Performance Enhancement of WDM Optical System with Coherent Detection

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CERTIFICATE

This is to certify that the thesis entitled **Performance Enhancement of WDM Optical System with Coherent Detection** has been prepared by **Mr. Rohit Bhimjibhai Patel (11EXTPHDE61)** under my supervision and guidance. The thesis is his own original work completed after careful research and investigation. The work of the thesis is of the standard expected of a candidate for **Ph.D. Programme** in **Electronics and Communication Engineering** and I recommend that it be sent for evaluation.

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ABSTRACT

Wavelength division multiplexed (WDM) optical communication is rapidly growing with deployment of multilevel modulation formats. Efficient utilization of optical fiber bandwidth with high spectral efficiency is the key advantage of this technology for long transmission reach. However, fiber linear and nonlinear impairments are still the challenges which prevent the growth of WDM optical communication at high data rates. Coherent detection technique with digital signal processing (DSP) at the receiver end has shown the capability to overcome these challenges. Further, multi-carrier generation at transmitter and the use of polarization division multiplexed (PDM) multi-level modulation format are the solutions to enhance the spectral efficiency of the system with narrow spacing between channels.

In this thesis, multi-carrier generation concept is applied at transmitter side employing coherent detection technique with DSP at receiver end to enhance the performance of WDM optical system. Polarization division multiplexed quadrature phase shift keying (PDM QPSK) and polarization division multiplexed 16- quadrature amplitude modulation (PDM 16-QAM) are used to realize the WDM optical system for long reach at high transmission rates. Hybrid transmission approach has also been considered in designing the system to represent the system performance in the dual modulation environment. Q-factor, Log of Estimated symbol error (Log (ESE)) and error vector magnitude (EVM) are considered as a performance metrics. Simulation results are obtained using optisystem software.

The performance of 12 x 160 Gb/s (1.92 Tb/s) wavelength division multiplexed WDM optical system employing dual carrier and coherent detection with DSP is investigated for three different cases: gray coding, with differential coding and without any coding. Results are compared for 100 km transmission using polarization division multiplexed quadrature phase shift keying (PDM-QPSK) format. The results exhibit that system with differential coding performs better in comparison with gray coding and without any coding technique. Improvement of 2 to 5 dB in Q factor is found for system using differential coding. Moreover, performance evaluation for long transmission distance up to 8000 km is carried out for WDM optical system with differential coding technique with maintaining the Q factor beyond the FEC limit (BER value 3.8 x 10^{-3}).

An effort is made to investigate the performance of 4 x 200 Gbps (800 Gb/s) coherent WDM Optical systems employing dual carrier concept for polarization division multiplexed 16-quadrature amplitude modulation (PDM 16-QAM) modulation format. Results are compared for the system with nonlinearity compensation and without nonlinearity compensation at the receiver end. Improvement in Q factor is observed almost 2.43 dB to 1.95 dB for system with nonlinearity compensation than system without nonlinearity compensation at 6 dBm power per channel for 200 km to 1000 km transmission reach. Spectral efficiency of 4 b/s/Hz is achieved by keeping 50 GHz channel spacing between generated sub-carriers. Another approach is made to evaluate 10 x 100 Gbps coherent WDM optical system using hybrid modulation. WDM system is designed using PDM QPSK and PDM 16-QAM modulation formats in combination with dual carrier concept. Results are reported with ULAF fiber and SSMF fiber for WDM optical system. System with ULAF fiber shows better results due to less influence of fiber nonlinearity at 2500 km transmission reach.

A Comparative analysis is carried out of of 23 x 100 Gbps (2.3 Tb/s) WDM Optical systems employing multicarrier generation for three different fibers: ultra large area fiber (ULAF), standard single mode fiber (SSMF) and large effective area fiber (LEAF). Enhancement in Q-factor is observed almost 3.21 dB and 4.63 dB for system with ULAF fiber than system with SSMF and LEAF fibers respectively for 5000 km transmission reach. Performance comparison is also carried out using ultra large area fiber (ULAF) and large effective area fiber (LEAF) for 39 x 100 Gbps (3.9 Tb/s) hybrid transmission WDM optical system employing multicarrier generation. Among 39 carriers, 20 sub-carriers utilize PDM-QPSK modulation format and 19 sub-carriers use PDM 16-QAM format. It is found that deployment of ULAF fiber outperforms than LEAF fiber in the system at long transmission reach.

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DECLARATION

I, **Rohit Bhimjibhai Patel**, registered as Research Scholar, bearing Registration No. **11EXTPHDE61** for Doctoral Programme under the **Faculty of Technology and Engineering** of Nirma University do hereby declare that I have completed the course work, pre-synopsis seminar and my research work as prescribed under R. Ph.D. 3.5.

I do hereby declare that the thesis submitted is original and is the outcome of the independent investigations / research carried out by me and contains no plagiarism. The research is leading to the discovery of new facts / techniques / correlation of scientific facts already known. This work has not been submitted to any other University or Body in quest of a degree, diploma or any other kind of academic award.

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Date: 19/09/2018

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Dr. D. K. Kothari
Guide

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List of Abbreviations

ASE	Amplified Spontaneous Emission
BER	Bit Error Rate
CD	Chromatic Dispersion
CW	Continuous Wave
CWDM	Coarse Wavelength Division Multiplexing
DCF	Dispersion Compensating Fiber
DFE	Decision Feedback Equalizer
DSP	Digital Signal Processing
DWDM	Dense Wavelength Division Multiplexing
EDC	Electronic Dispersion Compensation
EDFA	Erbium-doped Fiber Amplifier
ESE	Estimated Symbol Error
EVM	Error Vector Magnitude
FBG	Fiber Bragg grating
FEC	Forward Error Correction
FFE	Feed Forward Equalizer
FWM	Four Wave Mixing
GVD	Group Velocity Dispersion
LASER	Light Amplification by Stimulated Emission and Radiation
LEAF	Large Effective Area Fiber
MLSE	Maximum Likelihood Sequence Estimator
MUX	Multiplexer
NRZ	Non Return to zero
OA	Optical Amplifier
OPC	Optical Phase Conjugation
OSNR	Optical Signal to Noise Ratio
PDM	Polarization-division multiplexing
PMD	Polarization mode dispersion
QAM	Quadrature Amplitude Modulation
Q-FACTOR	Quality Factor
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency

Chapter 1 Introduction

In the last two decades, the optical fiber has become the primary and attractive transport medium for metro, regional and global telecommunications (Alfiad, M S; Kuschnerov, M; Wuth, T; Jansen, S J;). Commercial fiber-based communications companies have achieved communication beyond 10 Gb/s and 40 Gb/s data rate per-wavelength. In earlier days, the optical communication systems were deployed for operating around 850 nm wavelength window due to the availability of optical sources and photo detectors. However, the wavelength bands used for the optical communication are S, C and L-band. S-band was defined surrounding the wavelength of 1310 nm. It was having better performance due to lower attenuation in optical fiber. The third optical fiber window was C-band around 1550 nm wavelength range, which has almost uniformly lowest optical loss for the wavelength band. Another wavelength window covering 1625 nm wavelength for optical communication is under progress. This wavelength window is fourth wavelength window and lies in L-band (Agrawal; Govind). In the eighties, transport links typically carried a few hundred megabits per second. Regenerators at intervals of 40 km or so were required at that time. The length between regenerators was largely affected by the loss in the fibers. The transport data rate was limited by fiber dispersion and nonlinearities. Optical fibers have potential of huge information-carrying capacity, but they achieved widespread commercial success only after the development of optical amplification techniques. In the late eighties and early nineties with erbium-doped fiber amplifier (EDFA) was developed. EDFA allows to achieve long distance WDM optical communication due to its ability of wide band amplification. Thus, cost efficient data transport systems with increased system capacity was available. Simultaneously use of internet-connected computers was deployed with EDFA/WDM data transport technology (Mazurczyk, M;).

RF communication is also widely used for communication and mobile data connection. RF communication and optical communication both is lifeline of the society. RF communication and optical communication both have their own limitations and advantages. Both communication techniques can be compared with reference to two major parameters: Bandwidth and Non-linearity. RF communication provides limited bandwidth compared to optical bandwidth. Optical communication provides bandwidth of approximately 10THz which is far better than RF bandwidth. Optical network can carry extremely high data rate compared to a RF line which is impossible for RF communication to achieve because of its bandwidth limitation (RF and Optical Comparison Ref.). However, effects of fiber Dispersion and nonlinearities at higher data rate with tight channel spacing in WDM fiber optical system is a major issue to be addressed for future evolution of WDM optical systems. So, fiber impairment is considered a major challenge to WDM system, which is addressed in this thesis.

1.1 Motivation

There are different dispersion and nonlinearity compensation techniques like Dispersion compensating fiber, Fiber Bragg grating, Optical phase conjugation and Electronic dispersion compensation. Each of these has their own merits and demerits. Dispersion compensating fiber technique compensate positive dispersion of standard single mode fiber with its highly negative dispersion coefficient. DCF is used in different configuration like pre, post and mix compensation to compensate the optical system dispersion in a better way. However, due to the small size of core diameter, nonlinear effects are highly increased in optical system at high transmission power and fail to improve the performance of optical system at long reach (Agarwal, Ruchi; Mishra, Vivekanand;). Fiber Bragg grating is another attractive dispersion compensation technique, which is compact, passive and linear. It is used in transmission and reflection configurations and both possess high dispersion. Variable optical path lengths are obtained for different wavelengths contained in dispersed pulses from various positions in the grating. Though the results of this technique are impressive for dispersion compensation, it requires 3 dB coupler or optical circulator. It is difficult to design and fabricate complex grating structures of fiber Bragg grating method (Litchinitser, Natalia M; Benjamin, J Eggleton; Patterson, David B;). Transmission grating is used in line in the optical system, which is better solution than reflection type grating. But the maximum obtainable compression ratio has been limited severely due to small bandwidth of high dispersion regions in the spectrum of transmission grating. FBG has narrow range of optical wavelength to compensate which is not suitable for broad range wavelength optical communication system (Gnanagurunathan, Gnanam; Rahman, Faidz Abd;). Optical phase conjugation technique is also promising technique for dispersion and nonlinearity compensation of optical communication system. The signal phase in one segment of transmission link is conjugated by OPC to cancel the nonlinear phase shift generated in the second segment (Minzioni, Paolo;). However, for exact cancellation of nonlinearity, significant symmetry surrounding phase conjugator is required, which affects the flexibility of optical communication system. Perfect compensation with OPC can demand the identical fiber properties throughout optical transmission system and symmetrical power distribution, which is extremely impractical in realization. Feed forward equalizer with decision feedback equalizer (FFE-DFE) used as an electronic dispersion compensator at receiver side of optical system. However, performance of the system is limited with noise development due to FFE part and error propagation from the decision part (Xia, Chunmin; Werner, Rosenkranz;). Electronic dispersion compensator formed using Viterbi algorithm based Maximum likelihood sequence estimator (MLSE) allows detection with minimum bit error probability. Though MLSE is effective for mitigation of chromatic dispersion induced by inter-symbol interference, fiber nonlinearity limits its performance. Penalty in optical signal to noise ratio increases after certain dispersion level which creates fundamental limitation for MLSE to recover the penalty of chromatic dispersion. The growth of the penalty due to dispersion decides the complexity of MLSE (Zhu, Xianming, et al.;).

Coherent detection with DSP at the receiver end is considered as a promising solution in this situation for multi-channel wavelength division multiplexed optical communication systems. This technique exhibits high tolerance to carrier phase noise and resulting in better nonlinearity compensation. Chromatic dispersion and polarization mode dispersion are also compensated by DSP utilizing adaptive equalizer and digital back propagation modules. Spectral efficiency is also enhanced with the utilization of multilevel modulation formats with two degree of freedom per polarization PDM 16-QAM and PDM QPSK. This motivates to apply coherent detection with DSP technique to improve the performance of WDM optical communication systems employing higher data rate for long transmission reach.

1.2 Research Objectives

Based on the study of different impairments of WDM optical system and their mitigation techniques available currently in the literature, following research objectives are addressed in this thesis.

- Study of WDM optical communication systems for long reach.

- Performance evaluation of WDM systems considering the effects of dispersion and nonlinearity of fiber for dual carrier system.
- Design and analysis of multi-carrier WDM optical system using PDM QPSK modulation format.
- Design and analysis of hybrid transmission multi-carrier WDM optical system and to compare the obtained results with the published article to identify the performance improvement with multi-carrier concept at transmitter side and coherent detection with DSP approach at receiver end of WDM optical system.

1.3 Contribution to Thesis

In this thesis, the research objectives defined in the above section are addressed and attempt is made to utilize multi-carrier generation at transmission side and coherent detection with DSP at the receiver side, which can improve the performance of WDM optical system with increased spectral efficiency at long reach. Also attempt is made to design hybrid transmission multi-carrier WDM system, which supports the multiple multilevel modulation formats in same transport system for long haul communication. The contribution in this thesis are as follows:

1.3.1 WDM Coherent PDM-QPSK optical systems employing Dual Carrier

The main goal of this work is, to explore design of wavelength division multiplexed WDM optical system employing dual carrier at 1.92 Tb/s. Optical carriers are generated using three CW lasers. Two dual tone generators are utilized to generate twelve sub carriers, each with 80 GHz spacing apart. 160 Gbps is carried out by each subcarrier carrier ensuing the spectral efficiency of 2 b/s/Hz for WDM optical system. Performance of 12 x 160 Gb/s (1.92 Tb/s) polarization division multiplexed quadrature phase shift keying (PDM-QPSK) WDM optical systems are compared for three different cases like with gray coding, with differential coding and without any coding for 100 km transmission reach. Performance of WDM system with differential coding is evaluated at long reach.

The obtained results show that WDM optical system utilizing differential coding performs better than other two systems. Differential coding mitigates probability of burst errors due to cycle slips. Improvement of 2 to 5 dB in Q factor is found for system using differential coding. Each channel of 160 Gb/s with spacing of 80 GHz apart resulting in 2 b/s/Hz of spectral efficiency. Transmission reach is extended up to 8000 km for PDM-QPSK WDM optical system employing differential coding with maintaining the Q factor beyond the FEC limit (BER value 3.8 x 10^{-3}).

1.3.2 WDM Coherent optical systems employing Dual Carrier with PDM 16-QAM and Hybrid approach

The main goal of this work is, to explore design and performance of 4 x 200 Gbps (800 Gb/s) WDM Optical systems employing dual carrier concept. Each carrier of dual carrier transmits data at a transmission rate of 200 Gbps using polarization division multiplexed 16-quadrature amplitude modulation (PDM 16-QAM) modulation format. Extensive Simulations are carried out for WDM optical system with and without nonlinearity compensation at receiver for Ultra Large Area Fiber (ULAF). 4 b/s/Hz spectral efficiency is obtained for WDM optical system at the data rate of 200 Gb/s keeping 50 GHz channel spacing between carriers. Performance parameter like symbol error rate, error vector magnitude and Q-factor are verified for comparison. Another design of 10 x 100 Gbps coherent WDM optical system using hybrid modulation approach is also investigated. WDM system is designed using PDM QPSK and PDM 16-QAM modulation formats in combination with dual carrier concept. Results are reported with ULAF fiber and standard single mode fiber (SSMF) fiber for WDM optical system.

The performance is evaluated for systems with nonlinearity compensation and without nonlinearity compensation at receiver from 200 km to 1000 km. Q factor is almost 2.43 dB to 1.95 dB higher for system with nonlinearity compensation than system without nonlinearity compensation at 6 dBm power per channel for 200 km to 1000 km transmission reach. EVM values are reduced from 0.78% to 1.33% in system with nonlinearity compensation. Log of

Estimated symbol error (ESE) is 41.2% lower in system with nonlinearity compensation at 1000 km. Spectral efficiency of 4 b/s/Hz is achieved by keeping 50 GHz channel spacing at the data rate of 200 Gb/s of each sub-carrier. Dual Carrier PDM 16-QAM WDM optical system with nonlinearity compensation outperforms than the system without nonlinearity compensation. Performance of 10 x 100 Gbps WDM Optical systems using hybrid modulation employing dual carrier concept for WDM optical system is verified for the transmission distance up to 2500 km. The performance of WDM optical system is assessed with utilization of ULAF and SSMF fibers. Due to higher effective area, nonlinearity influence is low in case of system with ULAF fiber. WDM optical system with ULAF fiber outperforms in comparison with system with SSMF fiber.

1.3.3 WDM Coherent PDM-QPSK 2.3 Tb/s (23 ch.x100 Gb/s) Multi-carrier WDM Optical Transmission Systems

The main goal of this work is, to explore design and performance of 23 x 100 Gbps (2.3 Tb/s) WDM Optical systems employing multicarrier generation concept. Each sub carrier transmits at a transmission rate of 100 Gbps using PDM-QPSK modulation format with spacing of 25 GHz between sub carriers. The analysis is carried out for 23 x 100 Gb/s (2.3 Tb/s) PDM-QPSK WDM optical systems with ultra large area fiber (ULAF), standard single mode fiber (SSMF) and large effective area fiber (LEAF) at transmission reach from 600 km to 5000 km. Coherent detection with DSP is used for all the systems at the receiving end.

