Electronic Post-Compensation of Optical Fiber Nonlinearity in High-Speed Long-Haul Wavelength Division Multiplexed Transmission Systems

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Dedication

This thesis is dedicated to my parents for their unconditional support,
and to my wife for always being there whenever I needed her.

Abstract

A vast majority of optical fiber infrastructure deployed today utilizes 10 Gb/s transmission technology which is falling short of demands for current communication networks. To fulfill the ever increasing needs of bandwidth, the research trend since past few years has been in the direction of increasing the per channel data rate to ≥ 40 Gb/s. The transmission of optical pulses over ≥ 40 Gb/s data rates greatly suffers from degradations arising from interaction of dispersion and optical fiber nonlinearity. The work presented in this thesis focuses on the development and evaluation of a novel electronic signal processing technique that can undo the degradations already caused by the interaction between dispersion and intra-channel nonlinearities. The proposed technique tends to compensate degrading nonlinear effects by incorporating the knowledge of the neighboring bits and exploiting the fact that for a given bit pattern, the nonlinear degradation, deterministically, depends upon dispersion map and operating channel power. We have tested our proposed technique in WDM transmission systems using return-to-zero (RZ), carrier suppressed RZ (CSRZ) and differential phase-shift keying modulation formats, and have analyzed the system performance by using computer simulations. Our analysis shows that the proposed scheme can significantly undo the degradation caused by fiber nonlinearity and can significantly increase the overall system margin of a 40 Gb/s WDM system.

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List of Acronyms

ASE	Amplified Spontaneous Emission
BER	Bit Error Rate
BPF	Band Pass Filter
CD	Chromatic Dispersion
CSRZ	Carrier Suppressed Return-to-Zero
DAC	Digital to Analog Converter
dB	Decibel
DCF	Dispersion Compensation Fiber
DC	Decision Circuit
DGD	Differential Group Delay
DPSK	Differential Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
DSF	Dispersion Shifted Fiber
DSP	Digital Signal Processing
DWDM	Dense Wave-length Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
ESP	Electronic Signal Processing
FEC	Forward Error Correction
FWM	Four Wave Mixing
GaAs	Gallium Arsenide
GVD	Group Velocity Dispersion
IFWM	Intra-channel Four Wave Mixing
IM	Intensity Modulation
IM/DD	Intensity Modulated / Direct Detection
InGaAsP	Indium Gallium Arsenide Phosphorous
IXPM	Intra-channel Cross Phase Modulation

LED	Light Emitting Diode
LPF	Low Pass Filter
MLSE	Maximum Likelihood Sequence Estimation
MSSI	Mid-Span Spectral Inversion
MZDI	Mach Zehnder Delay Interferometer
MZI	Mach Zehnder Interferometer
NLSE	Nonlinear Schrödinger Equation
NRZ	Non Return-to-Zero
OOK	On-Off Keying
OPC	Optical Phase Conjugation
PD	Photo Detector
PMD	Polarization Mode Dispersion
PRBS	Pseudo Random Bit Sequence
ROADM	Reconfigurable Optical Add-Drop Multiplexer
RZ	Return-to-Zero
SPM	Self-Phase Modulation
SSFT	Split-Step Fourier Transform
SSMF	Standard Single Mode Fiber
WDM	Wave-length Division Multiplexing
XPM	Cross Phase Modulation

Chapter 1

Introduction

1.1 Overview

The work presented in this thesis aims on providing a novel solution to enhance the performance of high-speed optical fiber transmission systems. The thesis presents a discussion of various transmission impairments which significantly degrade the performance of high capacity lightwave networks. A novel electronic technique to undo such transmission impairments is proposed and evaluated by using standard performance measures used in optical fiber communication systems. Following section provides background and explains how the work presented in this thesis is important.

1.2 Motivation

The rapid global proliferation of the Internet is driving communication networks closer and closer to their limits and available bandwidth is disappearing due to ever-increasing network load. The capability of a single optical fiber to transmit vast amounts of data from one point to other has found its wide use as the backbone of the current generation information superhighway communication networks. A single strand in an optical fiber cable can be used to transmit multiple colors of light (or wavelengths) each carrying a large amount of data over longer distances. In addition to its huge capacity, optical fiber is extremely cost saving, which makes it the first choice for long reach as well short distance communication networks.

A vast majority of optical fiber infrastructure deployed today utilizes 10 Gb/s transmission technology. In state of the art optical fiber networks, capacity in excess of 2 Tb/s has already been achieved by simultaneously transmitting multiple wavelength channels [1,2]. However, the potential capacity of a single optical fiber is much higher than what is being materialized today. One way to fulfill the future needs of large information exchange is to increase the total number of wavelength channels transmitted simultaneously over a single fiber.

Another possibility to achieve maximum transmission capacity of optical fiber is to increase the data rate of wavelength channels. The research trend since past few years is in the direction of increasing the per channel data rate to ≥ 40Gb/s, which will not only drive down the cost per bit per second of information sent, but will also help increasing the total aggregate capacity of the optical fiber by at least four fold.

Migration from 10 Gb/s to 40 Gb/s transmission system is not easy due to a number of factors involved. First, the transmission over 40Gb/s is highly limited by the inherent properties of optical fiber itself, such as fiber dispersion and nonlinearity [3-8]. Fiber dispersion causes light energy to spread in time while propagating through the fiber. As a result, light intensity in any given bit time slot of a particular information channel is leaked through the neighboring bit time slots, thereby interfering with the other information bits of the same channel. Similarly, fiber nonlinearity causes light to exchange energies between multiple wavelength channels while propagating through the fiber. This results in light intensity of a particular channel leaking through the neighboring channels thereby interfering with multiple channels at the same time. The adverse effect due to both dispersion and nonlinearity as well as due to their complex interaction with each other is further exacerbated by increasing either the total number of wavelength channels or the individual data rate for each channel.

Secondly, there is an extremely large infrastructure installed to support the transmission over 10 Gb/s. A smooth transition from 10 Gb/s transmission systems to 40 Gb/s transmission systems, requiring fewer changes to the existing network infrastructure is therefore highly desirable. The majority of existing optical networks compensate both the dispersion and nonlinearity using optical techniques such as dispersion mapping and optical phase conjugation [9-11]. No doubt that the performance of optical compensation schemes is unmatched, but the disadvantages of using optical compensation schemes are in their bulkiness, inflexibility and cost. On the other hand, the use of electrical signal processing (ESP) to compensate fiber impairments is very promising in that such techniques are very flexible and cost effective. Owing to its flexible nature, an ESP module could easily be incorporated into existing lightwave networks without the need to alter the physical configuration of the system. Additionally, ESP techniques tend to compensate the degradation already caused by the interaction of fiber dispersion and nonlinearity [12-21].

The purpose of this thesis is to propose and evaluate a novel electronic signal processing technique that directly compensates the degrading effects resulting from interaction between optical fiber dispersion and nonlinearity in $\geq$ 40 Gb/s WDM transmission systems. The performance of the proposed technique has been evaluated using computer simulations, and results show that the proposed technique could effectively enhance the overall system margin of a $\geq$ 40 Gb/s WDM system.

1.3 Thesis Outline

The remainder of the thesis is organized as follows. Chapter 2 discusses the evolution of modern optical communication systems. It also describes the origin of various linear and nonlinear degradations in optical communication systems. Existing compensation techniques which have already been explored to compensate both linear and nonlinear impairments in optical fiber communications are also presented. Chapter 3 explains how complex interaction of linear and nonlinear impairments is detrimental to the performance of a high-speed long haul wavelength-division multiplexed transmission system. A novel electronic post-compensation scheme to undo such impairments in $\geq$ 40Gb/s long-haul wavelength-division multiplexed transmission systems is also presented. Chapter 4 discusses results. Finally, Chapter 5 summarizes the thesis work and concludes thesis by shedding light on advancing the proposed scheme.

Chapter 2

Modern Optical Fiber Communication System

2.1 Historical Background

Despite the extensive use of optical fiber in the modern communication networks around the world, the technology of guiding light in glass is fairly old. Although the principle of total internal reflection was discovered in the nineteenth century, but first glass-clad fiber was produced in 1950s. Glass-clad fibers facilitated the total internal reflection of light signals providing for longer distance transmission. Earlier optical fibers had very high losses (1000 dB / km) which restricted their use as a communication media [22]. In mid 1960s, Charles K. Kao proposed that the losses could be reduced by lessening the impurities in the silica glass [23,24]. In 1970s, optical fibers having loss value as low as 20 dB / km were being produced. In 1979, low loss fibers (loss equal to 0.2dB/km) around 1550nm wavelength were available.

While progress was being made on the optical fiber end, at the same time, new laser sources were also being explored. The advent of compact GaAs semiconductor laser operating at 800nm opened up the door for the first generation of lightwave transmission system. In 1980s, optical fiber communication systems used InGaAsP semiconductor lasers operated around 1300nm wavelength region, where loss is below 1 dB/km and optical fiber has minimum dispersion. By early 1990s, the rapid development in the optical fiber communications allowed for transmission of data rates up to 2.5 Gb/s. At the same time, the revolutionary introduction of Erbium Doped Fiber Amplifier (EDFA) expanded the capacity of optical fiber communication systems [25,26]. EDFA is produced by lightly doping the silica based optical fiber with a rare-earth element Erbium (Er), and is capable of amplifying multiple optical signals.

