occurring (line coding) or to correct the transmission errors (error correcting coding).

Historically, a very simple modulation format, simply sending light to signal a “1” and not sending light to signal a “0”, known as On-Off Keying (OOK), in its various flavors has been used in optical communications for decades because it is by far the simplest format in terms of hardware implementation and integration [26, 27]. Those applications in Fig. 1-2 that are identified to be implementation-constrained, are likely to use OOK.

As the per-wavelength bit rates and transmission distances increase, and the channel spacing decreases, more advanced modulation formats are employed to improve the receiver sensitivity, reduce the effect of nonlinear transmission impairments, or to facilitate per channel bit rate to increase beyond the limits of binary systems [28]. Many researchers have for some times, examined multilevel signaling, e.g. Amplitude Modulation-Phase Shift Keying (AM-PSK), polybinary, M-ary

Amplitude-Shift-Keying (ASK) and polyquaternary as a way of improving the system performance against Chromatic Dispersion (CD) [29-31]. The main issues in those techniques are degradation in receiver sensitivity due to the increased number of levels and signal dependence on signal-spontaneous beat noise [32]. Duobinary modulation is an attractive candidate because it is spectrally efficient (~ 0.8 b/s/Hz), simple to implement, and also highly CD tolerant [8, 33, 34]. So far, Differential Quadrature Phase-Shift Keying (DQPSK) [35] and/or polarization multiplex (PDM) [36] are needed to increase spectral efficiency beyond that of duobinary modulation, but considerable technical effort at the receive end is needed for their implementation (interferometer and its stabilization, polarization control, two independent photo-receivers to independently detect the two data streams), which reverberates in the cost [26, 37]. On the other hand, M-ary-ASK such as quaternary (4-level) intensity modulation (4-IM) [29, 38] is easy to detect using a direct detection receiver with a single photodiode, but has a relatively large power penalty. Meanwhile, the increase of signals levels in the multilevel Differential-Phase-Shift-Keying (DPSK) such as 8-DPSK, is another alternative [39]. However, in the 8-DPSK demodulation, the delay demodulated eye openings can easily be corrupted even by a small signal Inter-Symbol-Interference (ISI) and the small deviation in the signal constellation [40].

In general, ideal modulation format for long-haul, high speed WDM transmission links is the one with compact spectrum and good dispersion tolerance [8, 33, 34]. The exploration towards finding the systems that satisfy both requirements is the major challenge in telecommunication research and industry.