The performance of WDM coherent 23 x 100 Gbps (2.3 Tb/s) multi-carrier systems is evaluated using different fibers like ULAF, LEAF and SSMF for long reach. Enhancement in Q-factor is observed almost 1.66 dB to 3.21 dB and 2.08 dB to 4.63 dB for system with ULAF fiber than system with SSMF and LEAF fibers respectively for 600 km to 5000 km transmission reach. Lower EVM values are found around 2.24% to 2.68% and 2.68% to 12.43% in system with ULAF than other two systems using SSMF and LEAF fibers respectively. Log of Estimated symbol error (ESE) of system with ULAF is lower than systems with SSMF and LEAF at 5000 km. 25 GHz channel spacing is kept between sub-carriers to achieve spectral efficiency of 4 b/s/Hz at the data rate of 100 Gb/s of each sub carrier. PDM-QPSK WDM optical system with ULAF outperforms than the systems with SSMF and LEAF fibers at long transmission reach.

1.3.4 Hybrid Transmission Multi-carrier 3.9 Tb/s (39 ch.x100 Gb/s) WDM Optical System

The main aim of this work is to explore co-existence of multilevel phase and amplitude modulation formats to enable a new generation of high speed optical transport platform. 39 x 100 Gbps (3.9 Tb/s) hybrid transmission WDM optical system employing multicarrier generation concept is developed. 20 sub-carriers utilize PDM-QPSK modulation format and 19 sub-carriers use PDM 16-QAM out of 39 sub-carriers. Each sub-carrier transmits at a transmission rate of 100 Gbps with frequency spacing of 25 GHz between sub-carriers to achieve spectral efficiency of 4 b/s/Hz. The analysis is carried out for 39 x 100 Gb/s (3.9 Tb/s) hybrid WDM optical system with ultra large area fiber (ULAF) and large effective area fiber (LEAF) at transmission reach from 600 km to 4000 km. Systems are verified with parameters like Q-factor, estimated symbol error and error vector magnitude (EVM). Analytical and simulation results are presented.

The design is demonstrated for hybrid transmission of PDM-QPSK and PDM 16-QAM formats in WDM optical system for 39 x 100 Gb/s (3.9 Tb/s). 25 GHz channel spacing is kept between sub-carriers to achieve spectral efficiency of 4 b/s/Hz at the data rate of 100 Gb/s of each sub-carrier. 20 channels carry data with PDM QPSK format and 19 channels carry data with PDM 16-QAM format. The performance is evaluated for hybrid system with ULAF and LEAF fibers at transmission reach from 600 km to 4000 km. Enhancement in Q factor is observed almost around 6.93 dB and 7.05 dB higher with PDM QPSK modulation and 4.72 dB and 3.54 dB with PDM 16-QAM modulation in hybrid system using ULAF fiber than system with LEAF fiber respectively for 600 km to 4000 km transmission reach. EVM is 7.42% to 12.79% and 5.32% to 2.87% lower for hybrid system with ULAF in comparison with hybrid system using LEAF for PDM QPSK and PDM 16-QAM respectively. Log of Estimated symbol error (ESE) of hybrid system with ULAF is lower than system with LEAF at 4000 km. Hybrid transmission WDM optical system with ULAF outperforms than the system with LEAF fiber at long transmission reach.

1.4 Organization of thesis

The rest of the thesis is organized as follows.

Chapter 2 presents the working and classification of wavelength division multiplexed optical communication systems. A comparison of WDM system with existing technology is carried out. Various challenges of WDM system are presented and possible solutions are discussed. Fiber dispersion and nonlinearities are found as a major challenge. Different detection methods for optical system are discussed and compared. Different techniques for dispersion and nonlinearity compensation have been reviewed and found that coherent detection with DSP is most suitable for multi-carrier wavelength division multiplexed long haul optical communication system at high transmission rate.

Polarization division multiplexed quadrature phase shift keying (PDM-QPSK) 12 x 160 Gb/s (1.92 Tb/s) WDM optical system is presented in chapter 3. The performance of the system is evaluated by considering no coding, with gray coding and with differential coding for 100 km transmission distance by extensive simulation. The performance of the system is compared for different coding techniques with Q-factor. Log of estimated symbol error rate and error vector magnitude are considered as other parameters to judge the system performance. Long distance transmission of the system with differential coding is verified using coherent detection with DSP at the receiver side.

The performance of 4 x 200 Gbps WDM optical system is reported using polarization division multiplexed 16-quadrature amplitude modulation (PDM 16-QAM) modulation format in chapter 4. Dual carrier generation concept is deployed with 200 Gb/s data rate for each channel in WDM optical system. Results are reported for the system for long reach with and without fiber nonlinearity compensation at the receiver side. Effect of hybrid modulation (polarization division multiplexed quadrature phase shift keying (PDM QPSK) and polarization division multiplexed 16-quadrature amplitude modulation (PDM 16 QAM)) scheme is also examined for the 10 x 100 Gbps coherent WDM optical systems. Performance of the system is compared with standard single mode fiber and ultra large area fiber in this chapter.

Chapter 5 presents a coherent WDM optical systems with multicarrier generation concept applied at transmitter side. The system contain 23 sub carriers with 100 Gb/s data rate of each channel, which exhibits the transmission rate of 2.3 Tb/s for the WDM systems. Performance of the system is compared with analytical and simulation results using SSMF, LEAF and ULAF fibers. Results are reported with high spectral efficiency at long transmission reach. Similarly, co-existence of multilevel phase and amplitude modulation formats is investigated for 39 x 100 Gbps (3.9 Tb/s) hybrid transmission WDM optical system. Performance comparison is carried out for system with different fibers like ULAF and LEAF for long reach. Channel spacing is reduced with multi carrier generation concept to enhance spectral efficiency. Hybrid transmission is detected separately with separate provision of coherent detection with DSP arrangement for PDM QPSK format and PDM 16-QAM format. Results are compared with mathematical analysis and through simulations for WDM optical systems.

Lastly, the conclusion of this thesis is presented in chapter 6. The points are identified for future research based on this work and reported in this chapter.

Chapter 2 Literature Review

The current traffic scenario in optical transport network requires data rate as high as 100 Gb/s and beyond. This has given rise to efficient modulation formats with high symbol rate such as two or more bits per symbol. Recently, high speed Wavelength Division Multiplexing (WDM) optical systems using multi-level modulation formats are in demand for long distance communication. (WDM) is a technique to utilize optical fiber bandwidth efficiently and to increase the data transport capacity of an optical fiber. In WDM, data is transmitted simultaneously on multiple wavelengths. Multilevel modulation set-up with polarization division multiplexed (PDM) schemes are preferred for future WDM systems (Curri; Vittorio, et al.).

Such increased transmission capacity is obtained at the cost of increased linear and nonlinear impairments of fiber. As the light signals travel up to long distance in the fiber, the signals are degraded due to linear and non-linear fiber impairments (Zhu Xianming, et al;). Various linear impairments like Attenuation of the signal, dispersion caused by Polarization Mode Dispersion (PMD), Amplified Spontaneous Emission (ASE) and dispersion due to Chromatic Dispersion (CD) and various nonlinear impairments like Self-Phase Modulation, Cross Phase Modulation and Four Wave Mixing are major responsible factors for performance degradation of WDM optical communication system at long reach. Fiber nonlinearity and chromatic dispersion presents key challenges for realizing long distance WDM optical communication systems at higher data rates.

High power is confined in WDM optical system due to multiple wavelength propagation, which raises nonlinear effects in the system. Nonlinear effects such as cross-phase modulation (XPM) and self-phase modulation (SPM) are dependent on transmission power and denoted as Kerr effects (Anamika; Vishnu Priye;). SPM is the effect in which channel phase changes due to the own intensity of signal itself. Other channels' intensity changes the phase of signal in XPM effect. The change in detector response at the receiver end of coherent detection system happens when the signal phase gets distorted due to XPM and SPM. Phase distortion is represented as nonlinear phase shift or crosstalk. Input signal gets broaden during travelling through optical fiber in WDM optical system, which is known chromatic dispersion. Chromatic dispersion is

denoted as the second derivative of signal phase with respect to signal frequency. Nonlinearity and dispersion play major role in designing Light wave system. Interaction between these two effects is a key issue for performance evaluation of long reach WDM optical system.
Attenuation of signal limits the performance of system. Erbium-doped fiber amplifiers (EDFA) and distributed Raman amplifier (DRA) are used as optical amplifiers to compensate signal attenuation. However, Kerr nonlinearities (XPM and SPM) are boosted due to optical amplifiers. XPM leads at smaller spacing between channels. One more nonlinearity of fiber FWM, generates new wavelengths under the phase matching condition between signal wavelength and pump wavelength. Newly generated wavelengths fall in the range of pump and signal wavelengths.

Higher Spacing between sub carriers can improve performance by reduction in Q-penalty at the expense of spectral efficiency (Udalcovs; Aleksejs; Vjaceslavs, Bobrovs). Smaller channel spacing with high transmission data rates increases spectral efficiency of optical system. Optical transmission length is limited at higher spectral efficiency due to enhancement in fiber impairments (Bo-ning, Hui et al.;). Effects of fiber Dispersion and nonlinearities at higher data rate with tight channel spacing in WDM optical system is a major issue to be addressed for future evolution of WDM optical systems. So, the literature review on the fiber dispersion and nonlinearity mitigation techniques is carried out and discussed in this chapter.

2.1 Fundamentals of Channel Multiplexing Techniques

Effective utilization of fiber bandwidth can be possible with transmission of data at higher rate. Multiplexing technique is essential to fulfil this requirement. Time division multiplexing and Wavelength division multiplexing are two main techniques for generation and transmission of high information rates in optical systems. These two are defined as under.

2.1.1 Time Division Multiplexing (TDM)

Using Time Division Multiplexing (TDM) technique, lower speed data streams can be sent by multiplexing in a higher speed stream at transmission bit rate. In this technique, to obtain the higher data stream, multiplexer interleaves lower data streams (Rajiv Ramaswami; Kumar N. Sivarajan;). To achieve even higher data rates, research work is in progress to develop the optical techniques for the functions of TDM. The recent approach is called optical time division multiplexing. However, OTDM is not commercially implemented till date.

2.1.2 WDM - Wavelength Division Multiplexing

Wavelength Division Multiplexing (WDM) is the technique to increase the data transport capacity in an optical fiber. It is similar to frequency division multiplexing (FDM). In WDM, data is transmitted simultaneously at multiple carrier wavelengths. If wavelengths are kept sufficiently far apart, they do not interfere with each other in first order. Thus, WDM technique creates an image of virtual fibers. Every single fiber behaves as multiple “virtual” fibers. Every virtual fiber carries a single stream of data. Wavelength sensitive filters like Bessel filter, Gaussian and Butterworth filter are used at receiver side to get information back from individual wavelength (Rajiv Ramaswami; Kumar N. Sivarajan;).

Classification of Wavelength Division Multiplexing (WDM)

Multiple wavelengths are propagating along the sing optical fiber link by carrying data bits on each wavelength in WDM technique. WDM technique is classified as:

- Coarse Wavelength Division Multiplexing - CWDM
- Dense Wavelength Division Multiplexing - DWDM

2.1.2.1 Coarse Wavelength Division Multiplexing (CWDM)

Coarse wavelength division multiplexing contains large channel spacing between wavelengths. Channels are generally spaced 20nm apart in the wavelength range of 1470nm – 1610nm in CWDM. Less number of channels are used from 8 to 16 for optical communication using CWDM. So, cross talk between channels is minimum due to large separation between channels. The advantage of CWDM is its cost effectiveness, which is almost 1/3rd in comparison of Dense Wavelength Division Multiplexing (DWDM) (Agrawal, Govind P;) However, due to the less number of channels can be accommodated in optical fiber with high data rates, this technique is less attractive in comparison of Dense Wavelength Division Multiplexing (DWDM).

2.1.2.2 Dense Wavelength Division Multiplexing (DWDM)

Dense wavelength division multiplexing has narrow channel spacing in comparison with coarse wavelength division multiplexing (CWDM). DWDM utilizes C-band wavelength range. The system provides channel spacing 0.8 nm or less than that. DWDM provides large number of channels per fiber than CWDM. It is mainly used for its ability to guide dense packed wavelengths in to optical communication system. Various techniques are used for tightly packed 32 to 128 wavelengths as per requirement. EDFA and Raman amplifier can be deployed as optical amplifiers. Wavelength selective filters are required for separation of different wavelengths. Because of these requirements, DWDM systems are more expensive than CWDM (Agrawal, Govind P;). However, High speed and long distance, above thousands of km, are attractive features of the system.

Wave length Division Multiplexing is the technique to accommodate more than one user in same optical fiber where each user is allotted different wavelength. Simple WDM optical link is shown in Figure.2.1.

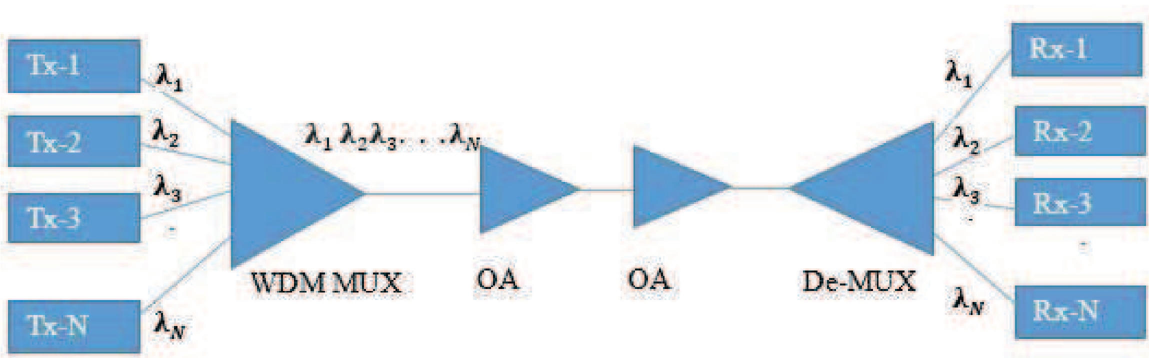


Figure 2.1 WDM Optical Link

The prime factor in designing the optical fiber communication networks in order to deploy the fiber's enormous bandwidth is to settle down multiple user data into optical communication systems. Different techniques like time-division multiplexing (TDM), code-division multiplexing (CDM) and wavelength-division multiplexing (WDM) are possible solutions for this. End user should be synchronized in given time slot for TDM method and optical TDM data rate should be the aggregated data rate of all TDM channels of the system. Moreover, the optical CDM chip rate may be beyond the data rate of user. In comparison to electronic processing speed, data rate of TDM and CDM is much higher and some part of network interface of end users' should be operated at higher rate than electronic speed. WDM has no requirement like this. Thus, WDM is more attractive than TDM and CDM. All end user equipment requires to be operated at the bit rate of WDM channel. So, recently WDM optical communication system is more favourite in designing long haul optical communication systems (Mukherjee; Biswanath;). Expansion with the addition of more data channels through the utilization of more wavelengths is one of the advantages of WDM system. In addition to this, liberty in switching and formatting is obtained in WDM optical system (Gunn; S, T A. N;). Multiple signals with variety of modulation formats are supported with WDM technique over a single optical fiber. WDM system incorporating four analog RF channels to fulfil the demand of avionic environment has been demonstrated in (Refai; Hakki, H; James, J Sluss; Mohammed, Atiquzzaman;). Characteristics of EDFA have been studied and performance improvement techniques have been discussed for utilization in WDM optical systems as multichannel amplifier (Yadlowsky, Michael and Evelyn). WDM optical networks for Local and wide area with the usage of different optical components have been demonstrated. Also, capabilities and limitations of these components are discussed (Borella; Michael, S., et al;). Due to the great potential of WDM system to enhance the optical system design and flexibility, WDM technology is recognized as key technology for optical fiber communication system design (Ishio; Hideki; Junichiro, Minowa; Kiyoshi, Nosu;). WDM system is implemented and analysed with and without DCF for different spacing between channels and different transmission distances (Karunya, J; P, Prakash;). Performance of WDM optical communication system has been verified through Optical Signal to Noise Ratio (OSNR) and Bit Error Ratio (BER) in presence of FWM for different values of chromatic dispersion (Alifdal; Hanane; Farid, Abdi; Fouad, Mohammed Abbou). Bottleneck of Electronic processing has been overcome by WDM technology for high-speed optical communication networks (Sivalingam; Krishna, M;).