After coping with fiber loss with the advent of optical amplifiers, the next major breakthrough in optical fiber communications was Wavelength Division Multiplexing (WDM). WDM provided an opportunity to exploit the transmission capacity of optical fiber by allowing multiple wavelengths channels to be transmitted simultaneously over a single mode fiber. Figure 2.1 explains the concept of a WDM system. Multiple information streams modulated over slightly different wavelengths are combined by means of an optical multiplexer. The wavelength of each wavelength channel is selected such that there is sufficient spacing (channel spacing) between adjacent channels. Allowing sufficient channel spacing between wavelength channels prevents cross-talk between the neighboring channels. Optically multiplexed information streams are then launched into the fiber. At the receive end, individual wavelengths channels are separated using filters and then sent to the specific receiver, where it is converted back to the original format.

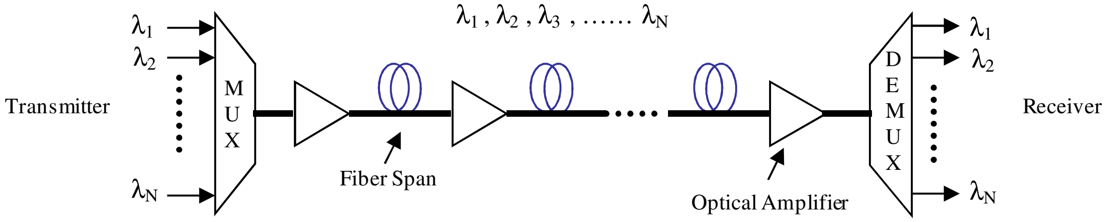


Figure 2. 1. Block diagram of a typical WDM transmission system showing multiple fiber spans. λ1 to λN are the multiplexed wavelengths channels transmitted simultaneously.

This chapter is organized as follows. Section 2.2 presents mathematical model of optical fiber. Section 2.3 covers various transmission impairments in optical fiber communications based on the mathematical model. Section 2.4 focuses on various compensation methods used to compensate the transmission impairments.

2.2 Transmission through Optical Fiber

The propagation of optical pulse in an optical fiber is governed by generalized (or extended) Nonlinear Schrödinger (NLS) equation given by equation 2.1 [27].

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A + \frac{i}{2}\beta_2 \frac{\partial^2 A}{\partial T^2} - \frac{1}{6}\beta_3 \frac{\partial^3 A}{\partial T^3} = i\gamma |A|^2 A \tag{2.1}$$

where A is the complex amplitude of optical signal, $|A|^2$ is the optical power, z is propagation distance (km), α is attenuation coefficient (in neper/km), i is complex operator = $\sqrt{-1}$, β_1 (in ps/nm), β_2 (in ps^2/nm) and β_3 (in ps^3/nm) are terms for the group-velocity dispersion (GVD) and dispersion slope, respectively, $T = t - z/v_g = t - \beta_1 z$, is frame of reference moving with the pulse at group velocity Vg, and γ is the nonlinearity coefficient (in $W^{-1}km^{-1}$).

NLS equation is a nonlinear partial differential equation whose analytical solution is not possible except for some special cases (e.g. solitons). To understand the evolution of optical pulse in optical fiber, NLS is often solved numerically. One such numerical method is the Split Step Fourier Transform (SSFT), which is commonly used to simulate the optical fiber using computer programs due to its use of fast Fourier transform [27]. To simplify the operation of SSFT, consider simplified version of NLS equation (2.2) as given below:

$$\frac{\partial A(z,T)}{\partial z} = \left(\hat{D} + \hat{N}\right)A \tag{2.2}$$

where $\hat{D}$ is linear operator, which accounts for both linear impairments of dispersion and attenuation, and $\hat{N}$ is nonlinear operator which accounts for nonlinear impairments. Mathematically:

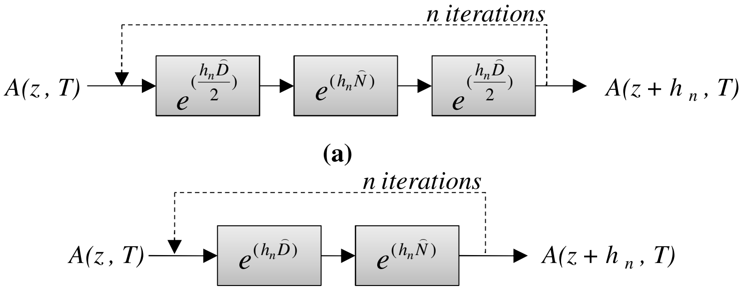
$$\hat{D} = -\frac{i\beta_2}{2}\frac{\partial^2}{\partial T^2} + \frac{1}{6}\beta_3\frac{\partial^3}{\partial T^3} - \frac{\alpha}{2} \tag{2.3}$$

and

$$\hat{N} = i\gamma\left|A\right|^2 A \tag{2.4}$$

SSFT solves for the evolution of optical signal by dividing the optical fiber into smaller segments. The effects of both linear and nonlinear impairments are then evaluated separately by using either Symmetric SSFT or Asymmetric SSFT as shown in figure 2.2.

In Symmetric SSFT, the smaller segment is further divided into two halves and only dispersion is evaluated for the one full segment ignoring effect of nonlinearity for the first half. The effect of nonlinearity is then included in the middle of the segment. On the other hand, asymmetric SSFT works by evaluating only one operator at a single time for one full segment while neglecting other. For example, for any given segment, dispersion could be evaluated first while ignoring fiber nonlinearity. Same process is carried out to calculate the nonlinear effects for the same fiber segment neglecting dispersion effects.



(a)

(b)

Figure 2. 2. Evaluation of Split Step Fourier Transform, (a) Symmetric SSFT, (b) Asymmetric SSFT [57].

2.3 Transmission Impairments

Modern optical fiber communication systems are characterized by their ability to operate at high data rates over longer distances. However, achieving the maximum available capacity and longest achievable transmission distance is limited by transmission impairments taking place due to various linear and nonlinear mechanisms. The major cause of such degradations is the material used to fabricate the optical fiber itself. Depending on the fiber material as well as on the properties of light, the optical signal launched into the fiber suffers from both linear and nonlinear degrading effects [28]. In linear regime, optical transmission suffers from two phenomenon viz. fiber loss (or attenuation) and fiber dispersion. Fiber loss originates from absorption and scattering of optical power, causing signal to lose power and thus limits the transmission distance. The problem of fiber loss has long been resolved by the advent of optical amplifiers, which could amplify the weak received optical signal. Use of a long optical amplifier chain makes transmission distances in excess of thousand kilometers possible.

The second important linear impairment in optical communications is fiber dispersion. Fiber dispersion (or simply dispersion) is due to the difference in the speed of different spectral components, which causes optical pulse to spread and distort the transmission. On the other hand, self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM) are so called nonlinear degradations. Whereby SPM and XPM cause optical pulses to exchange energy between multiple wavelength channels, FWM causes unwanted frequencies to emerge in the transmission while propagating through the fiber [28].

2.3.1 Dispersion

The light is composed of different spectral components. Ideally, all the spectral components associated with the optical signal must travel at same speed. In reality, however, this is not the case. The fact that refractive index of fiber (n) changes with frequency (ω) makes all the spectral component travel at different speeds. This causes broadening of the optical signal. The broadened optical pulses spread out of their bit time slot and overlap adjacent pulses causing the signal distortion. The phenomenon is called group velocity dispersion (GVD) commonly referred to as dispersion. Modal dispersion, chromatic dispersion (CD) and polarization mode dispersion (PMD) are the three types of dispersions of which only CD and PMD are present in single mode fiber. Modal dispersion is a consequence of difference in the speed of different modes in a multimode fiber and therefore communication over single mode fibers is not affected by it.

Polarization mode dispersion is caused by the birefringence of optical fiber. Due to the imperfection in the manufacturing process and/or mechanical stress, optical fibers do not possess circular symmetry throughout the length. The light energy launched into the fiber has two orthogonal polarization states at a given wavelength. Both polarizations are aligned when the light signal is launched into the fiber, but due to the slight asymmetry in the optical fiber the polarization states no longer remain aligned and undergo a group delay also known as Differential Group Delay (DGD), while travelling through the fiber [2]. The principle of DGD could be understood by the figure 2.3, which shows that two orthogonal polarization states experiencing group delay due to birefringence of the optical fiber. PMD could prove detrimental to the optical fiber communication systems due to its varying nature depending upon the environmental effects.

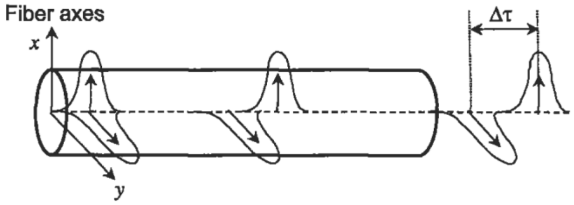


Figure 2. 3. Effect of PMD causing orthogonal polarizations to undergo Differential Group Delay (DGD). The two polarizations experience a DGD equal to Δτ at the other end of the optical fiber [2]

Chromatic Dispersion (CD) is the major contributor of pulse broadening in the optical fiber communications. Since the index of refraction varies as a function of wavelength of the optical signal, it causes the spectral components of a given mode to travel at different speeds. This difference in the speeds causes the optical pulse to spread. CD is also known as Group Velocity Dispersion (GVD). In addition to its dependence on the wavelength, CD also depends on the spectral width of the optical source. Narrower spectral width of the light source could significantly reduce the impact of CD. Therefore, laser sources are preferred over LED sources due to their narrower spectral width (or line width) [28].

Fiber dispersion is an important factor in the optical fiber communications and therefore should be taken care of. Dispersion is usually compensated by using dispersion management techniques as described in section 2.4.1.

2.3.2 Fiber Nonlinearities

The transmission of optical signal through optical fiber is greatly limited by the nonlinear impairments such as Self-Phase Modulation (SPM) and Cross-Phase Modulation (XPM). The SPM and XPM nonlinear impairments have their origin in the intensity-dependent variations of silica fiber refractive index. The refractive index of the silica fiber varies as the intensity of the optical signal travelling through the fiber changes, as depicted by equation (2.5):

$$n = n_o(\omega) + n_2 \frac{P}{A_{eff}} \tag{2.5}$$

where n_o is the ordinary refractive index of the material and n_2 is the nonlinear index coefficient [28]. The changes in the refractive index affect the speed of light signal causing phase modulation of the propagating signal that created it. For a single channel transmission, this effect pronounces SPM by converting fluctuations of the optical power into phase fluctuations. SPM causes the spectrum of the optical signal to spread depending on the rate of the change in the optical intensity and the value of the nonlinear coefficient γ of the fiber material. The spectral broadening produces dispersion like effects limiting the data rate. As bit rate increases, for example up to 40 Gb/s, the ultra-short pulses have rapid rise and fall which in turn enhances SPM effects. XPM affects WDM transmission by converting power fluctuations in one wavelength channel into phase fluctuations in a co-propagating field at other wavelength [29]. XPM is more pronounced as number of channels increase. In a WDM transmission system, both SPM and XPM affect the performance of the system.

Four-wave mixing (FWM) is a third order nonlinearity, which is caused by closely packing wavelength channels, such as in the case of Dense WDM (DWDM). Low dispersion values and high launch powers give rise to the generation of new frequencies due to FWM. As an example, three optical frequencies ω_1, ω_2 and ω_3 would mix to produce a fourth inter-modulation product ω_4 given by following equation:

$$\omega_4 = \omega_1 + \omega_2 - \omega_3 \tag{2.6}$$

Figure 2.4 depicts the concept of four-wave mixing. The wave propagating at frequencies ω_1 and ω_2 co-propagate, they mix and generate two more sideband frequencies at ω_{112} and ω_{221}. The generation of newer frequencies becomes severe as number of co-propagating waves increase. For example, three co-propagating waves will mix and generate nine optical sideband frequencies. Co-propagating sidebands exchange energies with the original signal degrading WDM system performance.

The effects of FWM could be eliminated by having high dispersion in the link. Since generation of new sideband frequencies in FWM depend on the phase matching of co-propagating wavelength channels, different wavelengths propagating under different group velocities serve for phase mismatch and hence eliminate FWM. Although high dispersion causes severs inter-symbol interference (ISI), this problem could be solved by proper dispersion mapping in which dispersion is fully compensated at the end of the link. Dispersion maps are discussed in section 2.4.1.

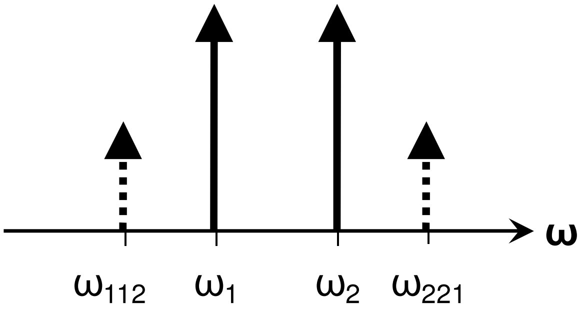


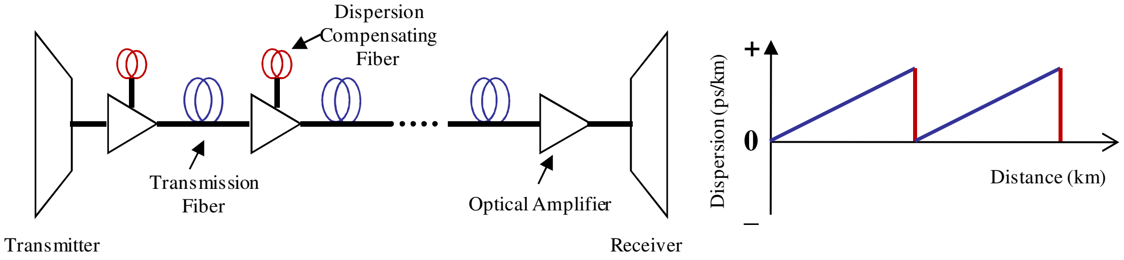
Figure 2. 4. Generation of sideband frequencies due to four-wave mixing.

2.4 Optical Compensation of Transmission Impairments

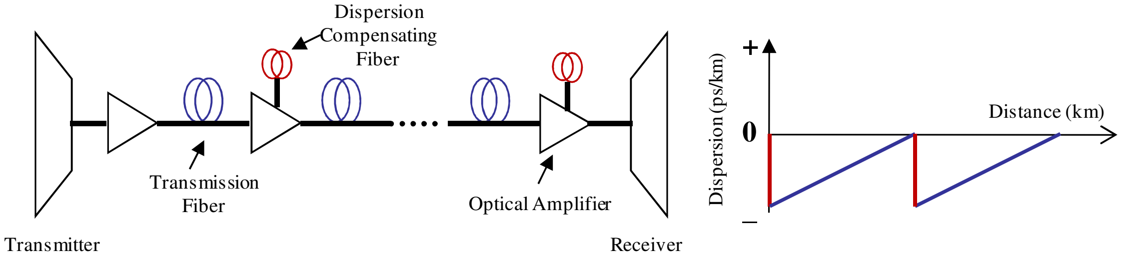
Majority of optical communication networks rely on optical techniques such as dispersion management to compensate transmission impairments. Similarly, the use of optical phase conjugation for spectral inversion has allowed compensating the optical fiber nonlinearity. Following sections describe existing solution to mitigate both linear and nonlinear degradations in optical communication system.

2.4.1 Dispersion Management

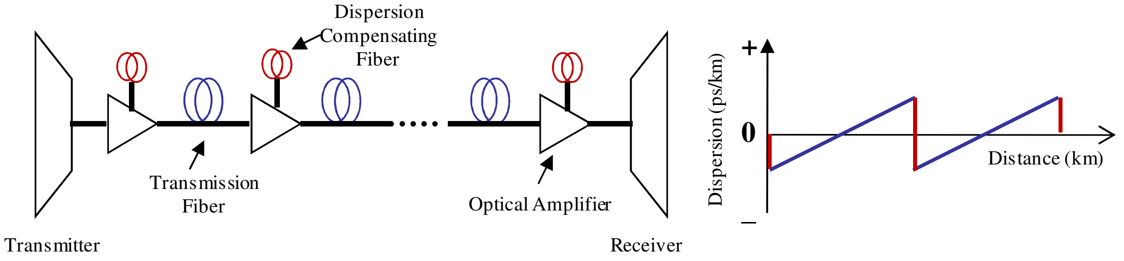
Dispersion management (also referred to as dispersion mapping) is most widely used optical technique to compensate both dispersion and fiber nonlinearity. In dispersion management technique, small lengths of specialty fiber such as dispersion compensating fiber (DCF) are placed along fiber link to control the spread of optical energy. DCFs are made of a special glass material blended with rare metals. DCFs compress the optical energy in time, and therefore allows for the compensation of the dispersion effect. Figure 2.5 shows three different configurations to implement a dispersion map.



(a) Pre-Compensation



(b) Post-Compensation



(c) Dual-Compensation

Figure 2.5. Different dispersion map configurations (a) Pre-compensation, (b) Post-compensation, and (c) Dual-compensation.

In pre-compensation scheme, the DCF is placed in the beginning of the fiber span before the transmission fiber. This allows for pre-compensating the dispersion of transmission fiber. For post-compensation scheme, the DCF is placed after the transmission fiber at the end of the fiber span. This allows for the compensation of residual dispersion at the end of the link. In dual-compensation schemes, the DCF is placed both at the beginning of the span as well as at the end. All the three schemes suit different scenarios and provide different levels of dispersion control.

In addition to compensate fiber dispersion, dispersion maps also reduce fiber nonlinearities. For example, having high local dispersion in a given span can destroy FWM effect. Similarly, due to high dispersion values optical pulses spread quickly reducing their high intensity peaks. Quick reduction of pulse peak provides for less XPM effects. Therefore, in a properly designed dispersion map, the pulses are allowed to spread by keeping local dispersion high, and then compensating total dispersion at the end of the span [30,31].