2.2 Comparison of Direct Detection and Coherent Detection

2.2.1 Direction detection

Development in the field of fiber optics communication systems was initially started around the year 1970. Optical systems were used intensity modulation of semiconductor lasers at the transmitter end to transmit information into fiber. Signal intensity was detected using photodiode, which was observed as square-law detector (Li Zhe, et al.;). This set up combining transmitter and receiver with optical fiber medium is known as intensity modulation/direct detection (IMDD) scheme, which has been used in some current optical communication systems too. Figure 2.2(a) shows the direct detection of optical signal at receiver end. Optical communication system makes decisions based on the intensity of received optical signal. Therefore, it permits only amplitude based modulation formats such as the on off keying (OOK), which performs poorly as number of stages are increased.

Short distance transmission optical channels using intensity modulation for direct detection is demonstrated using advance modulation schemes (Randel; Sebastian, et al.;). Intensity modulation with direct detection (IM-DD) method has been suffered from limitation of data rate beyond 100 Gb/s in WDM system due to its one dimension modulation and detection. Whereas multi terabits data rate in WDM long haul optical communication networks have been evolved with coherent detection method since last decade (Che, Di; William, Shieh;). 4 x 112 Gb/s WDM optical system employing DSP based receiver with electronics dispersion compensation for direct detection has been demonstrated in (Li Zhe, et al.;). Single side band 16 –QAM using nyquist subcarrier modulation with spectral efficiency of 2.8 b/s/Hz is investigated up to 240 km transmission reach for single mode fiber. Direct-detection (DD) is found attractive for short and medium reach due to its simplicity and low cost (Li Zhe, et al.;). Intensity modulation with direct detection (IM-DD) faces performance challenges at high data rate and long transmission reach (Di Che; Qian Hu; William Shieh;).

2.2.2 Coherent Detection

Coherent detection was extensively studied in year 1980. Optical signal is down converted to baseband electrical signal through optical coherent receivers, which used either heterodyne or homodyne detection (Kazuro Kikuchi;). It has following benefits in comparison to direct detection:

(1) Receiver sensitivity can be improved as local oscillator short noise overcomes the receiver thermal noise.
(2) Coherent detection can extract information of amplitude, phase and frequency from the optical signal. Thus boost the information carrying capacity in same bandwidth.
(3) Closely spaced optical wavelength-division multiplexed (WDM) channels can be separated at the electrical stage due to the high resolution of frequency at the intermediate frequency (IF) or baseband stage.
(4) Advance modulation formats such as PDM QPSK and PDM 16-QAM can be utilized for WDM optical communication systems.

Coherent detection is shown in Figure 2.2(b). It combines optical fiber signal coming out at receiving end with continuous-wave (CW) optical field of local oscillator coherently before falling on the photo detector.

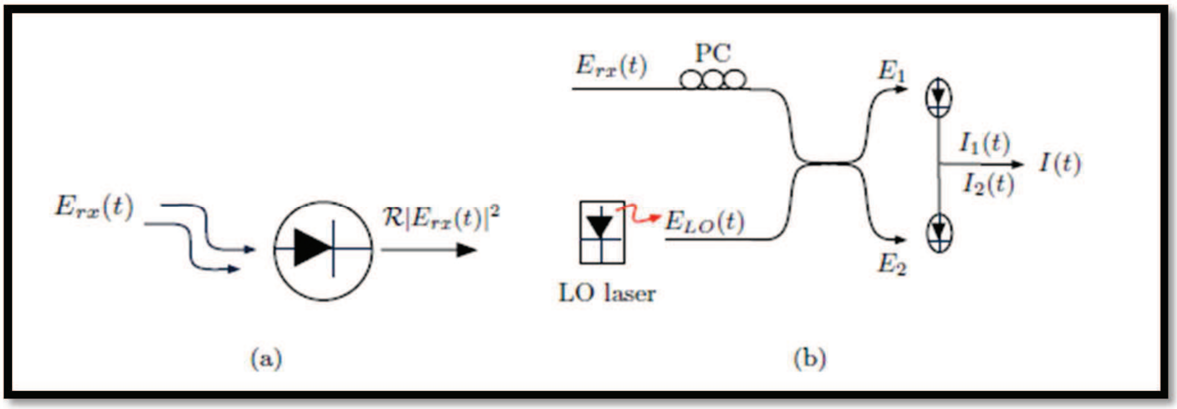


Figure 2.2 Block diagram of an optical receiver using: (a) Direct detection (b) Coherent detection

(Kazuro Kikuchi;)

If we represent the electric fields E_{rx} (t) for received optical signal and E_{LO}(t) of local oscillator then both the electric fields can be defined as :

$$E_{\mathrm{rx}}(t) = \sqrt{P_{rx}(t)} \cdot e^{i\cdot(\omega_{rx}t + \varphi_{rx}(t))} \tag{2.1}$$

$$E_{\mathrm{LO}}(t) = \sqrt{P_{LO}(t)} \cdot e^{i\cdot(\omega_{LO}t + \varphi_{LO}(t))} \tag{2.2}$$

Where, received signal power and local oscillator power are denoted as P_{rx} and P_{LO} respectively. Upper photo diode and lower photo diode electric field of balanced detector are presented as:

$$E_1 = \frac{1}{\sqrt{2}}\,(E_{rx}(\mathrm{t}) + E_{LO}(\mathrm{t})) \tag{2.3}$$

$$E_2 = \frac{1}{\sqrt{2}}\,(E_{rx}(\mathrm{t}) - E_{LO}(\mathrm{t})) \tag{2.4}$$

Therefore, output of the balanced detector is given as,

$$I(t) = I_1(t) - I_2(t) = 2R\sqrt{P_{rx}(t)P_{LO}(t)}\cos(\omega_{IF}(\mathrm{t}) + \varphi_{rx}(\mathrm{t}) - \varphi_{LO}(\mathrm{t})) \tag{2.5}$$

Where, R signifies the responsivity of the photo-diode and ω_{IF} denotes the intermediate frequency, which is represented as:

$$\omega_{IF} = \omega_{rx} - \omega_{LO} \tag{2.6}$$

Power enhancement can be exceeded up to 20 dB due to the much larger value of P_{LO} in comparison with P_{rx}. However, shot noise is also boosted but still the signal-to-noise ratio (SNR) improves by a large factor due to homodyne detection. Noise tolerance of about 4.3 dB is provided by BPSK coherent detection than the direct detection on off keying. Direct detection optical systems are used for bit rates 10 Gb/s or lower. However, higher bit rate systems more than 10 Gb/s can be constructed with coherent detection. Photo detector only detects the changes of received optical signal power for direct detection. It cannot respond to the frequency or phase information of optical signal carrier.

Two degrees of freedom per polarization and spectral efficiency for several b/s/Hz after considering the effects of nonlinearity are achieved in coherent detection. However, spectral efficiency can be significantly reduced for direct detection due to only one degree of freedom per polarization (Kahn, Joseph M; Keang-Po Ho;). The use of optical multilevel phase shift keying for optical system has been demonstrated using coherent detection. System performance with high tolerance to the carrier phase noise is investigated with coherent detection (Tsukamoto; Satoshi; Kazuhiro Katoh; Kazuro Kikuchi;). Transmission reach of optical WDM can be extended system due to the higher sensitivity of coherent detection. Crosstalk between channels is also reduced in multi-channel system. Optoelectronic conversion process becomes linear due to which optical signal processing can be done fully as a post processing in electrical domain. Coherent detection scheme can be applied to multilevel modulation formats like M-ary PSK and QAM (David and Reinhold). Deployment of coherent optical systems with and without polarization division multiplexing has been investigated with tolerance to chromatic dispersion, polarization mode dispersion and narrow band optical filtering. Mitigation of linear impairment in an efficient manner for 40 Gb/s QPSK coherent detection system has been demonstrated for 4080 km transmission reach (Renaudier; Jeremie, et al.;).

2.3 Challenges

Along with the advantage of high bandwidth, optical communication has a major limitation due to fiber dispersion and nonlinear effects. These effects limit the long haul WDM optical system performance at high transmission data rate on individual channel. Performance limiting factors which are known as fiber impairments are classified in to two categories: Linear effects and nonlinear effects.

2.3.1 Linear Effects

Linear effects are intensity independent. This includes attenuation, chromatic dispersion and polarization mode dispersion.

2.3.1.1 Attenuation

Electromagnetic waves suffer from attenuation as they travel distance in a waveguide. Optical cable is a dielectric circular waveguide due to which intensity of light decreases as it propagates through fiber. Attenuation is measured in dB/Km Attenuation can be compensated by using amplifiers at periodic distance. Electrical amplifiers can be used but they require Optical to Electrical conversion and then again Electrical to Optical conversion in optical system. Electrical amplifier adds extra cost in the system due to conversion. So, optical amplifiers are more preferred to compensate attenuation in fiber. Erbium Doped Fiber amplifier (EDFA) is widely used at periodic distances to compensate attenuation and boost the intensity level of the light in a cable.

Optical fiber exhibits minimum attenuation near 1.55 μm wavelength. Moreover, large bandwidth (>10 THz) utilization is possible near this wavelength. Maximum bandwidth can be effectively deployed with the transmission of several independent channels simultaneously in the optical fiber. Separate wavelength is assigned to each transmitted channel. WDM supports significant improvement in transmission capacity. Fiber attenuation degrades propagation of channels for long travelling, which is compensated with the help of Erbium-doped fiber amplifier (EDFA).

2.3.1.2 Chromatic Dispersion

Dispersion is the broadening of the light pulse due to wavelength dependent refractive index. As light propagates through the optical fiber dispersion effect introduces Inter Symbol Interference (ISI). Chromatic dispersion is mainly due to finite spectral width of the optical source. Optical source generates unwanted wavelength components along with the required wavelength due to its finite spectral width. Different wavelength components travel with different speed due to wavelength dependent refractive index n. As light travels a distance d in optical fiber, due to different speed of different wavelength components light pulse gets broad and after some distance two successive pulses overlapped with each other. Overlapping makes wrong detection at receiver side. Different dispersion compensating techniques are used to compensate chromatic dispersion like DCF (Dispersion Compensating Fiber), Pre compensation and post compensation. Dispersion is due to speed difference of each wavelength components generated by the source. In post compensation to compensate the dispersion high speed wavelength are delayed to match up with low speed wavelength at receiver side so it is known as post compensation. In pre-compensation spectral width of the source is reduced. Action is taken prior to transmission so it is known as pre-compensation.

Fiber chromatic dispersion and nonlinear effects are considered for pulse propagation in optical transmission system. Analytical expression is obtained to estimate the amount of pulse broadening in optical fiber after certain assumptions. Validation for the range of broadening is described with comparison of analytical prediction and numerically obtained calculation for pulse width. Results are verified conventional fibers and dispersion shifted fibers at 1.55 μm. Optical communication system bandwidth is reduced due to pulse broadening shown by results (Potasek, M J; Agrawal, Govind P; Steven, Pinault C;). Chromatic dispersion effect dominates than all other sources of signal degradation and restricts the data transfer capacity for glass fibers. Attention is also given for the transmission of information around dispersion minimum wavelength 1300 nm. However, minor variation in wavelength affects the amount of chromatic dispersion in optical fiber.

2.3.1.3 Polarization Mode Dispersion (PMD)

Irregularities occurred in fiber span like non circular diameter, embedded impurities or due to environmental stress acts as obstacles to an optical pulse propagating in the fiber. These obstacles cause in variation of group velocities for different polarizations of optical pulses. This results into spreading the optical pulse, which is known as polarization mode dispersion (PMD). Differential group delay (DGD) is defined as:

$$\Delta\tau = D_{PMD}\sqrt{L} \tag{2.7}$$

The differential group delay (DGD) is related to the square root of optical fiber length L, i.e., where D_{PMD} is the PMD parameter of the fiber and typically measured in $ps/\sqrt{km}$. Because of the $\sqrt{L}$ dependence, the PMD-induced pulse broadening is relatively small compared to chromatic dispersion (Mukherjee, Biswanath). The polarization mode dispersion parameter varies from fiber to fiber in the range of $0.01\text{-}10\ ps/\sqrt{km}$. PMD becomes a crucial limiting parameter for high transmission data rate long haul WDM optical systems. For high bit-rate more than 40 Gb/s WDM optical transmission systems, second order and higher order PMD become prominent. Performance of optical system at high data rate has been highly limited due to polarization-mode dispersion (PMD). (Henrik, Sunnerud; Xie, Chongjin et al.;). Low PMD value has observed in recent fibers than older fibers. However, nominal dependencies on PMD exist due to in-line discrete elements such as dispersion-compensating fiber, EDFA and isolators. Therefore, PMD will considerably restrict the utilization of 40 Gb/s data rate systems over new fibers (Willner, Alan E;). Although compact pulses have been transmitted in optical communication system at transmitting end, PDM results in optical pulse broadening and leads to the corruption of bit pattern. Birefringence in optical communication systems gradually but significantly changes with time due to the fluctuations in stresses, temperature etc. conditions of environment. Thus, dynamically compensation PMD is a prime issue for advance high speed optical fiber communication technology (Vladimir, Chernyak; Michael, Chertkov et al.;). Correlation properties of PMD in dispersive medium such as optical fibers have been demonstrated with theory (Qiang and Agrawal), which has incorporated the broadening of optical pulses induced through different-order PMD and pulse distortion occurred by PMD.

Nonlinear effects are shown in the chart as below. The major two causes of nonlinear effects are refractive index of the medium changes with variation in optical intensity and elastic scattering phenomenon takes place in optical fiber. The Kerr-effect occurs due to the dependency of refractive index on input signal power of optical system. Three effects result based on fiber Kerr-nonlinearity. These effects are Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM) and Four-Wave Mixing (FWM). Whereas at higher power level, the stimulated effects like Stimulated Brillouin-Scattering (SBS) and Stimulated Raman-Scattering (SRS) are induced because of inelastic scattering phenomenon. There is a certain threshold value of the incident power. Once the input signal power exceeds this threshold power value, scattered light intensity increases exponentially. Stimulated Brillouin-Scattering (SBS) has lower threshold power value than Stimulated Raman-Scattering (SRS). Nonlinear effects are discussed in detail in this session.

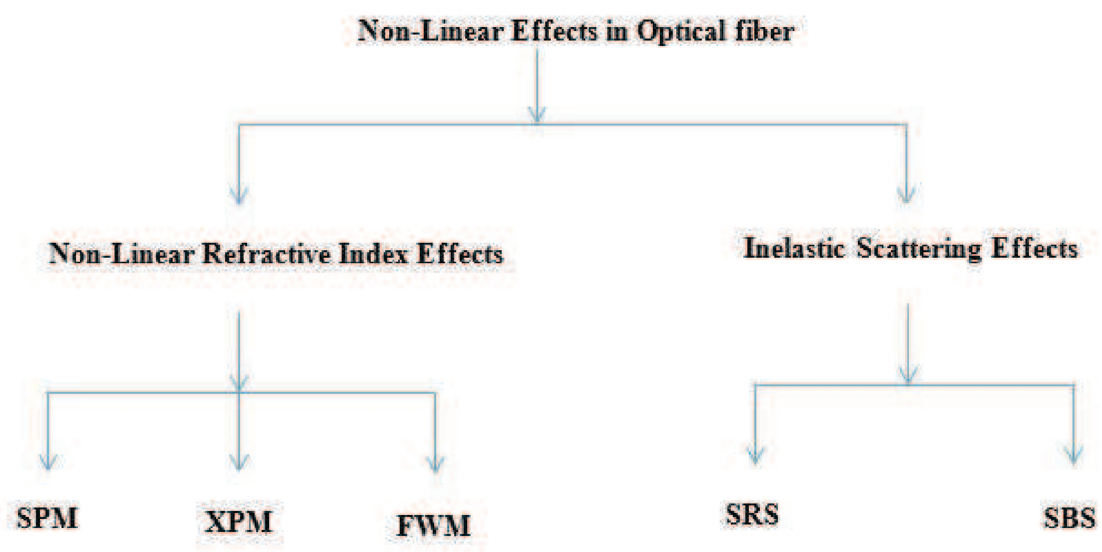


Figure 2.3 Various Non-Linear Effects in Optical Fibre

Nonlinear parameter in optical fiber is given by:

$$\Upsilon = \frac{2\pi n_2}{\lambda A_{eff}} \tag{2.8}$$

Here,

Non-linear refractive index coefficient is defined as n_2 and effective area of core as A_{eff}. λ is wavelength of the signal.

2.3.1.4 Self-Phase Modulation (SPM)

Own intensity of optical pulse causes phase changes resulting in phase modulation, which is called SPM. Kerr effect produces the change in refractive index with intensity during pulse propagation in optical fiber. So, refractive index is a function of light intensity I and given by,

$$n(I) = n_1 + n_{n_l} \cdot I \tag{2.9}$$

Where, n_1 and n_{nl} are linear refractive index and second-order nonlinear refractive index of the medium respectively.

Nonlinear phase in SPM is given by:

$$\emptyset_{NL} = \gamma P L_{eff} \tag{2.10}$$

Self-phase modulation was initially reported as a spectrum of modulated frequencies surrounding the LASER frequency in a cell filled with liquid, which was denoted as self phase modulation due to dependency of refractive index on intensity. Frequency broadening in optical fiber was reported resulting from self-phase modulation (Stolen, R H; Chinlon, Lin;). Effects of chromatic dispersion and SPM were jointly examined for optical subcarrier multiplexed transmission systems. By keeping small modulation index per channel and large spacing between channels, dispersion compensation accompanying worked independently for each subcarrier (Kim; Kyoung-Soo; Ji-Chai, Jeong; Jae-Hoon, Lee;). Analytical expression for optical pulse broadening after solving nonlinear Schrödinger equation (NLSE) has been obtained after detail analysis. Cross phase modulation with self-phase modulation and group velocity dispersion for WDM system are considered in mathematical analysis. Broadening factor of optical pulse has been observed after analysis. Results are obtained for different data rates, variable input power and various transmission distances (Sultana; Nasrin; Islam, M S;).

2.3.1.5 Cross Phase Modulation (XPM)

Cross phase modulation occurs due to multiple optical signals propagation simultaneously in optical fiber. In XPM nonlinear phase modulation occurs due to other co-propagating optical pulses. XPM leads to cross talk and hence it limits the number of channels simultaneously transmitted through WDM network. XPM converts power fluctuation in one wavelength channel to phase in other wavelength channel. Nonlinear phase is given by:

$$\emptyset_{NL} = 2\gamma P_{other} L_{eff} \tag{2.11}$$

In WDM, XPM contributes twice than SPM.

The distortion resulting due to XPM has demonstrated numerically and through experiment as a function of separation between channels (Rapp, Lutz;). Larger spacing between channels is the way to reduce XPM. Result reflects that XPM influence is minimized even at moderate spacing between channels. The effect of intensity fluctuation due to XPM and its dependency on optical fiber length, chromatic dispersion, separation between channels and modulation frequency is studied analytically and through simulations (Cartaxo, Adolfo VT.;). Cross-phase modulation effect is investigated experimentally and analytically for optical system including dispersion compensators and optical amplifiers. Aggregation of phase shift due to each frequency component denoted as total cross phase modulation induced phase shift. Walk off parameter is one of the influencing factor of XPM frequency response, which can be approximated equals to wavelength separation and fiber dispersion product. XPM effect can be approximated independent of frequency in single piece optical fiber link when walk-off parameter is small. For large value of walk-off parameter, frequency response of XPM depends approximately on inverse proportion to the product of frequency, dispersion and separation between channel wavelengths (Chiang, T K., et al.;). Prediction of transmission penalties causes from XPM has large impact in designing the future WDM optical networks using narrow spacing between channels and high bit rate per channel (Killey, R I., et al;). Under compensation technique for inline dispersion compensation can be beneficial in reduction of XPM distortion. Residual dispersion for each span is responsible for inter span channel walk off resulting in reduction of localized build-up of huge phase distortions. Intensity distortion due to interaction between fiber chromatic dispersion and cross-phase modulation can be responsible for performance degradation of dispersion compensated optical system (Bellotti, Giovanni, et al;).

2.3.1.6 Four Wave Mixing (FWM)

Multiple optical field travels through fiber resulting in generation of new optical fields due to interaction cause four wave mixing. If three optical fields travel in fiber then the generated frequency of the new field is given by,

$$\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3 \tag{2.11}$$

The frequencies of actual optical signals are defined as ω_1, ω_2, ω_3. FWM is dependent on channel spacing and dispersion of fiber instead of bit rate like SPM and XPM. FWM limits the number of simultaneous channels by limiting channel spacing.

Fiber chromatic dispersion and nonlinear effects impact on propagating wave fronts through the fiber medium, which limit the system performance of optical networks. Chromatic dispersion related issues are resolved with dispersion-shifted fiber (DSF) at 1550 nm. However, utilization of low dispersion fiber results in increase of four wave mixing (FWM) effect due to the phase mismatch reduction. FWM induced cross talk dominates in long transmission WDM optical systems designed with DSF. Channel frequency allocation based technique is presented to reduce the FWM induced cross talk. Unequal separation between channels can be considered suitable technique for which no product term due to four wave mixing falls on desired transmission channel. However, this technique is implemented at the cost of system bandwidth. Effectiveness of the technique is verified through simulation for 10 channel WDM system with 10 Gb/s data rate per channel. Suitable choice unequal spacing between channels enhances receiver power margin more than 9 dB (Forghieri, Fabrizio, et al;). The impact of FWM on multichannel WDM transmission optical system is investigated (Inoue, Kyo, et al.;). Comparison between intensity dependant nonlinear effects is shown in Table 2.1.

Table 2.1 Comparison between nonlinear effects

Parameter	Self-phase modulation	Cross phase modulation	Four wave mixing
Data rate	Depends on	Depends on	Not dependent
Third order nonlinear effects ($X^{(3)}$)	Non-linear Phase modulation due to pulse itself	Non-linear Phase modulation due to co propagating pulse	Additional wavelength generation
Broadening	Symmetric	Asymmetric	N.A.
Channel spacing	Independent	Increases as reduction in channel spacing.	Increases as reduction in channel spacing.

2.3.1.7 Stimulated Brillouin Scattering (SBS)

Transfer of energy into acoustic wave results in backwards scattering in fiber. Brillouin frequency shift equal to $2nv/\lambda$,

Where, n= the mode index
v= the speed of sound in the material
λ = Operating wavelength

For fiber, scattered light is 11 GHz lower in frequency than signal wavelength (speed of sound is 5.96 km/s). Stimulated brillouin scattering effect is directly associated with transmitter power and independent of number of transmitted channels. SBS affects the performance of passively multiplexed systems carrying few channels than many channels (Andrew, Chraplyvy R:).

SBS limits the transmitter side optical power that propagates into single mode fiber for long haul optical systems. Input power limitation due to SBS has been observed for amplitude-shift-keying (ASK), frequency-shift-keying (FSK), and phase-shift-keying (PSK) modulated optical signal (Aoki, Yasuhiro et al.;). Stimulated brillouin scattering effect in optical fiber is responsible for degrading the performance of multi giga bit optical communication system. Extreme fluctuation in optical signal due to SBS decrease signal-to-noise ratio and subsequently degrade the BER of the optical system (Kobyakov, Andrey et al.;).

2.3.1.8 Stimulated Raman Scattering (SRS)

When light is scattered due to vibrating silica molecules, scattered photon can be decreased (Stokes) or increased (anti-Stokes). Stokes shift scatters 1550 nm light up to 1870 nm light. SRS is used as an amplifier if pump wavelength is chosen suitably. Raman gain introduces cross talk in WDM system which can be reduced by reducing channel power which also limits the number of channel. As nonlinear effects like SPM and XPM depends on data rate so these effects becomes severe as data rate increases. FWM depends upon channel spacing. In WDM as number of channels increase to accommodate more number of users channel spacing is to be reduced which increases FWM. In modern data network where we are aiming to achieve high data rate nonlinear effects must be evaluated to compensate or to find the solution where we can beat the effect of nonlinearity to take the advantage of optical bandwidth.

Different nonlinear processes observed at lower transmitter power level in optical fibers in comparison to bulk glasses, which is due to long length of interaction for optical fiber. Stimulated Raman scattering causes remarkable cross talk between different channels at 1mW of optical power of CW LASER diodes. Thus, WDM optical system performance can be affected significantly by stimulated Raman scattering. The extent of cross talk has been estimated from Raman gain, which is measured with high power pulsed lasers and relative short fibers. Raman cross talk was measured in single mode fiber of 21 km length for 1.3 μm wavelength region with cw laser diodes (Tomita, Akira;). SRS and SBS effects have been investigated for power handling capability of optical fibers with low loss. Input power level for the optical fiber has been evaluated for each scattering process in terms of critical power (Bromage, Jake;).

2.4 Dispersion and Nonlinearity Compensation Techniques

2.4.1 Dispersion Compensating Fiber

Dispersion is one of the parameters to degrade the performance of WDM optical system for long reach. One of the ways to compensate the dispersion for improvement of optical link performance is dispersion compensating fiber. This fibers possesses -70 to -90 ps/nm.km negative dispersion to compensate the positive dispersion of standard single mode fibers (Sheetal, Anu; Sharma, Ajay K; Kaler, R S;). DCF is used in optical span with SMF to compensate dispersion per span.

$$D_{SMF} \times L_{SMF} = -D_{DCF} \times L_{DCF} \tag{2.12}$$

Where, *D* and *L* are the dispersion and length of each fiber segment, respectively.

Based on the position of DCF in span pre, post or mix compensation methods are used for dispersion compensation (Agarwal, Ruchi; Mishra, Vivekanand;). Pre-compensation: DCF is situated before SMF in pre-compensation technique to compensate the positive dispersion of SMF in optical communication system. Post-Compensation: Post – compensation is the technique in which large negative dispersion fiber DCF is used after SMF to compensate the dispersion of link. Mix-Compensation: Pre-compensation and post-compensation both are used in same link for mix-compensation technique. Figure shows the post, pre and mix-compensation schemes.

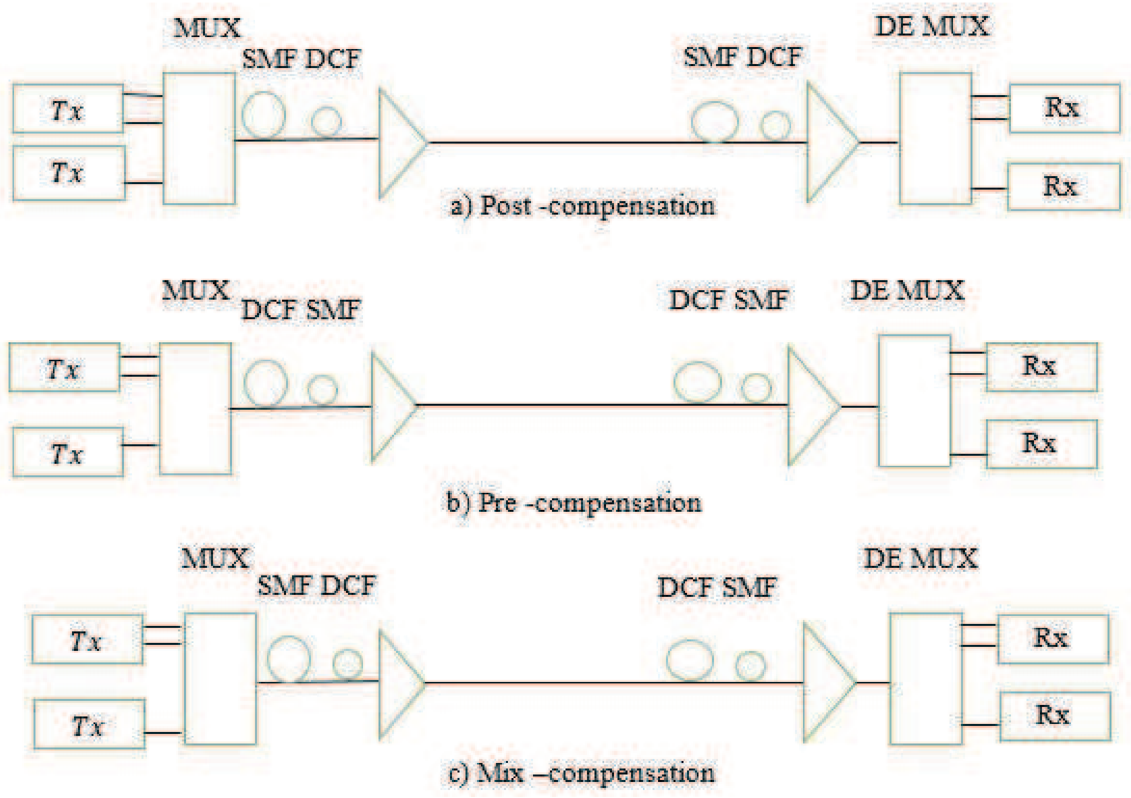


Figure 2.4 pre, post and mix compensation

In (Bo-ning, Hui et al.;), authors have applied this method to analyse Q-factor and BER for 8 channel WDM optical transmission system with pre,post and mix- compensation techniques. 40 Gb/s data rate was carried by each WDM channel for 160 km transmission distance. They have observed 2 dB improvement in Q factor and minimum BER for mix-compensation technique than other two techniques. In (Anna, Pizzinat et. al.;), authors have reported a comparison between periodic (DM) and all-at-the-end (HDP) dispersion compensation schemes on G.652 fibers. High chromatic dispersion was obtained with such fibers, due to which it was quite difficult to realize 40-Gb/s systems with long amplifiers spacing. They have observed trade-off between performances, feasibility, and simplicity for HDP scheme. Moreover, the drawback of non-exact fiber impairment compensation with the DCF has been found with long-haul terrestrial systems. In (Agarwal, Ruchi; Mishra, Vivekanand;), authors have demonstrated the comparisons between all three schemes pre-, post-, pre- post compensation for fiber link of 120km using subcarrier multiplexing technique (SCM). They have observed that BER increases with increase in input optical power due to fiber nonlinearity effects. They concluded that symmetrical and post compensation schemes were better than pre- compensation. In (Sheetal, Anu; Sharma, Ajay K; Kaler, R S;), authors have demonstrated performance of 16 channel dense wavelength division multiplexed (DWDM) system at 40 Gb/s transmission rate. In this system channel spacing of 25 GHz was kept for transmission reach of 2000 km using modulation formats like CSRZ, DRZ and MDRZ. System performance was verified with different configuration of dispersion compensation as pre, post and symmetrical schemes at variable input power. They have found that Q-factor rises with signal power in the limit of (0–5 dBm) and gets reduce due to cross phase modulation and four wave mixing at higher transmission power. System performance was verified with parameters like received optical power, Q-factor and percentage eye opening. They concluded that symmetrical compensation performs better in comparison to other techniques. It is found that DCF has higher nonlinearity coefficient due to small core size. In high power WDM optical system DCF is generally avoided due to its negative impact to promote high fiber nonlinearity.

2.4.2 Dispersion Compensation using Fiber Bragg grating

Dispersion is also compensated by fiber Bragg gratings. When dispersed pulse travels along the FBG, different wavelengths are reflected from various positions in the grating. Path length differs for different wavelengths resulting in dispersion reduction of optical communication system. FBG is placed in line with optical fiber in the link. Figure shows the technique to compensate dispersion using FBG.

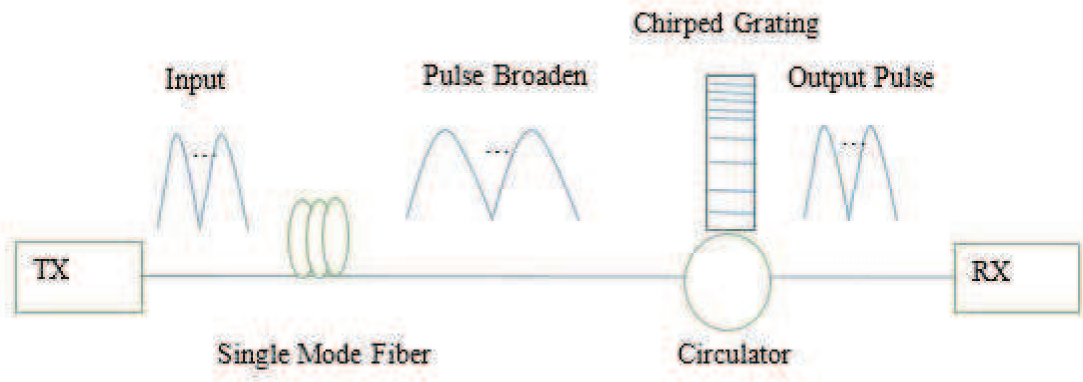


Figure 2.5 Dispersion compensation using FBG

In Fiber Bragg grating method (FBG), different wavelengths are reflected from various positions in the grating when dispersed pulse travels along the. Path length is differing for different wavelengths resulting in dispersion reduction of optical communication system. FBG is placed in line with optical fiber in the link. In (Dochhan, Annika, et al;) , authors have demonstrated the use of fiber Bragg gratings (FBGs) in long transmission WDM optical systems as in-line dispersion compensation for the data rates from 10.7 Gb/s to 43 Gb/s. They have verified the performance of system using optical duo binary (ODB) and differential phase shift keying (DPSK). The channelized FBG performed satisfactory up to 800 km of transmission distance. In (Khairi, K et al.;), authors have demonstrated the performance of Multi-Channel Chirped Fiber Bragg Grating (MC-CFBG) in optical system as a dispersion compensator in pre and post compensation configurations for 100 km transmission distance with 10 Gb/s data rate using Non-Return to Zero (NRZ) modulation format. They have found that the MC-CFBG is encouraging alternate method with respect to the Dispersion Compensating Fiber (DCF), specifically as a pre-compensation technique. 10 Gb/s data rate system with low loss 1550 nm wavelength window together with EDFA was demonstrated in (Vojtech, J M; Radil, J;). Authors have addressed CD compensation schemes like FBG, Channelized FBG and channelized tuneable FBG (TFBG). Greater insertion loss was found responsible of performance degradation of system for TFBG. Architecture using FBG is complex.