2.4.2 Optical Phase Conjugation Technique

Optical phase conjugation (OPC) allows for the compensation of both the dispersion and fiber nonlinearity. The scheme works by spectral inversion of the transmitted optical signal. The spectral inversion of the transmitted optical signal is carried out at the theoretical mid-point of the transmission fiber by using Phase Conjugator module. The mid-point spectral inversion technique is also referred to as Mid-Span Spectral Inversion (MSSI). In MSSI, the optical signal is allowed to undergo transmission impairments such as dispersion and nonlinearity in the first half of the transmission fiber. Those impairments, after conjugation, can be cancelled by the impairments of the second half of the fiber link [32-39]. The principle of OPC could be understood by re-arranging the equation (2.1) in following manner:

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A - \frac{i}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + \frac{1}{6}\beta_3\frac{\partial^3 A}{\partial T^3} + i\gamma |A|^2 A \tag{2.8}$$

From Ref. [38], the complex conjugate of equation (2.8) is given as following:

$$\frac{\partial A^*}{\partial z} = -\frac{\alpha}{2}A^* + \frac{i}{2}\beta_2\frac{\partial^2 A^*}{\partial T^2} + \frac{1}{6}\beta_3\frac{\partial^3 A^*}{\partial T^3} - i\gamma |A^*|^2 A^* \tag{2.9}$$

where * denotes complex-conjugate operation.

The sign inversion of β_2 (dispersion), and γ (nonlinearity) in (2.9) suggests that after mid-span conjugation process, both dispersion and fiber nonlinearity could be compensated by the second half of the fiber. However, no change in the signs of α (attenuation) and β_3 (dispersion slope) suggests that those two effects cannot be compensated by OPC and should be taken care of by other means. In fact, for dispersion, OPC can only compensate even-order dispersion terms (β_2, β_4 , etc.).

Traditionally, OPC was known for compensating fiber dispersion only [39]. In which case, the signal was allowed to disperse in the first half of the fiber so that the short wavelength spectral components of the pulse lead the long wavelength spectral components. After the spectral inversion, the long wavelength spectral components lead the short wavelength spectral components. However, a number of recent experiments have proved that OPC can be used to compensate the fiber nonlinearity in high speed long-haul WDM transmission systems [40,41].

OPC is a promising technique which has many advantages over other techniques. However, for perfect compensation through OPC, few important considerations must be taken into account. First important consideration is the homogeneity of transmission fiber which requires that both the fibers before and after OPC must be perfectly symmetric in terms of dispersion and fiber nonlinearity. Only then the compensation of both transmission impairments would be possible. OPC also requires symmetric power envelop of optical amplifiers before and after OPC. The requirement of symmetric power envelope could be circumvented by using Raman amplifiers. Moreover, the phase conjugation process should be transparent and must not depend on the bit rate and modulation formats. Additionally, OPC should be polarization independent [42-44].

2.5 Electronic Compensation of Transmission Impairments

The disadvantages of using optical compensation schemes are in their bulkiness, inflexibility and cost. In 1990, a revolutionary change in the field of optical fiber communications was observed when Winters *et al*. proposed electrical signal processing to compensate the impairment in optical fiber communications [12]. Since then electronic signal processing (ESP) has gained huge attention and many electronic techniques incorporating digital signal processing (DSP) have been proposed for mitigating the dispersive and nonlinear degrading effects in WDM transmission systems [13-21].

In high-speed optical fiber communication systems, electronic compensation techniques are being pursued in two directions. First, efficient optical modulation formats and line coding are being explored due to their resilience to both linear and nonlinear transmission impairments. Advance modulation formats also provide high spectral efficiency [45,46]. Spectral efficiency is defined as the number of bits transmitted per unit time per unit available bandwidth (Bits / sec / Hz). In the other direction, ESP focuses on the use of various DSP techniques such as electronic equalization and maximum-likelihood sequence estimation (MLSE). Similarly, forward error correction (FEC) is widely being used in modern optical communication networks.

In this context, a review of commonly used optical modulation formats is presented in following section. A description of nonlinearity compensation by using digital back propagation technique is given in next section.

2.5.1 Modulation Formats

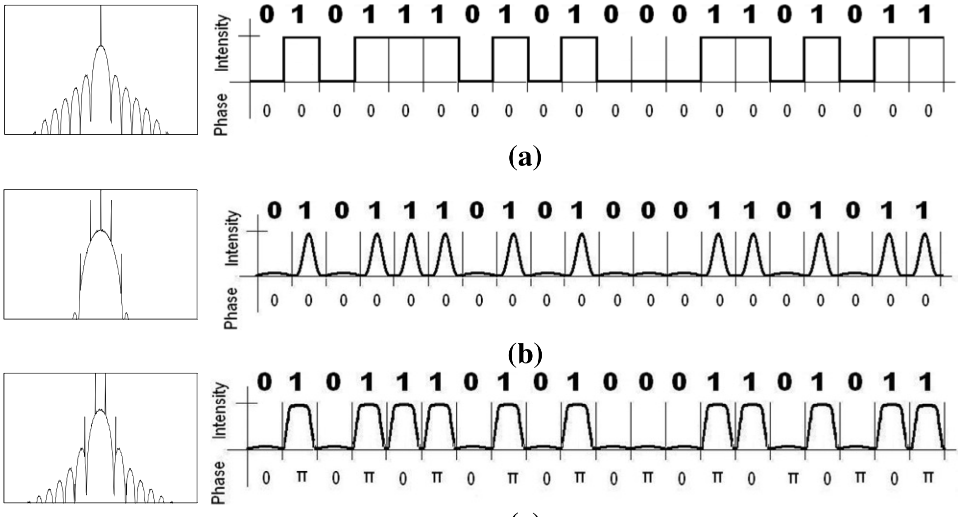
As described above, an optimal modulation format not only combats transmission impairments but also provides for high spectral efficiency. Therefore, signifying a given modulation format as an ‘optimal modulation format’ depends on properties such as its spectral efficiency, power margin, and resistance to dispersion and nonlinearity. The spectrum of a given modulation format is a good measure of its spectral efficiency and immunity to dispersion effects. Narrower spectrum directly translates into reduced dispersion and increased spectral efficiency. Narrower spectrum also provides for efficient use of available EDFA spectrum. Another property to look for is the number of signal levels. A modulation format with constant optical power can significantly reduce SPM and XPM effects. On the other hand, modulation format having multiple signal levels can significantly reduce CD induced distortion. Modulation format also determines the complexity of transmitter and receiver, hence impacts the system cost [47-49].

In optical fiber communication systems, the three attributes of an optical field could be altered to modulate the carrier signal are intensity of the optical signal, its phase and polarization. In earlier transmission systems, intensity modulation was very popular due to its ease of generation and detection. However, the availability of sophisticated electronic and optical components has enabled the use of more complex modulation schemes which can modulate phase of the optical field. While both intensity and phase modulation formats are widely used in optical fiber communication systems, little attention has been given to polarization based modulation format due to its increased complexity and less performance [45,46,50,51].

In Intensity Modulated (IM) modulation format (also known as on-off keying or OOK), the baseband signal is intensity modulated by switching it between two states, i.e. presence of light signal signifies logical ‘1’ (or ‘On’ state) and its absence indicates logical ‘0’ (or ‘Off’ state). The simplest OOK scheme used in optical fiber communication systems is Non-Return-to-Zero (NRZ-OOK). In NRZ modulation scheme, both ‘1’ and ‘0’ occupies the full bit time slot. The main advantage of NRZ is therefore simple transceiver design as well its requirement of low electrical bandwidth as compared to other modulation formats. Generally, NRZ modulation format has the most compact spectrum as compared with other modulation formats, suggesting its immunity to residual fiber dispersion. However, as data rate increases, NRZ suffers from severe SPM due to longer pulse time and from XPM due to longer interaction between pulses of neighboring channels in WDM systems [52,53]. Figure 2.6a depicts the pulse shape and spectrum of NRZ modulation format.

Return-to-Zero (RZ-OOK) is another common modulation format under intensity modulation category. In RZ modulation format, the ‘1’ occupies a fraction of bit time slot, which varies depending on the duty cycle. RZ modulation format is more resilient to fiber nonlinearity as compared to NRZ due to its shorter pulse time allowing for less interaction with other pulses. Shorter pulse time allows for quicker walk-off between pulses of co-propagating channels, which in turn reduces XPM. The uniform pulse shape for single ‘1’ and multiple ‘1s’ in a sequence also provides for better immunity to nonlinearity. Figure 2.6b shows pulse shape and spectrum of RZ modulation format. A disadvantage of RZ is its wider spectrum as compared to NRZ which reduces spectral efficiency in a WDM system.

CSRZ modulation format is most widely used in modern high speed long reach WDM transmission systems due to its resistance to fiber impairments. When it comes to resilience to fiber impairments, the performance of CSRZ is comparable to that of advanced modulation formats such as DPSK. CSRZ modulation format is similar to RZ modulation format as ‘1’ is represented by a high intensity level for a fraction of full bit time, and ‘0’ is represented by absence of light signal. However, the difference lies in the changing phase in CSRZ modulation format. In CSRZ, the phase is changed by π for every bit in CSRZ as shown in figure 2.6c. Another difference between RZ and CSRZ is the duty cycle. Generally CSRZ has 67% duty cycle which could be reduced to 50% at expense of increased insertion loss. The carrier at optical center frequency is suppressed, hence the name carrier suppressed.