2.4.3 Dispersion Compensation using optical phase conjugation

Chromatic dispersion and Kerr nonlinearities are simultaneously compensated by optical phase conjugator. Spectral inversion process is operated using optical phase conjugator which is a promising technology for compensation (Jansen, S L; Krummrich, P M et al.;). OPC is utilized in two different ways in optical fiber transmission link.

2.4.3.1 Inline optical phase conjugation

An inline OPC link is created by adding an OPC module in optical transmission link. In such a link, dispersion compensation is realized by DCF modules and compensation of nonlinear impairments by the OPC unit. The key advantage of inline OPC is that the dispersion map of the transmission link can be optimized for the compensation of nonlinear impairments in combination with OPC. Figure shows the block diagram of inline-OPC.

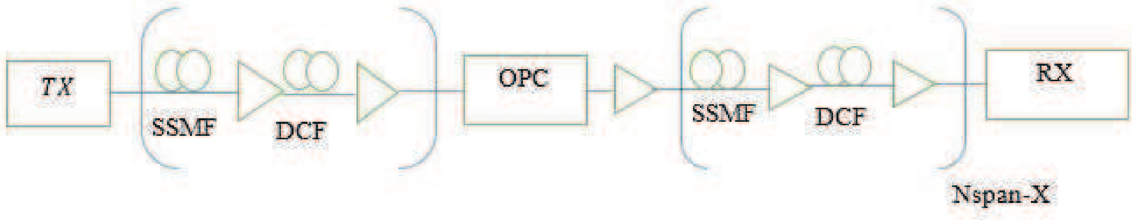


Figure 2.6 Inline – Optical phase conjugation

OPC is placed in the transmission line to conjugate the signal and thereby invert the distortions in the phase, caused by nonlinear impairments. As a result, phase distortions before conjugation that occur through the Kerr-effect are undone by phase distortions after conjugation.

2.4.3.2 Mid-link optical phase conjugation

OPC is situated at mid-link in the optical link. Signal phase is conjugated at mid – link through OPC in optical communication system. During the travelling of signal up to mid-link, it is severely distorted by chromatic dispersion and nonlinear impairments. Distortion accumulated in the first half is compensated through the distortion of second half after OPC due to reverse impairments. Full compensation for nonlinear impairments occurs when the nonlinear effects before and after OPC are identical. The use of mid-link OPC is twofold. Firstly, mid-link OPC can compensate for impairments caused by the Kerr-effect. The Kerr effect causes a change in the refractive index of the transmission fiber in response to an electric field. In fiber-optic transmission systems, the Kerr effect leads to distortions in the phase of the signals and can significantly reduce the system performance. Through the compensation for Kerr-effect, the feasible transmission distance is significantly extended and the amount of required OEO repeaters reduced. Secondly, OPC can be used to compensate for chromatic dispersion. In such a link, no inline DCF modules are required. The block diagram of mid-link OPC is shown in figure below (Jansen, S L; Krummrich, P M et al.;).

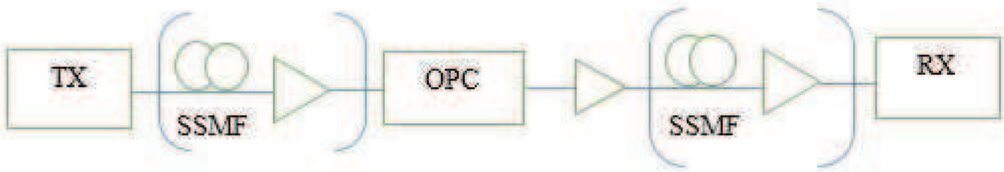


Figure 2.7 Mid-link Optical phase conjugation

A more cost-effective solution is to use mid-link OPC. In this configuration OPC is used for both chromatic dispersion compensation and compensation of the Kerr-effect. Hence no inline DCF modules are used in this configuration. Instead the dispersion accumulates along the transmission line and is compensated for by placing an OPC mid-link. Nonlinear Schrodinger equation for signal propagation in a nonlinear, dispersive and lossy medium can be expressed as

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2} A - \frac{i}{2}\,\beta_2\,\frac{\partial^2 A}{\partial T^2} + \frac{1}{6}\,\beta_3\,\frac{\partial^3 A}{\partial T^3} + i\gamma |A|^2 A \tag{2.13}$$

Where z denotes propagation distance in km, A signifies the complex amplitude of the signal, γ is the nonlinearity coefficient (Kerr effect) in 1/ (W·km), α denotes the attenuation coefficient in neper per kilometre, group velocity dispersion (GVD) β_2 in ps^2/nm and dispersion slope β_3 in ps^3/nm.

After OPC the complex conjugate of signal can be denoted as

$$\frac{\partial A^*}{\partial z} = -\frac{\alpha}{2} A^* + \frac{i}{2}\,\beta_2\,\frac{\partial^2 A^*}{\partial T^2} + \frac{1}{6}\,\beta_3\,\frac{\partial^3 A^*}{\partial T^3} - i\gamma |A^*|^2 A^* \tag{2.14}$$

Where * signifies the complex-conjugate operation. It is observed from the expression that the sign of the chromatic dispersion term (β_2) and the Kerr effect term (γ) both inverted. Thus in the transmission link with same fiber GVD and kerr effect are cancelled out before and after OPC by keeping OPC in mid of the link. OPC is situated at mid-link in the optical system. Phase of signals is conjugated at mid – link through OPC in optical communication system. During the travelling of signal up to mid-link, it is severely distorted by chromatic dispersion and nonlinear impairments. Distortion accumulated in the first half is compensated through the distortion of second half after OPC due to reverse impairments. In (Pelusi, M D., et al.;), authors have demonstrated 3 x 40 Gb/s (100 GHz spaced) Optical WDM systems with dispersion free transmission. Optical phase conjugation method was utilized in system for RZ-DPSK modulation format over the transmission distance of 162 km. In (Pelusi, Mark D;), authors have applied this method to compensate the fiber kerr nonlinearity for 40 Gb/s WDM optical system at the data rate of 40 Gb/s. They have observed the Q^2 – factor improvement from 1.3 dB to 2.9 dB for single channel to four channel WDM optical link. They have found that the BER performance is degraded by linear and nonlinear inter channel cross talk. In (Li, Jianqiang, et al;), authors have shown the dispersion compensation schemes for 1200 km transmission link using for 160 Gb/s transmission data rate. OPC module was situated at the mid of the link. Optical system was design using single mode fibers, dispersion compensation fibers, erbium doped fiber amplifiers and optical phase conjugation modules. Optical phase conjugation with dispersion compensation scheme was introduced in system with the aim to compensate dispersion as well as fiber nonlinear impairments. In (Ayotte, S.,et al;) , authors have deployed 40 Gbit/s NRZ data for single channel transmission over 320 km. They have shown simultaneous spectral inversion of input signals for four dense wavelength division multiplexed channels with 100 GHz spacing between channels using OPC. They have found that if the pump wavelength and the signal wavelength have 100 GHz frequency grid then some unwanted frequency signals due to FWM products can take part to increase the crosstalk effect due to the interaction with desired OPC signals. Therefore, they kept the pump by half-channel spacing (50 GHz) to remove unwanted FWM products through filtering out efficiently using ordinary dense wavelength division multiplexed filters. Utilization of OPC has found a trade-off between conversion efficiency and bandwidth. Multichannel operation for WDM optical system degrades conversion efficiency.

2.4.4 Electronic Dispersion Compensation

Dispersion compensation can also be done at the receiving end of optical communication system through electrical equalizer. Different electrical equalizers are discussed subsequently utilized in optical system (M, S O'Sullivan et al.;). EDC (Electronic Dispersion Compensation) is chromatic dispersion compensation technique used in optical fiber communication. It can be used to mitigate the effect of PMD first order. A complementary PMD vector is produced for this purpose. Different techniques like Electronic equalization are used to detect the signal. A technique like direct detection is also used with it. Basically, a linear distortion exists over optic domain. Chromatic dispersion is transferred to the nonlinear distortion. This is done after electrical conversion from optic domain. Decision feedback equalizers (DFE) and feed forward equalizer (FFE) are two basics structures used for dispersion compensation. One disadvantage of using EDC is that speed of optical communication and speed of analog to digital alteration are decreased. Figure 2.8 shows the dispersion compensation in optical system using equalizer used at receiver end.

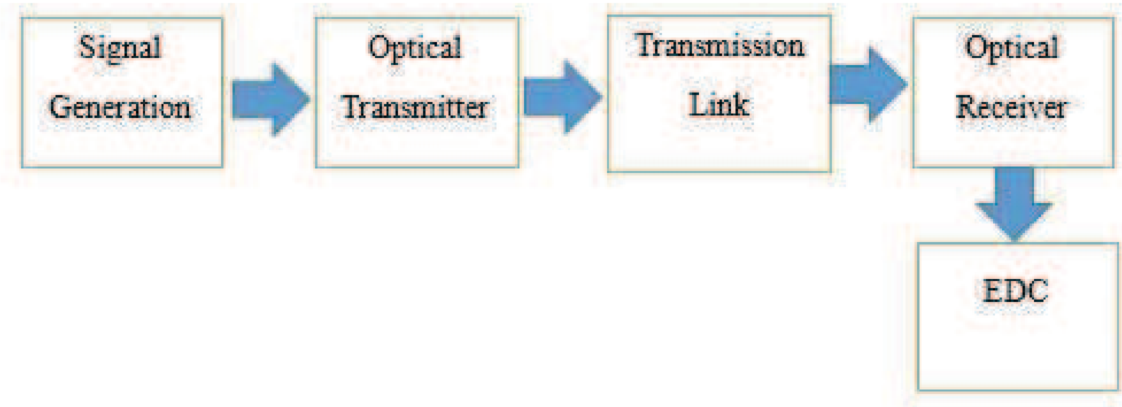


Figure 2.8 Block diagram of dispersion compensation using EDC

The details of above mentioned equalizers are as below:

2.4.4.1 Feed Forward Equalizer and Decision Feedback equalizer

In feed forward equalizer, filter coefficients linearly weights past values of received symbols. Output is produced by summation of current values with weighted past values as shown in Figure 2.8. After sampling of equalizer output at the symbol rate, it is applied to decision device, if the delays and tap gains are analog in nature. Samples are stored in shift register for the implementation carried out in digital domain. Equalizer output is denoted prior to decision making as:

$$\hat{d}_k = \sum_{n=-N_1}^{N_2} C_n^* \, y_{k-n} \tag{2.15}$$

Where C_n^* represents complex filter coefficients or tap weights, $\hat{d}_k$ is the output of equalizer and y_i is the input received signal.

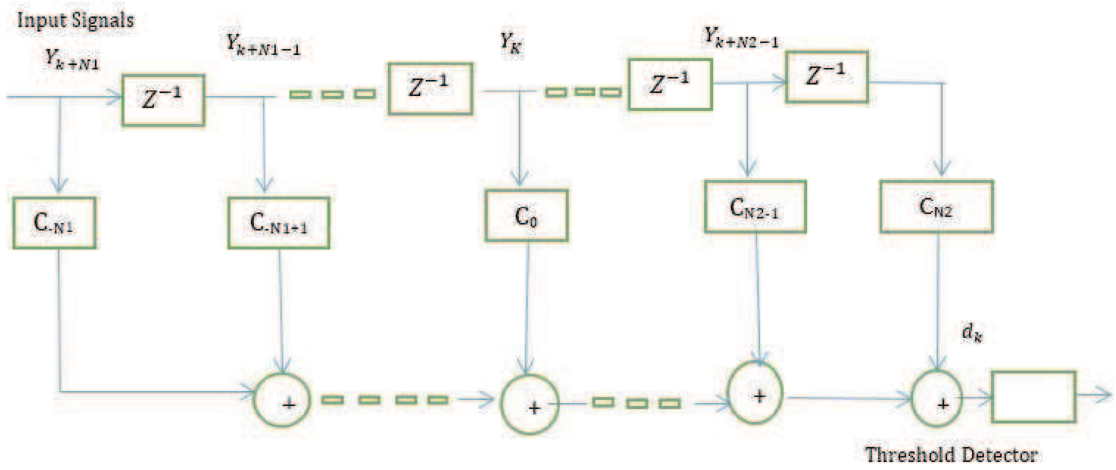


Figure 2.9 Block diagram of feed forward equalizer

Inter symbol interference (ISI) is predicted on future symbols after detection of information. It is subtracted from the subsequent symbols before detection. DFE consists feed forward (FFE) filter and feedback filter as shown in Figure 2.9. Decisions on the output of detector drive the FBF. The coefficients of FBF are adjusted on the basis of past detected symbols which leads to cancel out the ISI from currently detected symbols. The output of this equalizer before decision making is

$$\hat{d}_k = \sum_{n=-N_1}^{N_2} C_n^* y_{k-n} + \sum_{i=1}^{N_3} F_i d_{k-i} \tag{2.16}$$

Where C_n^* represents complex filter coefficients or tap weights, $\hat{d}_k$ is the output of equalizer and y_n is the input received signal. F_i is the tap gain for feedback filter and d_i is the previous decision made on detected signal.

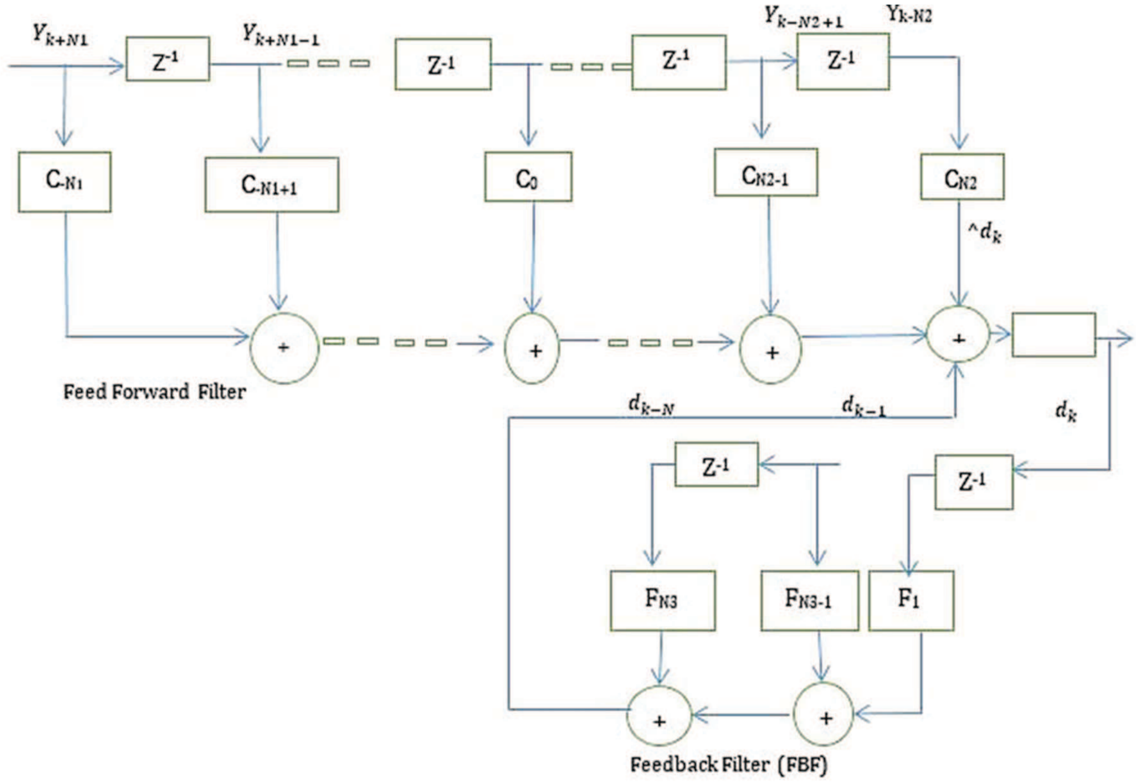


Figure 2.10 Block diagram of FFE-DFE equalizer

Dispersion compensation can also be done at the receiving end of optical communication system through electrical equalizer. In (Majid Moghaddasi), authors have demonstrated the comparison of efficiency of OOK NRZ and RZ modulation formats for electrical and optical dispersion compensation schemes. They have concluded that NRZ performs better than RZ for electrical compensation technique for optical system. In (Xia, Chunmin; Werner, Rosenkranz;), authors have presented electronic dispersion compensation scheme for 10 Gb/s direct detection optical system through extensive simulations. They have shown comparison of nonlinear equalizer technique with maximum-likelihood sequence estimation and conventional decision-feedback equalizer. They have demonstrated the use optical filter having narrow band for optical signal accompanying with nonlinear equalizers. Noise reduction was the benefit in system due to narrowband filtering. They have shown that, distortion due to strong optical filtering can be efficiently removed through nonlinear equalizers. Performance of NL-FFE–DFE was considered by the number of delay taps as well as the nonlinear order consideration in both FFE and DFE parts. Optical system with short reach realized less filter order and nonlinear order. Required performance was achieved with the compromise in complexity of the filter design. Main reason of performance degradation of conventional FFE–DFE is due to the square-law detection of the photodiode. NL-FFE–DFE suffers from noise development due to the feed forward equalizer (FFE) part and propagation of error from the decision feedback equalizer (DFE) part similar to conventional FFE–DFE.

2.4.4.2 Maximum Likelihood Sequence Estimator (MLSE)

Probability of sequence errors is minimized by MLSE as shown in Figure 2.10 (Theodore, S Rappaport;). It consists of Viterbi algorithm followed by match filter. MLSE selects most probable sequence resulting in minimum error. Possible data sequences are checked by MLSE and selects the data sequence with the maximum probability as the output.

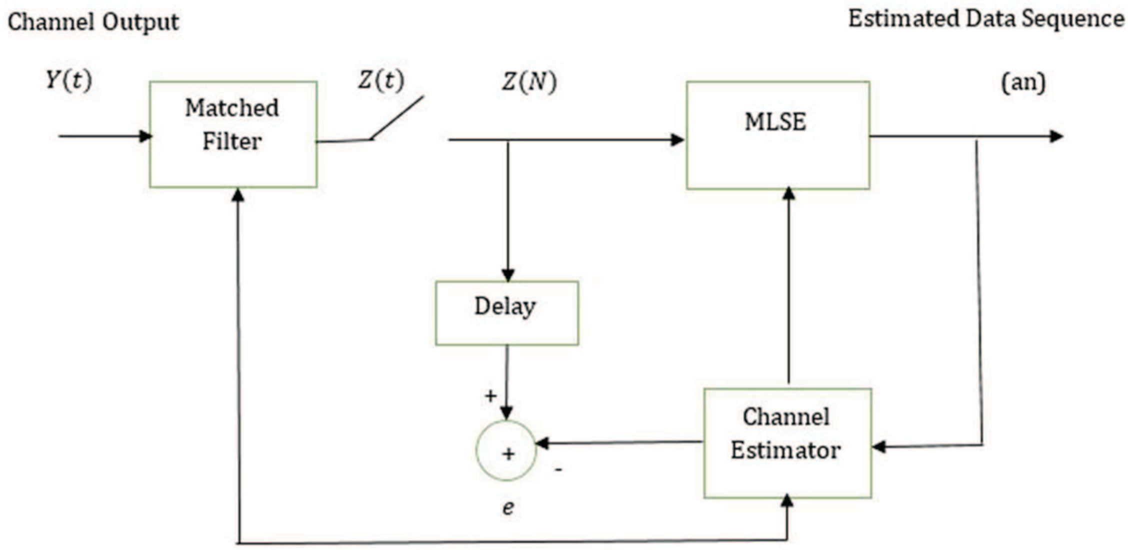


Figure 2.11 Block diagram of MLSE equalizer

Possible data sequences are checked by MLSE and selects the data sequence with the maximum probability as the output to minimize BER. Fractionally-spaced decision feedback equalizer have been proposed with nonlinear canceller depends on 3rd order Volterra theory in (Zhu Xianming, et al;). It has the ability to remove inter symbol interference caused by chromatic dispersion, nonlinearity raised from square-law detection and effects based on fiber Kerr nonlinearity. They have demonstrated 10 Gb/s uncompensated optical systems with NRZ-OOK modulation with input power of 10 dBm. They have demonstrated transmission reach beyond 300 km using the maximum likely hood sequence estimator (MLSE) receiver at BER of 10^{-3}. In (Zhu, Xianming, et al.;), authors have demonstrated standard single mode fiber based optical system for more than 700-km transmission reach with MLSE, which was used with sufficient states for dispersion limited optical system at 10-Gb/s rate. 16-state MLSE receiver was used to compensate chromatic dispersion and fiber nonlinearity based intra-channel impairments. They have verified system performance with BER of 10^{-3} at 6 dBm input power over 10 Gb/s non return to zero – dispersion shifted fiber (NZ-DSF) optical communication system for transmission reach of 960 km. However, there is a trade-off between performance and complexity of MLSE based system, which is a key issue for long reach WDM system at high data rate.

Beyond 40-Gb/s optical transmission polarization mode dispersion is another major limitation. However, for WDM optical system with excessive PMD, either PMD compensation is needed or the system cannot upgradable to 40 Gb/s. In (Faure, Jean-Paul, et al.;), authors have explored solutions to commercially available 40G links. They concluded that coherent detection technique using PDM-QPSK with dispersion managed link better ability to compensate linear and nonlinear effects. Optical system using RZ, NRZ and CSRZ modulation formats in combination with differential quadrature phase shift key (DQPSK) was demonstrated for 200 km at 40 Gb/s data rate in (Li, Li, et al;). CSRZ-DQPSK modulation format was found more suitable due to anti-dispersion and anti-PMD (polarization mode dispersion) properties for wider power range. In (Chen, Lawrence R; Junjia, Wang;), authors have demonstrated that multi-level modulation formats like QPSK, 8-QAM and 16-QAM are more appropriate for long reach optical transmission reach at higher data rates, while tradition modulation formats like OOK are used for short reach. Non-linear impairments with inline dispersion compensation using DCF and with electrical compensation at receiver side was verified for 111-Gb/s polarization multiplexed return-to-zero differential quadrature phase-shift keying (POLMUX–RZ–DQPSK) optical signals in (Alfiad, Mohammad S., et al.;). Along with differential group delay (DGD), nonlinear tolerance was reduced for optical compensation, whereas for electrical compensation the nonlinear tolerance remains unaffected at 111 Gb/s. In (Gavioli, Giancarlo, et al;), authors have demonstrated 16x100 Gb/s PM-QPSK WDM optical system with different dispersion maps and pre compensation using coherent detection. They have tested the optical system by keeping channel spacing of 50 GHz. Metro Network of Torino (Italy) has been adopted this system. They have experimentally shown that system performance with dispersion compensation unit (DCU) and without inline DCU. They have achieved transmission reach of 1335 km with DCU and 2417 km without DCU for coherent WDM optical system. However, for reduced channel spacing, fiber impairments are severely degrading the system performance for long reach optical transmission system.

2.5 Comparison of fiber dispersion and nonlinearity compensation techniques

Deployment of Coherent Detection with DSP for performance improvement of WDM optical system has more advantage than other compensation techniques. The use of this technique at the receiver end makes this scheme more attractive and robust to overcome high nonlinearities. Moreover, it does not contribute to high insertion loss and effective at high transmission power also. Further, it also does not require symmetrical fiber properties and power distribution throughout optical fiber communication link, which is must in case of optical phase conjugation. This technique has potential to compensate fiber dispersion and nonlinearity both compared to FFE-DFE electronic compensation technique. Apart from this, MLSE fails to fiber mitigate nonlinearity completely. Similarly, there is no significant improvement obtained with dispersion compensation fiber at high power for long transmission reach. Fiber Bragg grating technique can only suitable for narrow band wavelength WDM optical system. However, it includes insertion loss in the system and also difficult to design complex grating structure. This comparison reveals that coherent detection with DSP is a prime applicant to compensate fiber dispersion and nonlinear effects in long haul optical WDM system. The summary of different compensation techniques for fiber dispersion and nonlinearity is shown in Table 2.2.

Table 2.2 Summary of different dispersion compensation techniques

Compensation Technique	**Advantages**	**Disadvantages**
Dispersion Compensation Fiber (DCF)	• Simple inline dispersion compensation technique • Good dispersion compensation for reference wavelength	• Higher insertion loss • Less effective at high transmission power • Promotes nonlinearities
Fiber Bragg Gratings (FBG)	• Compact, passive and linear	• Difficult to design and fabricate complex grating structures • Narrow range of optical wavelength
Optical Phase Conjugation (OPC)	• Compensate dispersion and fiber nonlinearity both	• Requires symmetrical fiber properties and power distribution throughout link • Less flexible

Electronic Dispersion Compensation (EDC) FFE-DFE	• Residual chromatic dispersion is compensated effectively • Compensate PMD • Relatively simple and easy to implement than MLSE	• Performance of the system is limited with noise development due to FFE part and error propagation from the decision part • Cannot mitigate fiber nonlinearity
MLSE	• Greatly improves the dispersion tolerance map • Partially mitigate the impact of fiber nonlinearity	• Growth of OSNR penalty due to dispersion decides the complexity • Fiber nonlinearity cannot be fully compensated
Coherent Detection with DSP	• Exhibits high tolerance to carrier phase noise and resulting in better nonlinearity compensation • Effectively compensate fiber CD and PMD for long transmission reach	• Increase complexity at receiver end

2.6 Comparison of different Transmitter Designs for WDM Optical Systems

Table 2.3 shows the various transmitter designs used for WDM optical system. Spectrum sliced WDM transmitter is optimised and low cost design for optical communication system. However, chromatic dispersion of fiber degrades the system performance at high data rates. Optical spectrum is sliced of incoherent optical source like LED, which results in power fluctuation for different channels. Transmitters using 8 channels for 10 Gb/s data rate uses narrow band LASERs. Channel spacing can be reduced to maintain large number of wavelengths in the fiber to efficiently utilize fiber bandwidth. However, Individual LASER is required for each channel causing the impact of LASER phase noise on system performance. In 112 Gb/s PDM QPSK transmitter design, improvement in spectral efficiency is observed at high data rate for long transmission reach. However, the requirement of individual LASER for each channel is similar to the 8 x 10 Gb/s transmitter design, which incorporate additional cost in overall WDM optical system. Odd and even channel generation transmitter deployed for all-optical OFDM and Nyquist WDM system is cost effective solution due to only two data sources. However, it generates stronger nonlinear distortions during transmission to affect system performance adversely. Multi carrier generation is an attractive concept in transmitter design for WDM optical system. It generates multiple sub-carriers with the use of only few LASERs contributing high spectral efficiency in long haul WDM optical communication system with narrow channel spacing at high data rates

Table 2.3 Summary of various transmitters used for WDM optical systems

WDM Transmitter Design	**Advantages**	**Disadvantages**
Spectrum-sliced WDM (Sandis, Spolitis; Vjaceslavs, Bobrovs; Girts, Ivanovs;)	• Low cost incoherent light source is sufficient to generate multiple channels • More energy efficient	• Chromatic dispersion (CD) considerably degrades the system performance more than LASER based transmitter. • Optical power fluctuation is more for different channels.
8x10 Gb/s transmitter (Deepak Malik; Kuldip, Pahwa; Amit, Wason)	• Reduced channel spacing of 50 GHz	• Requirement of Individual LASER source for each channel • Inter channel cross talk degrades system performance at long reach
112 Gb/s PDM QPSK transmitter (Zhang; Fangzheng, et al)	• Spectral efficiency of 2.24 b/s/Hz is achieved	• Requirement of Individual LASER source for each channel • Phase noise caused by transmitter impacts on system performance
Odd and even channel generation for all-optical OFDM and Nyquist WDM system (Liang, Du B; Arthur, Lowery J;)	• Channels can derived from only two data sources	• Generates stronger nonlinear distortions during transmission

2.7 Conclusion

From the literature survey, it is clear that there is no single technique available to overcome fiber impairments for long distance high spectral efficient WDM optical system. Coherent detection contributes to mitigate fiber nonlinearity at the receiver side. The optical communication system with multilevel modulation format for high data rate and long distance communication with coherent detection at the receiver side is widely considered to address the current traffic requirement. The use is made of digital signal processing (DSP) with coherent detection as an emerging technology to mitigate the effects of such impairments. Performance of WDM optical communication system with Multi-carrier generation at the transmission end to create tight channel spacing for enhancement of spectral efficiency and the use of coherent detection with DSP to compensate fiber dispersion and nonlinearity are addressed and discussed in this thesis for high transmission rate at long reach.

Chapter 3 WDM Coherent PDM-QPSK optical systems employing Dual Carrier

3.1 Introduction

WDM optical transportation systems with per channel data rate of 100 Gb/s or more are in demand to meet the ever increasing requirement of traffic growth (Savory and Seb). These systems are realized employing coherent detection with digital signal processing (DSP) at the receiver side. Linear fiber impairments like chromatic dispersion (CD) and polarization mode dispersion (PMD) are limiting factors for WDM optical systems at higher data rates. DSP at the receiver side is well developed technology to compensate these linear fiber impairments (Ip, Ezra and Joseph) (Savory; Seb, J;). Coherent detection at receiver side contributes in compensation for fiber nonlinearities (Ip, Ezra and Joseph) (Savory; Seb, J;). Fiber nonlinearities can also be compensated by DSP through implementation of numerical inversion of optical fiber propagation (Ip; Ezra; Joseph, M Kahn) (Millar; David, S., et al).

For high speed WDM optical system, two or more bits per symbol transmission is preferred for long distance communication. Phase modulation schemes like QPSK and DQPSK are appropriate choices to fulfill the current and future requirements of optical communication systems. Multilevel phase modulation formats with polarization multiplexing schemes are extensively preferred for future high speed optical communication systems (Curri; Vittorio, et al). Higher spectral efficiency can be obtained by increasing transmission data rates with smaller spacing between channels. Fiber impairments get worse at higher spectral efficiency which reduces the optical communication link length (Udalcovs; Aleksejs; Vjaceslavs, Bobrovs).

The main goal of this work is, to explore design and performance of 1.92 Tbps WDM Optical System. Three CW lasers are used to generate optical carriers. Twelve sub carriers, each spaced 80 GHz apart are produced using two dual tone generators. Each subcarrier carries information at transmission rate of 160 Gbps to enhance the spectral efficiency to 2 b/s/Hz. The analysis is carried out for 12 x 160 Gb/s (1.92 Tb/s) PDM-QPSK WDM optical system considering three different cases that is without coding, with gray coding and with differential coding for 100 km transmission distance. Extensive simulations are carried out to evaluate symbol error rate, error vector magnitude and Q-factor in each case. From the comparison, it is observed that the system with differential coding gives better performance in comparison with other two cases. An improvement in Q-factor with differential coding is achieved in the range of 2 to 5 dB with respect to other two cases. It is also shown that the transmission distance for PDM-QPSK WDM optical system with differential coding can be extended up to 8000 km keeping the Q factor above the FEC limit requirement (BER value 3.8×10^{-3}).

The performance of WDM optical system for 160 Gb/s transmission rate employing PDM-QPSK modulation format is compared for with and without forward error correction (FEC) coding. Gray coding and differential coding are used for FEC. Channel spacing is reduced to increase the spectral efficiency (SE) using the concept of sub carrier generation.

3.2 System Design

3.2.1 Transmitter section

Figure 3.1 shows the transmitter section setup created for 12 x 160 Gbps (1.92Tb/s) PDM-QPSK WDM optical system. Three optical signals from CW lasers with frequency centered at 193.1 THz, 193.42 THz and 193.74 THz are multiplexed through WDM multiplexer at power level of 0 dBm for each channel. Spectrum of this multiplexed signal is shown in Figure 3.2(a). 320 GHz spaced apart multiplexed signal is applied to PDM-QPSK modulator. PDM-QPSK modulator comprises of 4 $LiNbo_3$ (Lithium Niobate) Mach zehnder modulators (MZMs). MZMs are driven through multiplexed optical signal and data sequence with sequence length of 2^{14}-1 generated by PRBS sequence generator as shown in Figure 3.1. MZMs are biased at 6 volts.