(a)

(b)

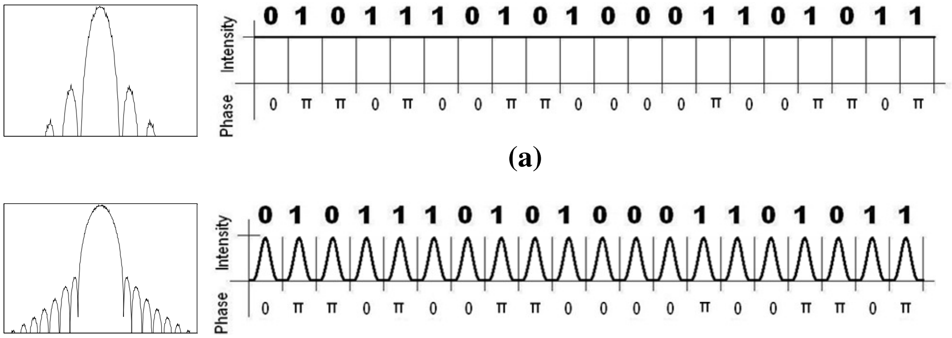
(c)

Figure 2. 6. Pulse shape and spectrum of Intensity Modulation Formats (a) NRZ (b) RZ and (c) CSRZ.

CSRZ reduces nonlinearity in dispersion managed systems due to its greater SPM tolerance as compared to RZ. The property of alternating the phase from one to other in CSRZ provides for reduced FWM [45,46].

In phase modulation, the phase of the carrier signal’s optical field is modulated to carry information. A popular form of phase modulation is Differential Phase Shift Keying (DPSK) in which a ‘1’ is represented by π phase change and a ‘0’ is represented by absence of phase change. The pulse shape of DPSK modulation format is similar to either of NRZ or RZ modulation formats. When implemented as NRZ-DPSK modulation format, the intensity of optical signal is held constantly high and a ‘1’ is represented by π phase shift while a ‘0’ is represented by absence of phase shift as shown in figure 2.7a. The flipping of phase while intensity is held constant results in elimination of the carrier signal in the spectrum of DPSK. Figure 2.7a also shows the time domain representation of NRZ-DPSK signal, its spectrum.

The main advantage of using DPSK over OOK is its 3dB receiver sensitivity improvement. Additionally, the constant optical power reduces the fiber nonlinearity arising from varying power signals. However, CD impacts NRZ-DPSK due to conversion of phase modulation into intensity modulation [54]. Another limitation of DPSK in long reach transmission system is the effect of nonlinear phase noise arising from optical amplifiers [55,56]. This occurs due to Amplified Spontaneous Emission (ASE) noise generated by optical amplifiers contributes to phase noise causing waveform distortions.



(a)

(b)

Figure 2. 7. Spectrum and pulse shape of Phase Modulation formats (a) NRZ-DPSK and (b) RZ-DPSK.

The performance of DPSK can be improved by implementing it using RZ modulation format. Like NRZ-DPSK, in RZ-DPSK the ‘1’ is represented by π phase shift and ‘0’ is represented by zero phase shifts between adjacent pulses. However, the pulse shape of RZ-DPSK differs from that of NRZ-DPSK as the optical intensity is not held constant, rather RZ-like pulse shape is used as shown in figure 2.7b. The lower duty cycle of RZ-DPSK allows for more resistance to the fiber nonlinearity. The narrow optical pulse of RZ-DPSK signal translates into wider optical spectrum than NRZ-DPSK, which would make the system less tolerable to the CD effects. However, optimal dispersion compensation could improve the tolerance level of RZ-DPSK.

2.5.2 Digital Back Propagation

Digital back propagation is similar to OPC in that it mitigates fiber impairments by channel inversion. The difference between two techniques is in their implementation; OPC being an optical technique directly operates on the optical signal, whereas digital back propagation works in electrical domain and thus accounts for benefits provided by DSP.

Digital back propagation technique mainly relies on the fact that NLSE is an invertible equation. The main idea of digital back propagation technique is to compensate the transmission impairments in the optical fiber by digitally 'back-propagating' the received signal through inverse NLSE equation [57]. This could be done by altering the equation (2.2) in such a way that both dispersion and nonlinearity operators have opposite signs, as given by equation (2.10):

$$\frac{\partial A(z,T)}{\partial z} = \left(-\hat{D} - \hat{N}\right)A \tag{2.10}$$

Since digital back propagation technique deals with the optical field of the transmitted signal and does not depend on the modulation format or pulse shape, therefore it can be applied on all optical fiber transmission systems. Digital back propagation technique can be used on transmitter or receiver side. However, the receiver side implementation only works for coherent communication systems. When implemented at transmitter end, the signal is pre-distorted using DSP techniques and then launched into the actual transmission fiber. The pre-distorted signal is then 'corrected' by the transmission fiber [19]. If the digital back propagation technique is implemented at receiver end, the 'fictitious' fiber compensates the transmission impairments produced by the actual transmission fiber. However, back propagation can also be implemented in a hybrid configuration, that is, at both transmitter and receiver ends. In this case, the transmitter side digital back propagation module inverts the first half of the transmission fiber, whereas the receiver side digital back propagation module inverts the second half of the fiber [17,57].

For using back-propagation technique properly, many factors must be considered. For example, it is very important to take care of noise, PMD and other effects, failing to which results in decreased performance. Similarly, the signal-noise interaction during the transmission through the optical fiber also limits the performance of digital back-propagation technique. Additionally, use of Reconfigurable Optical Add-Drop Multiplexers (ROADMs) complicates the situation. It becomes very difficult to estimate the transmission impairments for the channels being added or dropped from the link, hence limiting the benefits of back propagation technique. For pre-distorting the transmitted signal, digital back propagation technique is also limited by the capability of the Digital-to-Analog Converters (DACs) used to generate the desired signal and becomes ineffective as spectrum of desired signal grows beyond the processing power of electronic components. Furthermore, such compensation scheme requires large memory capacity, which increases with the increase in data rates [21].

Chapter 3

Electronic Post-Compensation of Optical Fiber Nonlinearity

3.1 Overview

In this chapter, a novel electronic scheme is presented that can directly compensate the degrading effects resulting from fiber nonlinearity in 40 Gb/s or higher bit rate WDM transmission systems. The performance of the proposed scheme has been evaluated using intensity modulation direct-detection (IM/DD) formats such as RZ and CSRZ. The uniqueness of the proposed scheme is due to its implementation at the receive-end in IM/DD systems operating at ≥ 40 Gb/s or higher data rates.

Following sections provide background of complex interaction between dispersion and fiber nonlinearities. The working principle of proposed scheme will also be explained and its performance is evaluated by using different modulation formats. Similarly, the impact of different dispersion maps will also be discussed.

3.2 Background

A vast majority of existing lightwave transmission systems use intensity modulation formats due to their simplicity in generation and detection [58]. The nonlinear effects in such systems results in different mechanisms such as SPM, XPM and FWM. While XPM and FWM are mainly present due to interaction between pulses of neighboring channel in WDM systems, SPM is independent of interaction between pulses. SPM causes the high intensity peak of a given pulse to experience a different refractive index than the tail where intensity is lower. Consequently, SPM effect is always present both in WDM as well as in single channel transmission and therefore is difficult to eliminate. However, in high bit rate systems, the standard definition of aforementioned nonlinearities is not applicable; rather, to understand the transmission impairments, concept of intra-channel nonlinearities is used, which is described below.

In high speed transmission systems, such as operating at 40 Gb/s or higher data rates, the energy of a given pulse spreads very quickly over a much wider time window. The quick spread of optical pulse allows for interaction with many neighboring bits within the same channel before its energy is pulled back in the proper bit-time slot via dispersion management. This interaction can occur many times over the course of long-haul transmission due to dispersion mapping and gives rise to intra-channel nonlinear effects other than SPM. These intra-channel nonlinear effects are referred to as Intra-channel Cross-Phase Modulation (IXPM) and Intra-channel Four-Wave Mixing (IFWM). The interaction between dispersion and intra-channel nonlinearities causes the pulse to experience timing and/or amplitude jitter. IXPM causes the pulse to undergo timing shift, whereas IFWM results in amplitude shift and appearance of ghost pulses at the place of '0' bits [3, 8, 59].

The interaction between dispersion and intra-channel nonlinearities manifests in timing and/or amplitude shift in any given pulse. We observe that timing and/or amplitude shift in a given pulse is deterministic as it depends upon the neighboring bits, with which that pulse interacts over the course of the transmission. To undo this timing and/or amplitude jitter, a novel electronic post-compensation technique is proposed. The study shows that the proposed technique tends to compensate this timing and amplitude shift resulting from degrading nonlinear effects in a single channel by incorporating the knowledge of the neighboring bits and exploiting the fact that nonlinear degradation, deterministically, depends upon dispersion map and operating channel power.