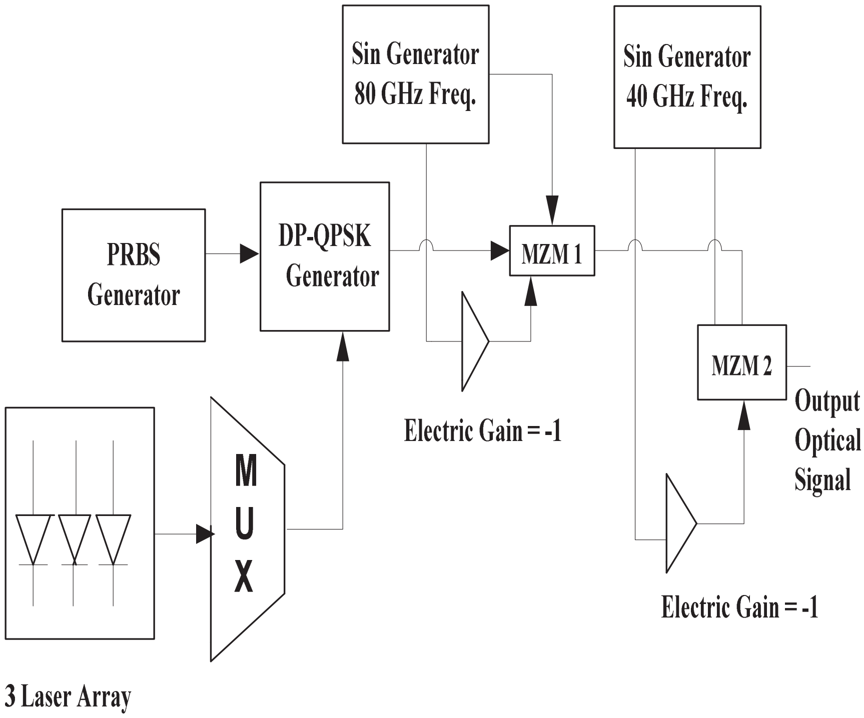
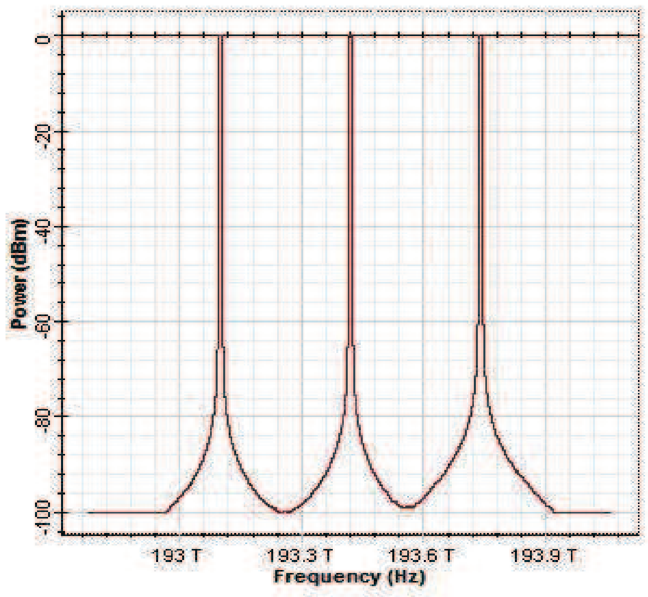


Figure 3.1 Transmitter section

Four MZMs form two pairs of IQ modulators. Single IQ modulator modulates the data signal into two components named as I (In-phase) and Q (Quadrature) component. A phase shift of π/2 is applied between I and Q components. Two pairs of IQ modulators generate I and Q components for X and Y polarizations. The WDM Optical System is created on optisystem software.



(a)

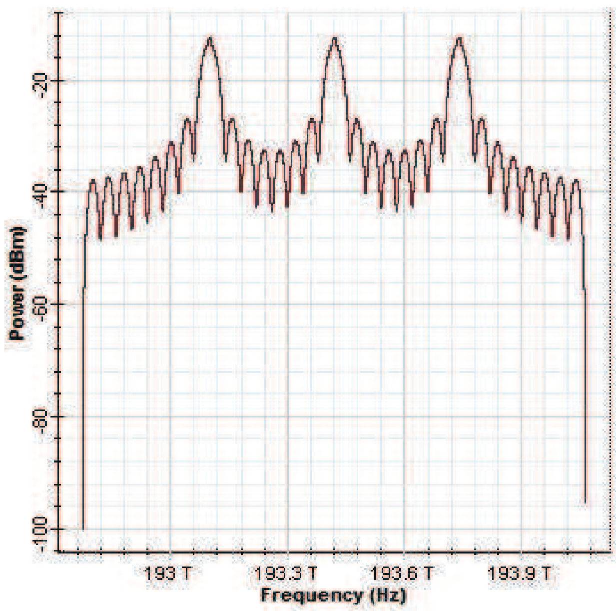


Figure 3.2 (a) Spectrum of multiplexed optical signal (b) Spectrum of optical signal after PDM-QPSK Modulator

First dual tone generator is driven by sinusoidal signal of 80 GHz frequency. So, each of the three optical signals is converted into two frequency-shifted copies at ±80 GHz from the original lasers frequencies. Six channels are created by first dual tone generator, which are applied to second dual tone generator. Second dual tone generator is driven by sinusoidal signal of 40 GHz frequency. Frequency shifted copies of ±40 GHz are obtained of six channels. So, total number of twelve channels (sub carriers) are generated which are 80 GHz apart. Figure 3.3 shows spectrum of twelve sub carriers. It can be seen that subcarrier frequencies are in the range of 192.98 THz to 193.86 THz.

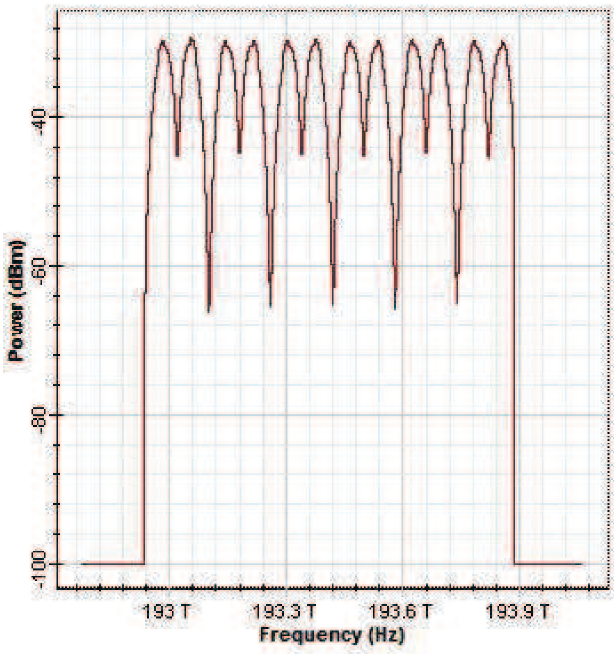


Figure 3.3 Spectrum of twelve sub carriers

3.2.2 Fiber Span

Optical signal containing twelve sub carriers propagating through large effective area fiber (LEAF) as shown in Figure 3.4. Transmission of the signal is carried out through 100 km fiber span with effective area of 80 μm^2.

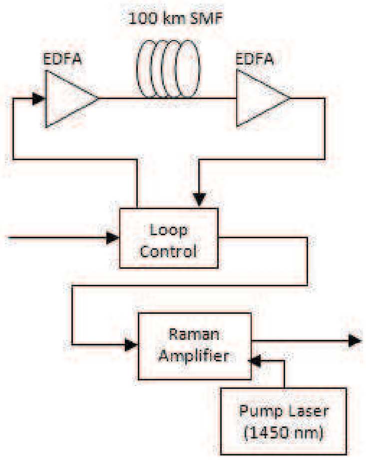


Figure 3.4 Fiber span

Two erbium doped fiber amplifiers (EDFA) are used to provide pre and post amplification of optical signal. For long distance communication, recirculating loop is arranged in design, which repeats 100 km fiber span multiple times based on requirement. Gain of the EDFAs placed in each span compensates the attenuation of fiber. Raman amplifier is used at the end to provide distributed amplification of signal and ultimately maintains the signal to noise ratio throughout the fiber length. Parameters of fiber are listed as in Table 3.1.

Table 3.1 Parameters of Fiber

Parameter	Value
Reference wavelength	1550 nm
Length	100 km
Attenuation	0.185 dB/km
Dispersion	20 ps/nm/km
Dispersion slope	0.075 ps/nm^2/km
PMD co-efficient	0.05 ps/sqrt(km)
γ	1.31W^{-1}km^{-1}

3.2.3 Receiver Section

For recovery of individual sub carrier, rectangular filter is placed at the receiver side with the bandwidth of 40 GHz. Figure 3.5 shows the structure of single channel PDM-QPSK receiver with DSP.

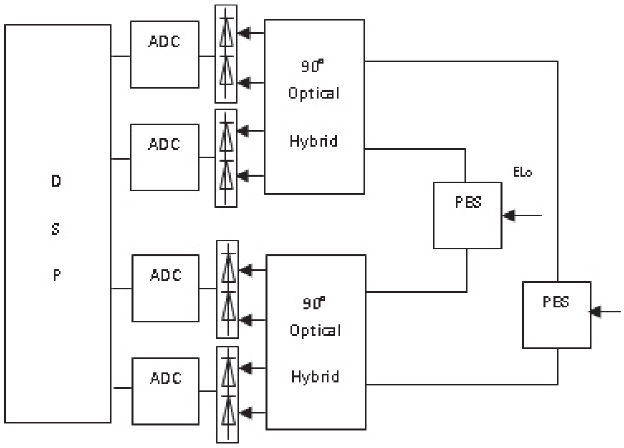


Figure 3.5 Single channel PDM-QPSK Receiver

Figure 3.6 shows the separation of single channel at 192.98 THz from received 12 channels (sub carrier) at receiver.

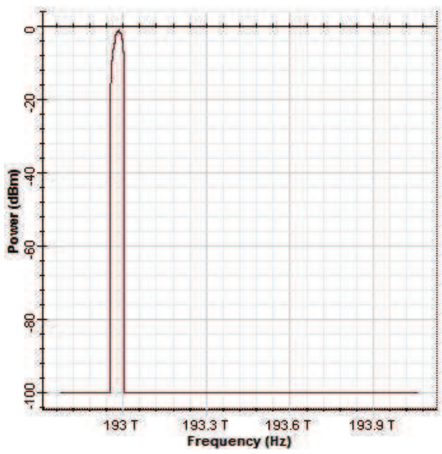


Figure 3.6 Single channel at 192.98 THz separated from 12 channels using rectangular filter

Signal is coherently detected at the receiver which recovers the phase information of signal after influence of impairments in fiber (Zhang; Fangzheng, et al). Four output signals from optical coherent PDM-QPSK receiver are I and Q components of the two polarizations (X and Y), which contain the full information of transmitted signals.

Signal is further processed in DSP (Raybon; Gregory, et al.;). Dispersion and nonlinearity are compensated in electric domain by DSP. Q-factor criterion for the performance evaluation of optical transmission systems are frequently used in combination with BER or SER measurement. It enables an efficient representation of relevant noise statistics (Personick; Stewart, D). Q-factor is defined as:

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_1 - \sigma_0} \tag{3.1}$$

Error vector magnitude (EVM) describes the effective distance of the received complex symbol from its ideal position in the constellation diagram (Schmogrow; Rene, et al) (Shafik; Rishad, A; Md, Shahriar Rahman; AHM, Razibul Islam). The EVM is calculated as follow:

$$EVM\,rms[\%] = \sqrt{\frac{\frac{1}{n}\sum_{N=1}^{N}\left|S_{Rx,n} - S_{Tx,n}\right|^2}{\frac{1}{N}\sum_{n=1}^{N}\left|S_{Tx,n}\right|^2}} \tag{3.2}$$

In equation (3.2), STx,n and SRx,n represent the nth transmitted and received symbols, respectively, and N is the number of symbols.

3.3 Results and discussion

First, the system performance of WDM optical system at 100 km for launch power from -4 dBm to +5 dBm is investigated. Figure 3.7 shows the Q factor performance of 5th channel (193.3 THz) at different launch powers.

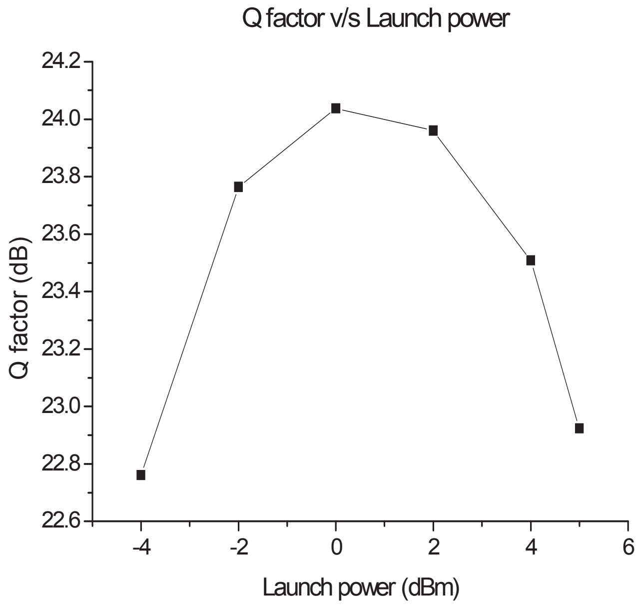


Figure 3.7 Q-factor vs. Launch power

The graph shows that higher value of Q-factor is obtained at 0 dBm power level. At this power level fiber nonlinear impairment compensation is better. We have initially evaluated the performance of WDM optical system without applying any coding scheme at 100 km transmission distance. Gray coding and differential coding are applied on same WDM optical system to verify the performance in terms of symbol error rate (SER), Q factor and error vector magnitude (EVM). Transmission distance of 100 km is considered for sack of simplicity and comparative evaluation of three cases.

Table 3.2 shows values of Log of estimated SER for WDM optical system without coding scheme, with gray coding and differential coding for 12 different channels. The plot of log of estimated symbol error rate is shown in Figure 3.8. Q factor and EVM values are compared for these three cases in table 3.3 and table 3.4 respectively.

Table 3.2 Comparison of log10 of estimated SER without coding, with Gray and differential coding schemes for 100 km

Channel number (freq. in THz)	Without coding	Gray coding	Differential coding
1(192.98)	-66.1663	-78.8524	-103.838
2(193.06)	-57.7181	-61.4618	-126.948
3(193.14)	-44.707	-50.929	-100.31
4(193.22)	-42.8132	-48.4185	-106.505
5(193.3)	-38.3059	-39.2939	-98.7921
6(193.98)	-34.982	-36.5571	-103.958
7(193.46)	-34.0177	-35.4663	-98.3562
8(193.54)	-41.48	-42.7084	-133.069
9(193.62)	-45.6827	-53.0772	-94.7162
10(193.7)	-58.8341	-64.0458	-103.812
11(193.78)	-58.7933	-71.1004	-123.652
12(193.86)	-63.9013	-59.4319	-128.562

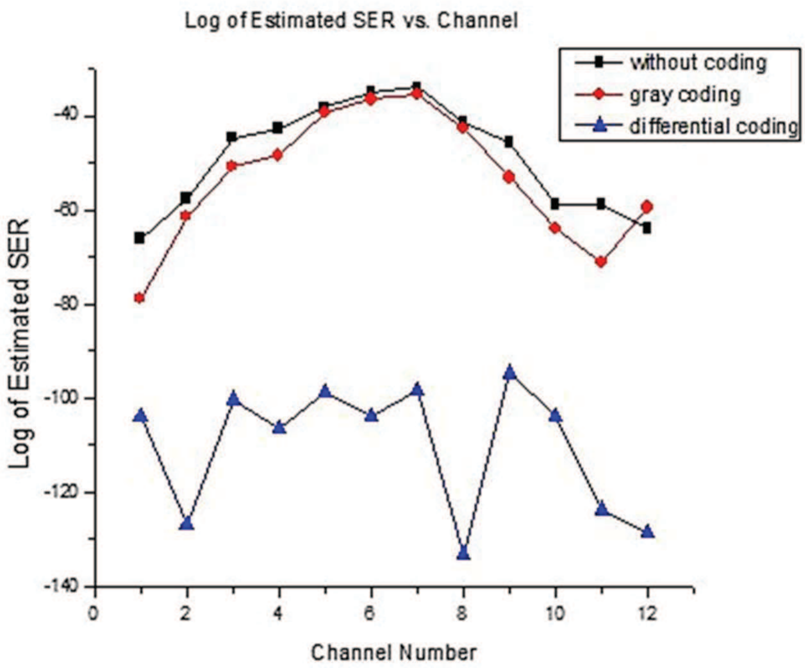


Figure 3.8 Log of Estimated SER vs. Channel

WDM Optical system with differential coding exhibits lower symbol error rates than other two cases. Differential encoding removes the possibility of burst errors due to cycle slips. Log of Symbol error rates are varying from channel to channel due to imperfect gain equalization of EDFA in WDM optical system. Log of Estimated SER is found lower in channel 2 and channel 8 as compared to other channels due to variations of fiber nonlinearities from channel to channel as shown in Figure 3.8. Similar results are also observed in terms of Q factor and EVM from Figure 3.9 and

Figure 3.10 respectively. Table 3.3 Comparison of Q-factor without coding, with Gray and Differential coding schemes for 100 km

Table 3.3 Comparison of Q-factor without coding, with Gray and Differential coding schemes for 100 km