The rest of the chapter is organized as follows. Section 3.3 describes the principle of proposed technique followed by analysis of timing and amplitude jitter in section 3.4. A method for determining time delays and decision thresholds of multiple decision circuits (DCs) is described in section 3.5. Section 3.6 presents simulated system model. Chapter summary is presented in section 3.7.

3.3 Principle of Proposed Technique

A schematic block diagram delineating the working principle of the proposed technique is shown in figure 3.1. Please note that the proposed technique takes advantage of the FEC gain in estimating the neighboring bits and enhances the overall system margin above and beyond FEC gain.

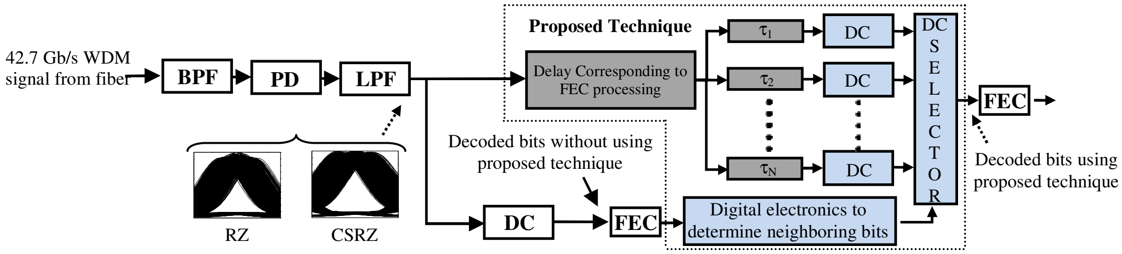


Figure 3. 1. Block diagram of the proposed technique. Please note that DC is the decision circuit and τ's are time delays of the DCs with respect to the center of the bit time. "DC selector" is a high speed electrical switch. The eye diagrams are the 42.7 Gb/s simulated eyes for RZ and CSRZ modulation formats at transmission distance of 1000 km for average channel power for 4 dBm.

The scheme uses multiple DCs, each sampling the incoming bit at a different time within the bit-time slot at an optimized decision threshold. Depending upon the neighboring bits, the output of only one decision circuit is selected. The approximate time delay (τ) and decision threshold of each DC is predetermined for each unique combination of the neighboring bits. However, both time delay (τ) and decision threshold of each DC can be further optimized the same way as is done in a traditional single DC case by monitoring the BER while system is operating. Please note that each DC can be independently optimized without affecting the optimal settings of the other DCs using the proposed technique.

3.4 Timing and Amplitude Jitter

We analyzed the interaction between dispersion and fiber nonlinearity using RZ and CSRZ modulation formats. Both modulation formats were simulated using a 2^{12} pseudo random bit stream (PRBS). The time delays and decision thresholds of the multiple DCs used in the proposed technique can be estimated by determining the time shift and amplitude change in a given pulse for each unique combination of neighboring bits. The time shift and amplitude change in a given pulse due to each unique combination of "one neighboring bit" on each side can be seen in figure 3.2 for an exemplary simulated 40-Gb/s RZ transmission system. For this exemplary system, if a pulse is neighbored by two "1s" or two "0s", there is almost no average time shift in the pulse (Figure 3.2a and 3.2b). However, if the neighboring bits are different on each side, then there is a distinct average time shift (~ 3ps) towards the direction of "1" bit (Figure 3.2c and 3.2d).

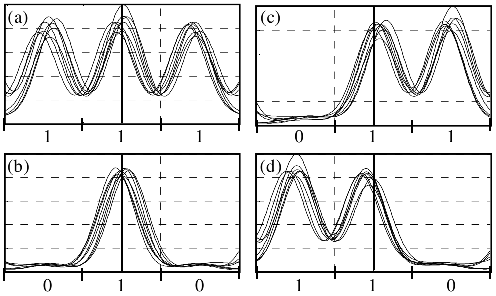


Figure 3. 2. The subsets of eye diagram with selective bits showing average time shift and amplitude shift in "1" pulse with unique combinations of neighboring bits at the transmission distance of 1000 km.

The four average time shift values (i.e., 0, 0, +3, and -3 ps) shown in figure 3.2 correspond to the 4 mutually exclusive combinations of "1" neighboring bit on each side (i.e., 0x0, 1x1, 0x1, and 1x0). Further analyses of "two" and "three" neighboring bits on each side also showed the average time and / or amplitude shift in a given pulse could be determined by using the unique combination of neighboring bits. The average time shift due to "one" and "two" neighboring bits on each side is depicted in figure 3.3. Please note that "X" corresponds to the middle bit which undergoes the timing and/or amplitude shift induced by the neighboring bits. A middle bit could either be a "1" or a "0", but only "1" is considered here as "0" has negligible effect. The different combinations of "three" neighboring bits are given in Appendix A. As far as decision threshold is concerned, we noticed that for RZ and CSRZ the average amplitude change is similar for all combinations of one neighboring bit on each side (shown in Figure 3.2) for this exemplary system.

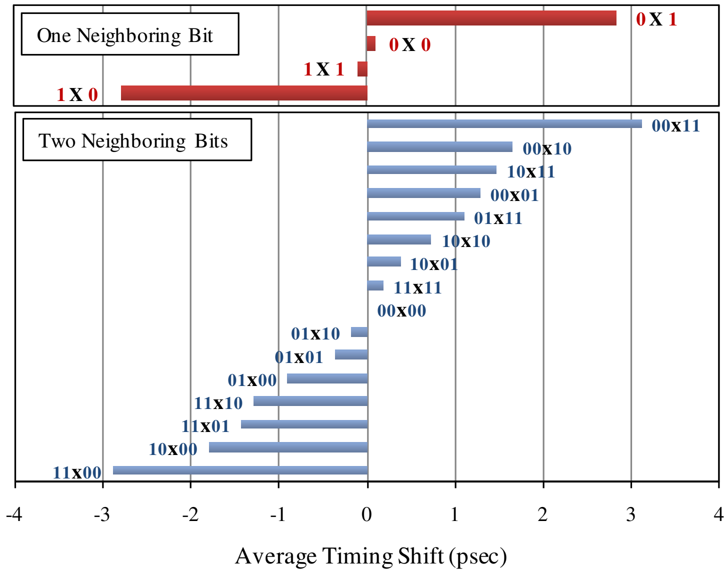


Figure 3. 3. The trend showing the variation of average timing shift in different patterns of neighboring bits.

To undo the timing and/or amplitude jitter caused be the interaction of dispersion and fiber nonlinearity, we propose as novel electronic post-compensation technique. Our proposed technique tends to compensate the timing and/or amplitude shift resulting from nonlinear intra-channel degradations by incorporating the knowledge of the neighboring bits and exploiting the fact that nonlinear degradation, deterministically, depends upon dispersion map and operating channel power. Detailed description of the working principle of proposed scheme is given in the following section.

3.5 Time Delays and Decision Thresholds of DCs

Please note that with *n* neighboring bits on each side, a maximum of 2^{2n} DCs can be used. More neighboring bits require the use of more DCs. However, some of the DCs turn out to have the same time delays and decision thresholds due to symmetric patterns. For example, in the above case, two symmetric combinations of “one neighboring bit” on each side i.e., 0x0 and 1x1 require the same time delay and decision threshold. Therefore, only 3 DCs are actually needed instead of 4. Similarly, we noticed that 2n+1 DCs are sufficient to obtain comparable results as with 2^{2n} DCs for n neighboring bits on each side, as shown in table 2.

Table 3.1: Number of Decision Circuits required for "one" neighboring bit on each side.

No. of DCs Required	DC 1	DC 2		DC 3
Neighboring Bits	1 x 1	1 x 0	0 x 1	0 x 0

Table 3.2: Number of Decision Circuits required for "two" neighboring bits on each side.

No. of DCs Required	DC 1	DC 2	DC 3	DC 4	DC 5
Neighboring Bits	10x00	01x01	11x01	01x10	01x11
	11x00	10x10	11x10	00x00	00x01
	-	-	01x00	10x01	10x11
	-	-	-	11x11	00x10
	-	-	-	-	00x11

3.6 Simulated System Model

A block diagram of the simulated system is shown in figure 3.4. In order to simulate the WDM transmission system, a simulator developed in *C* language was used. The simulator numerically solves Nonlinear Schrödinger Equation using split-step Fourier method and has capability to simulate WDM channels using RZ, CSRZ and DPSK modulation formats at 40 Gb/s data rate. The simulation included fiber effects such as dispersion and nonlinearity accounting for SPM, XPM and FWM.

At the transmitter side, five WDM channels carrying 2^{12} pseudo-random bit pattern (PRBS) each operating at 40 GB/s with 7% FEC overhead were optically modulated using Mach-Zehnder Interferometer (MZI) based modulator. All the channels were then optically multiplexed together and launched into the fiber. Two different dispersion maps of 1000 km length were used to analyze the performance of proposed scheme. Please note that residual dispersion was fully compensated at the end of the link. Total noise calculated was then added at the receiver to estimate the Q factor [60].

At the receive end, the middle channel of the five launched channels was demultiplexed using a 2nd order Gaussian shaped optical band-pass filter (BPF) with 3dB bandwidth of 200 GHz, optimized to limit the crosstalk between the WDM channels. The middle channel was selected because it is evenly affected by neighboring channels. After demultiplexing the middle channel, the optical signal is photo-detected and passed through an electrical LPF with 3dB bandwidth of 30 GHz.

The received signal was then processed using both a conventional receiver and by using the proposed receiver. The model of the conventional receiver contained a single decision circuit (DC) whose optimal decision threshold and sampling time is fixed for all received pulses regardless of the timing and/or amplitude jitter. On the other hand, the optimal decision threshold and sampling time of all the DCs in the proposed technique is preset for different the bit patterns. The processing using conventional receiver was important as it not only provided the information of neighboring bits, but also allowed to evaluate the performance of the proposed technique.

Once the received signal is decoded using single DC conventional receiver, the information of the neighboring bits is then used to select the output of a given DC in the proposed scheme. To show the improvement using proposed technique, the Q-factor is recalculated. The results of processing using both conventional and proposed receiver are discussed in detail in chapter 4.

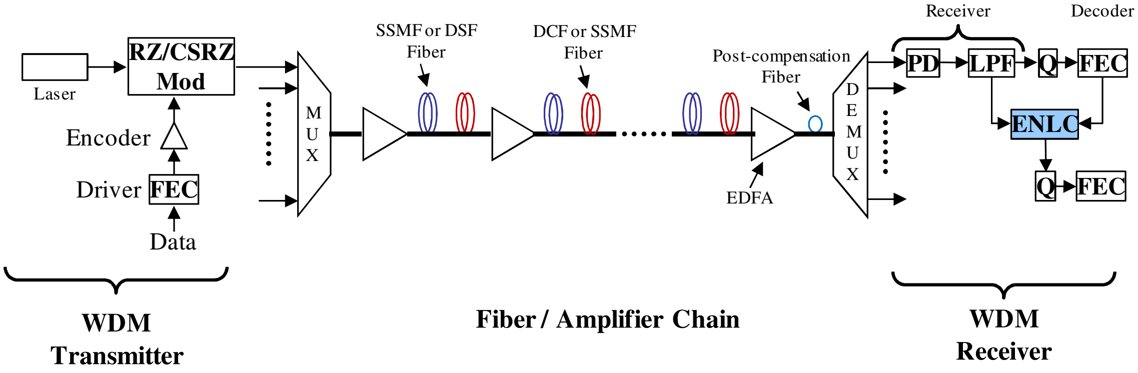


Figure 3. 4. Block diagram of simulated system.

3.7 Summary

As we have seen in this chapter, in high-speed optical communication systems, the complex interaction between dispersion and fiber nonlinearity manifests in timing and/or amplitude jitter. This timing and/or amplitude shift in a give pulse is deterministic as it depends on the neighboring bits with which that pulse interacts over the course of transmission. The proposed electronic nonlinearity post-compensation technique takes advantage of this deterministic behavior and effectively enhances the performance optical communication system operating at ≥ 40 Gb/s data rates.

Chapter 4

Transmission Results and Discussion

4.1 Transmission Results for Intensity Modulated System

To explore the validity of the proposed technique, we performed the simulations of 42.7 Gb/s (40 Gb/s data rate + 7% FEC overhead) RZ and CSRZ modulated WDM system using the model shown in figure 3.4. We simulated two different dispersion maps. In the first dispersion map hereafter referred to as DSF+SSMF, each fiber span consisted of 80 km of dispersion shifted fiber (DSF) followed by 20 km of standard single mode fiber (SSMF). In the second dispersion map (SSMF+DCF), each span consisted of 100 km of transmission SSMF followed by 20 km of lumped dispersion compensating fiber (DCF). The typical fiber parameters used in the simulations are given in table 5.3. The total losses in DSF+SSMF and SSMF+DCF dispersion were 25dB and 35dB, respectively. To compensate total span losses in both dispersion maps, we used two stage EDFA (noise figure = 6dB). The path average dispersion for both dispersion maps was -0.1ps/nm-km. A fixed post-dispersion compensation was used before the demultiplexer where all the channels were still combined.

Table 4.1: Typical Fiber parameters for the two dispersion maps

Dispersion Map	Fiber	Loss (dB/km)	Dispersion (ps/nm-km)	A_{eff} (μm^2)	Length (km)
DSF+SSMF	DSF	0.25	-4.5	50	80
	SSMF	0.25	+18	80	20
SSMF+DCF	SSMF	0.25	+18	80	100
	DCF	0.50	-90	25	20

Five WDM channels each carrying 4096 PRBS were modulated with RZ and CSRZ modulation formats (extinction ratio = 12dB) before optical multiplexing. The propagation of multiplexed WDM signal was simulated using the split step Fourier scheme. The total calculated amplifier noise was added at the receiver before the photo-detector (PD) to calculate an average bit error rate (BER) using the BER of each bit separately [60]. The average BER was then converted to a Q value to evaluate the system performance.

First, we simulated both RZ and CSRZ modulation formats with 200 GHz channel spacing for 1000 km of transmission distance by varying the average channel power and calculated the Q value of the middle of 5 simulated WDM channels using the conventional receiver. The resulting Q values vs. average channel power are shown (as dashed lines) in figure 4.1a and 4.1b, respectively for RZ and CSRZ modulation formats. We then used the proposed receiver with multiple DCs by using the neighboring bits as a guide to which DC should be chosen for the final decision for a given bit. We re-calculated the Q values using the proposed technique with 4, 16 and 64 DCs, respectively, for 1, 2 and 3 neighboring bits on each side. The resulting Q values are plotted (as solid lines) in figures 4.1a and 4.1b, respectively for RZ and CSRZ modulation formats, showing that the proposed technique can increase the overall system margin by more than 1.5 dB using 3 neighboring bits on each side for both RZ and CSRZ modulation formats.

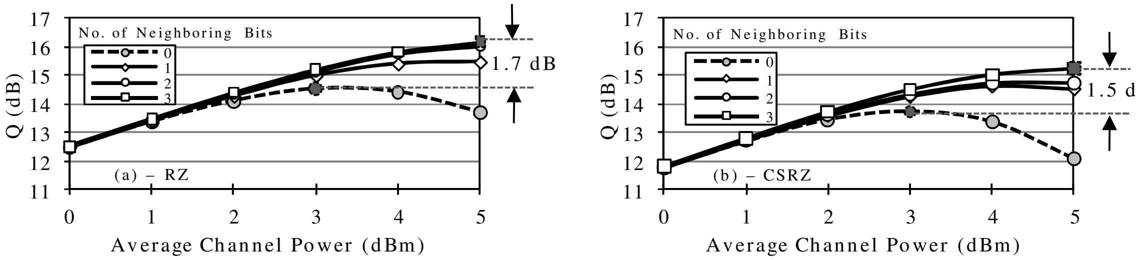
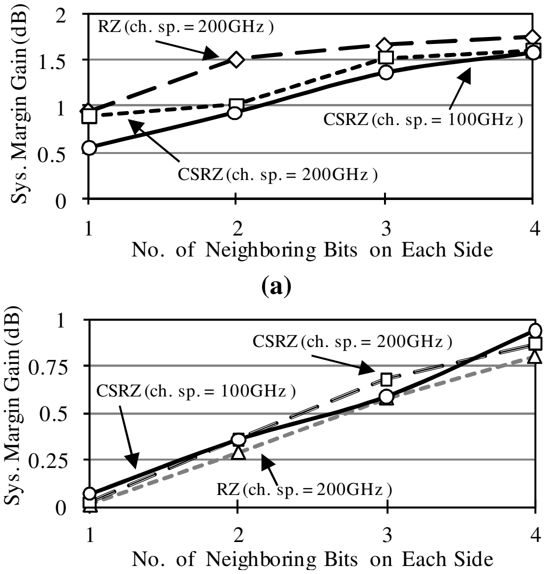


Figure 4. 1. Q vs. average channel power for 42.7 Gb/s WDM transmission system after 1000 km transmission distance for (a) RZ and (b) CSRZ modulation formats. The three curves with solid lines are for using the proposed technique with 1, 2 and 3 neighboring bits on each side.

We also recalculated the Q values using only 2n+1 DCs instead of 2^{2n} DCs, where *n* is the number of neighboring bits on each side. We noticed that 2n+1 DCs are sufficient to obtain comparable results as shown in Figure 4.2a. In Figure 4.2a, we have plotted the system margin improvement versus number of neighboring bits on each side using only 2n+1 DCs, which shows that ~1.5 dB system margin is achievable with 3 neighboring bits on each side for both RZ and CSRZ modulation formats with 200 GHz channel spacing.

Finally we repeated the WDM simulations for SSMF+DCF dispersion map. We simulated the three systems; 200 GHz RZ, 200 GHz CSRZ and 100 GHz CSRZ systems and the achieved system margin improvement for all three systems is also shown in figure 4.2b. We noticed that the system margin improvement increases linearly with number of neighboring bits for all simulated systems as opposed to saturation effect which was observed in DSF+SSMF dispersion map.



(a)

(b)

Figure 4. 2. System margin gain vs. number of neighboring bits on each side for 200-GHz RZ and CSRZ, and 100-GHz CSRZ systems at transmission distance of 1000 km. (a) DSF + SSMF dispersion map (b) SSMF + DCF dispersion map.

We then repeated the WDM simulations for CSRZ with 100 GHz channel spacing (please note that RZ with 100 GHz channel spacing was not possible due to linear crosstalk resulting from large bandwidth). Although, the optimal system Q value was decreased by 2.3 dB in 100

GHz CSRZ system (not shown) as compared to 200 GHz CSRZ system because of increased cross-phase modulation at lower channel spacing, the resulting system margin improvement was still similar to that of 200 GHz system using 2 or more neighboring bits on each side with only a handful of DCs as shown in Figure 4.1a. This shows that the intra-channel degradation caused by fiber nonlinearity is comparable in both 100 and 200 GHz WDM systems.

4.2 Transmission Results for Phase Modulated System

The performance of proposed technique has been evaluated by using RZ-DPSK modulation format. Since the information in RZ-DPSK systems is encoded in the relative phase change for the two consecutive pulses, therefore, each pulse representing “1” or “0” bit is neighbored by similar pulses on each side. This suggests that the average time shift in a given pulse is expected to be almost zero regardless of its neighboring bits, implying that multiple DCs in the proposed technique for the RZ-DPSK system will have similar time delays. However, because the nature of the detection is different in the RZ-DPSK system, the distinct combination of neighboring bits can manifest in distinct decision thresholds. To estimate these distinct decision thresholds, a typical RZ-DPSK received signal after Mach-Zehnder delay interferometer (MZDI) can be split into selective bit patterns based upon 4 unique combinations of neighboring bits i.e., 0x0, 0x1, 1x0 and 1x1. The resulting 4 subsets of eye diagram are shown in figure 5.1. Two unique combinations, i.e., 0x0 and 1x1 produce asymmetrical eye diagrams suggesting that the optimal decision thresholds for these patterns can be moved in the opposite direction. On the contrary, 0x1 and 1x0 combinations produce symmetrical eyes suggesting that the decision thresholds can be close to zero for these combinations. This can be explained by noticing that 0x0 or 1x1 combinations of bits will affect the middle bit differently depending upon “1” or “0” as the middle bit. For example, the combination “000” or “111” have no phase change relative to the middle bit on each side but 010 or 101 will have a phase change on either side with respect to the middle bit. The asymmetrical phase change in 0x0 or 1x1 patterns manifests as asymmetrical eyes. Similarly, 1x0 or 0x1 will have a phase change on only one side of the middle bit for either

"1" or "0" as the middle bit producing symmetrical eyes as shown in figure 4.3. Therefore, in the RZ-DPSK system, the three different DCs with distinct decision thresholds can be used for the three unique combinations of one neighboring bit on each side i.e., 0x0, 0x1/1x0, and 1x1.

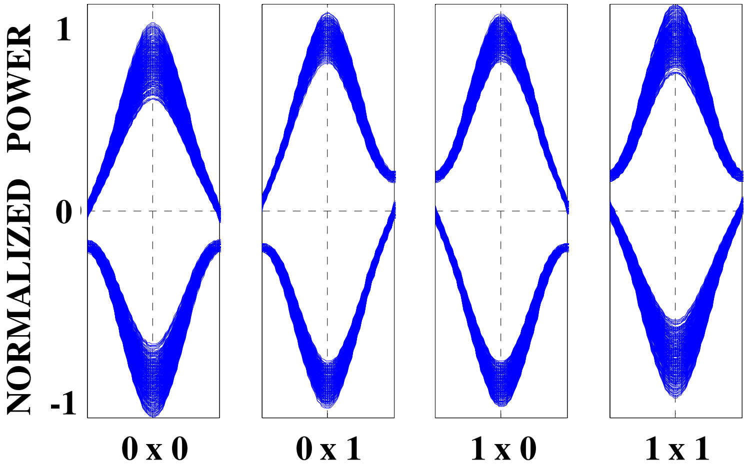


Figure 4. 3. The subsets of eye diagram for selective bit patterns for RZ-DPSK system at the transmission distance of 2000 km.

We analyzed the performance of our proposed technique for RZ-DPSK modulation format using WDM system have channel spacing of 200 GHz for the transmission distance of 2000 km. The resulting Q values for the WDM case are plotted vs. average channel power in figure 4.4, showing that almost 1 dB system margin can be obtained using the proposed technique for RZ-DPSK system.

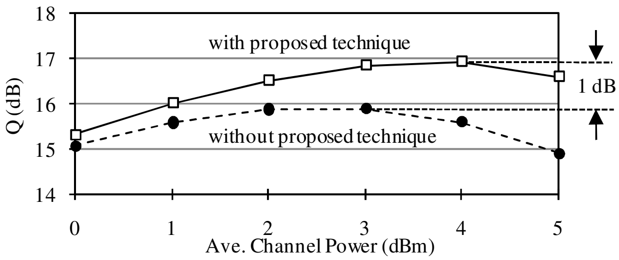


Figure 4. 4. Q of the middle channel vs. average channel power for 42.7 Gb/s WDM RZ-DPSK system at a transmission distance of 2000 km.

4.3 Discussion

The majority of the gain using the proposed technique for DSF+SSMF dispersion map comes from 4 DC case using only one neighboring bit on each side. This is because the nonlinear interaction in this dispersion map is more significant in the beginning of the fiber span when the power is high. Low fiber dispersion (-4.5 ps/nm-km) value at the beginning of the span limits pulse spread. Similarly, due to fiber loss (0.25dB/km) pulses lose power along with the distance reducing nonlinear interactions with neighboring pulses. Therefore, the pulses can only strongly interact with their first immediate neighbors during the first 10 – 15 km of transmission in each span where optical pulse power is strong enough.

On the other hand, for SSMF+DCF dispersion map, high dispersion value of SSMF fiber (+18ps/nm-km) allows optical pulses to spread very quickly and interact with a number of neighboring bits in the beginning of the fiber when channel power is high. Therefore, many neighboring bits are needed to be included for this dispersion map to obtain a reasonable system margin improvement using the proposed technique. As shown in figure 4.2b, more than 4 neighboring bits are needed for this dispersion map to obtain ~1 dB system margin improvement, using the proposed technique.

4.4 Summary

We have proposed a novel scheme to electronically post-compensate fiber nonlinearity in ≥ 40 Gb/s WDM transmission systems. The scheme works by incorporating the knowledge of the neighboring bits to compensate the amplitude and timing jitter caused by the nonlinear interaction of neighboring bits. We tested our proposed scheme on a 42.7 Gb/s WDM transmission system using both RZ and CSRZ modulation formats and found that, depending upon the dispersion map, the proposed technique can effectively enhance the overall system margin by more than 1.0 dB in both RZ and CSRZ WDM transmission systems.

Chapter 5

Conclusion & Future Work

5.1 Overview

This chapter summarizes the research work carried out presented in this thesis. A proposal to enhance the capability of the proposed electronic nonlinearity compensation schemes is also presented.

5.2 Conclusion

The main aim of the research work presented in this thesis is to propose a novel electronic technique which could effectively undo the degradation caused by the interaction of dispersion and fiber nonlinearity in ≥ 40 Gb/s WDM transmission systems. As data rate increases, optical fiber communication mainly suffers from intra-channel nonlinearities such as SPM, IXPM and IFWM. The interaction between dispersion and intra-channel nonlinearities manifests in terms of amplitude and/or timing jitter. We observed that the timing and/or amplitude shift in any given pulse depends upon the neighboring bits, with which that pulse interacts over the course of the transmission. On basis of our observations, we propose an electronic post-compensation technique which tends to compensate this timing and amplitude shift resulting from degrading nonlinear effects in a single channel by incorporating the knowledge of the neighboring bits and exploiting the fact that nonlinear degradation, deterministically, depends upon dispersion map and operating channel power.

We validated the working of proposed scheme by simulating 42.7 Gb/s WDM transmission system by using RZ and CSRZ modulation formats. The degrading effects were analyzed using two different dispersion maps. For both modulation formats and both dispersion maps, our technique effectively improved overall system margin by 1 dB.

5.3 Future Work

The work presented in this thesis could be further extended by using more advanced modulation formats. An example of advanced modulation format is DQPSK which is becoming more popular in high-speed WDM transmission systems. DQPSK is a multi-level modulation format which operates on lower symbol rate [46]. Due to it lower symbol rate, it has narrower spectrum providing high tolerance to dispersion. It would be interesting to see how dispersion and nonlinearity interact and degrade the performance of transmission system. Although changes in the receiver would be required, but the principle of neighboring bits could still be applied for any system in which neighboring bits are affected.

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Appendix

This research work has resulted in following conference papers:

1. Nisar Ahmed and M. I. Hayee, "Electronic Compensation of Optical Fiber Nonlinearity in on-off Keyed 40 Gb/s WDM Transmission Systems," in Frontiers in Optics, OSA Technical Digest (CD) (Optical Society of America, 2009), paper FTuC3

2. Nisar Ahmed and M. I. Hayee, “Electronic Compensation of Fiber Nonlinearity for 40 Gb/s WDM Transmission Systems”, LEOS Annual Meeting Conference Proceedings, 2009. LEOS '09. IEEE, pp.197-198, 4-8 Oct. 2009.

A patent application has also been filed with United States Patent & Trademark Office (USPTO).