Channel number (freq. in THz)	Without coding	Gray coding	Differential coding
1(192.98)	24.80999	25.54118	26.74839
2(193.06)	24.21493	24.446	27.62808
3(193.14)	23.10186	23.61742	26.5969
4(193.22)	22.91325	23.39466	26.8595
5(193.3)	22.42857	22.47246	26.52999
6(193.98)	22.03357	22.15302	26.75318
7(193.46)	21.91175	22.01912	26.51072
8(193.54)	22.77552	22.8409	27.83422
9(193.62)	23.19555	23.79991	26.34538
10(193.7)	24.29794	24.62684	26.74719
11(193.78)	24.29529	25.08661	27.51291
12(193.86)	24.6584	24.29794	27.68348

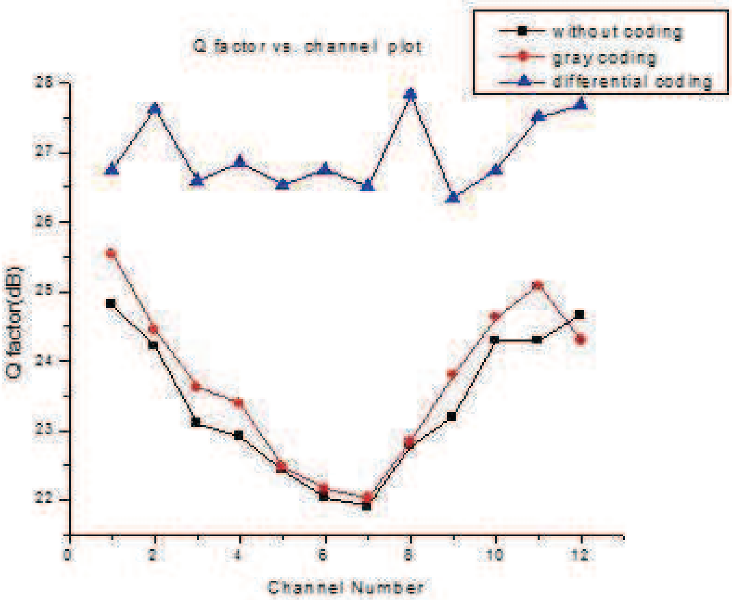


Figure 3.9 Q factor vs. Channel

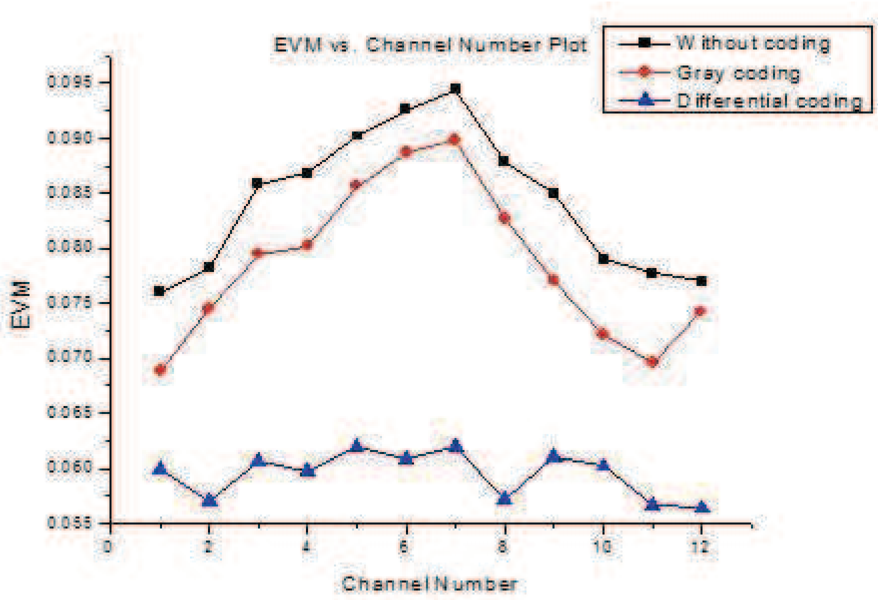


Figure 3.10 EVM vs. Channel

An improvement in the range of 2 dB to 5 dB is observed in Q factor for WDM optical system with differential coding in comparison with other two cases. Figure 3.9 highlights the better performance of WDM optical system with differential coding. Differential coding is highly preferred scheme for forward error correction (FEC) to enhance the system performance.

Table 3.4comparison of EVM without coding, with GRAY and differential coding schemes for 100 km

Channel number (freq. in THz)	Without coding	Gray coding	Differential coding
1(192.98)	0.076053	0.068887	0.059957
2(193.06)	0.078211	0.074508	0.057066
3(193.14)	0.085871	0.079507	0.060614
4(193.22)	0.086864	0.080234	0.059751
5(193.3)	0.090163	0.085697	0.061918
6(193.98)	0.09261	0.088692	0.060904
7(193.46)	0.094456	0.089786	0.061907
8(193.54)	0.08785	0.082758	0.057248
9(193.62)	0.085061	0.077046	0.060963
10(193.7)	0.07901	0.07219	0.060218
11(193.78)	0.077688	0.069635	0.056707
12(193.86)	0.07698	0.074238	0.0564

Low value of error vector magnitude (EVM) indicates better system performance. Table 3.4 clearly shows that EVM performance is enhanced for differential coding as compared to gray coding and without coding schemes.

Differential coding shrinks EVM around 26% to 35% for respective channel in comparison with other two cases. EVM values for WDM optical system with differential coding seems to be lowest as shown in Figure 3.10

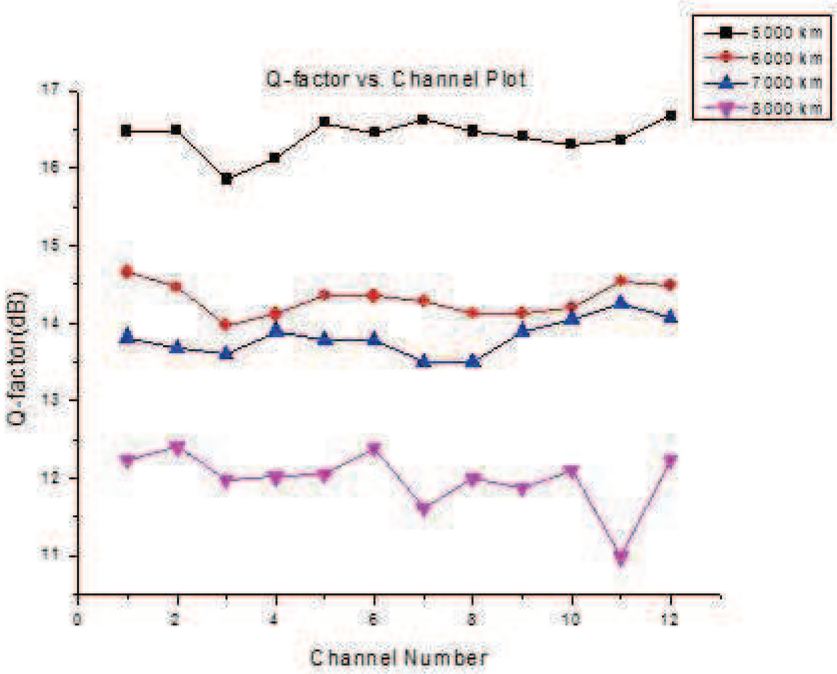
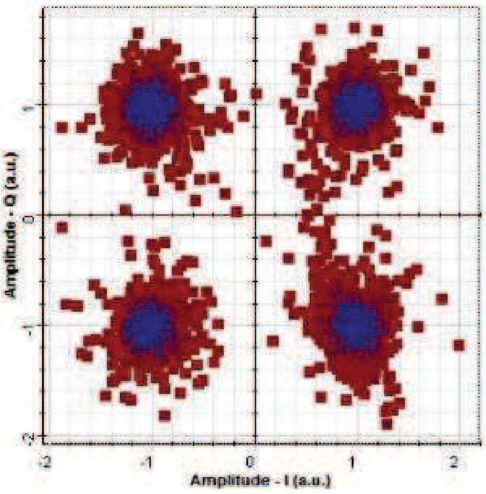
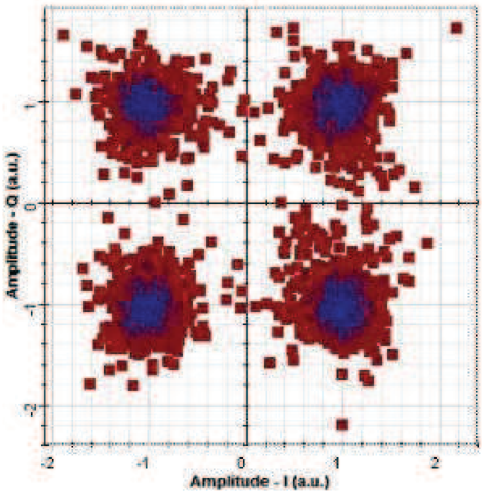


Figure 3.11 Q factor vs. channel (5000 km to 8000 km)

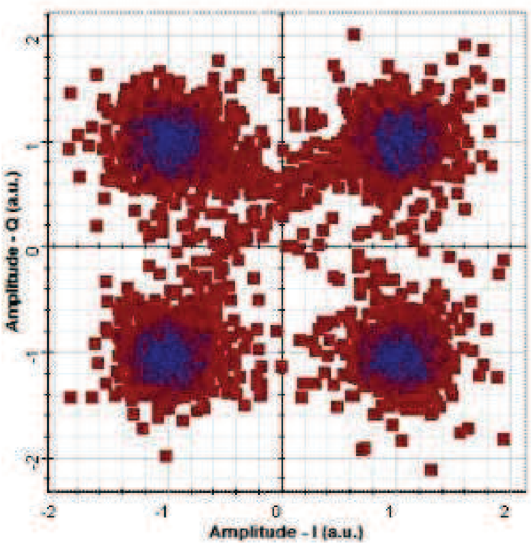
Plot of twelve channels vs. Q-factor considering the distances of 5000 to 8000 km in step of 1000 km for WDM optical system is shown in Figure 3.11. Q-factor for transmission distance from 5000 km to 7000 km is above 13 dB as shown in Figure 3.11. WDM optical system with differential coding can reach long distance upto 8000 km for which minimum Q factor is 10.97 dB. This value of Q factor is above the required value of 8.53 dB per channel at BER of 3.8 x 10^{-3}.



(a)



(b)



(c)

Figure 3.12 Constellation diagram of channel 5 (193.3 THz) at (a) 6000 km (b) 7000 km and (c) 8000 km

Constellation diagram of WDM optical system with differential coding at three different link lengths of 6000 km, 7000 km and 8000 km for channel 5 (193.3 THz) is shown in Figure 3.12. Four separate points related with symbols of bit patterns (00, 01, 11 and 10) are clearly visible for 6000 km, 7000 km and 8000 km transmission distances from constellation diagrams of Fig. 3.12(a), Fig. 3.12(b) and Fig. 3.12 (c) respectively.

WDM optical system with differential coding gives satisfactory performance at 1.92 Tbps data rate up to a distance of 8000 km.

Table 3.5 Brief comparison between proposed technique and earlier reported work

Dispersion compensation technique	Modulation	Q factor / BER	Transmission Distance
DCF (Chong, Han et al.;)	Hybrid QPSK/OOK	10.5 dB	1000 km
OPC (Jansen, S L; Krummrich, P M et al.;)	NRZ	13.3 dB	800 km
FBG (Valts, Dilendorfs et al.;)	NRZ	$< 10^{-12}$	221 km
DCF with digital back propagation (DBP) (Zhang; Fangzheng, et al)	PDM QPSK	5.95 dB	2810 km
Coherent detection with DSP **(Proposed Work)**	PDM QPSK	10.97 dB	8000 km

Inline dispersion compensation technique has deployed for compensation of chromatic dispersion using dispersion compensating fiber (DCF) (Chong, Han et al.;). Hybrid QPSK/OOK modulation demonstrate 10.5 dB Q factor for 1000 km transmission reach. DCF promotes fiber nonlinearity due to it’s small diameter, which degrades the system performance at long distance. Optical phase conjugation technique was employed for NRZ format to improve the system performance for 800 km reach (Jansen, S L; Krummrich, P M et al.;). However, OPC demands equal properties of fiber throughout link length for better compensation of fiber dispersion and nonlinearities.

Fiber bragg grating exhibits the potential for better dispersion compensation than DCF with less insertion loss (Valts, Dilendorfs et al.;) reported transmission of NRZ data for 221 km distance considering BER < 10^{-12}. However, FBG has a limitation of bandwidth and less preferable in the system with high nonlinear effects of fiber. DCF with digital back propagation (DBP) is utilized to achieve the transmission reach of 2810 km for WDM optical system. DCF is deployed inline and DBP is used at receiver end to compensate dispersion and nonlinearity. However, DBP is less effective to compensate inter channel nonlinearities of fiber and hence limits the system performance at long transmission distance (Zhang; Fangzheng, et al). Table 3.5 shows that, using our proposed technique of coherent detection technique with DSP at the receiving end, we obtained maximum Q factor of 10.97 dB at 8000 km transmission reach for PDM QPSK format. PDM format provides two degree of freedom to transmit the data using each polarization. Our proposed technique gives higher Q factor at long distance as compared to earlier reported work as shown in Table 3.5.

3.4 Conclusion

The performance of 12 x 160 Gb/s (1.92 Tb/s) PDM-QPSK WDM optical system is evaluated and compared by considering no coding, with gray coding and with differential coding for 100 km transmission distance by extensive simulation. System with differential coding outperforms than system with gray coding and without coding, because differential coding will remove the possibility of burst errors due to cycle slips. Q factor of WDM optical system with differential coding is improved in the range of 2 to 5 dB. Spectral efficiency of 2 b/s/Hz is achieved by keeping 80 GHz channel spacing at the data rate of 160 Gb/s of each sub carrier. Transmission distance for PDM-QPSK WDM optical system with differential coding can be extended up to 8000 km at maintaining the Q factor above the FEC limit (BER value 3.8 x 10^{-3}).

Chapter 4 WDM Coherent Optical Systems Employing Dual Carrier with PDM 16-QAM and Hybrid Approach

4.1 Introduction

Now a days, 100 Gb/s optical transmission systems are commonly used for commercial WDM networks. To assemble larger data traffic, higher spectral efficiency is a promising way to enhance the capacity of WDM networks (Pincemin; Erwan, et al.) (Lach; Eugen; Wilfried, Idler;). Dual carrier concept is used in WDM networks with tight channel spacing. Polarization division multiplexed multilevel modulation formats are used to meet growth in global data demand (Winzer; P, J., et al.). WDM optical systems with PDM 16-QAM format are under strong examination to settle current traffic demand (Faure; Jean, Paul, et al.). PDM 16-QAM optical communication systems permit enhancement in spectral efficiency at the cost of transmission reach.

Higher transmission launch power is used to maintain required optical signal to noise ratio (OSNR) at receiver side (Udalcovs; Aleksejs, et al.). However, power-dependent nonlinear distortion from the Kerr nonlinearity in the transmission fiber including intra-channel and inter-channel crosstalk and self phase modulation degrades the transmitted signal in WDM optical systems, and therefore, decreases the transmission reach. It has been reported that higher order modulation formats are more prone to Kerr nonlinearity distortions and are severely degraded in tightly packed channels (Sackey; Isaac, et al). Therefore, transmission reach is shorter for advanced modulation formats (e.g. 16-QAM) with acceptable signal degradation compared to less spectrally efficient formats (Gnauck; A, H., et al.). Moreover, modulation formats with higher symbol rates are easily affected by dispersion induced distortion, which can interact with nonlinear effects even over short fiber lengths.

The main goal of this work is, to explore design and performance of 4 x 200 Gbps WDM Optical systems employing dual carrier concept. Each carrier of dual carrier transmits data at a transmission rate of 200 Gbps using polarization division multiplexed 16-quadrature amplitude modulation (PDM 16-QAM) modulation format. Extensive Simulations are carried out for WDM optical system with and without nonlinearity compensation at receiver for Ultra Large Area Fiber (ULAF). Spectral efficiency of 4 b/s/Hz is achieved by keeping 50 GHz channel spacing at the data rate of 200 Gb/s of each carrier. Performance parameter like symbol error rate, error vector magnitude and Q-factor are verified for comparison. Better Q factor of almost 2.43 dB to 1.95 dB is achieved for system with nonlinearity compensation than system without nonlinearity compensation for 200 km to 1000 km transmission reach. EVM values are reduced from 0.78% to 1.33% in system with nonlinearity compensation. Log of Estimated symbol error (ESE) is obtained 41.2% lower in system with nonlinearity compensation at 1000 km. Dual Carrier PDM 16-QAM WDM optical system with nonlinearity compensation outperforms than the system without nonlinearity compensation. The performance of WDM optical systems with only EDFA as inline amplifier for 200 Gb/s transmission rate employing PDM-16 QAM modulation format with concept of dual carrier generation is investigated. Obtained results are compared for WDM optical communication systems with and without nonlinearity compensation at receiver side.

4.2 Theoretical Background

A generalized nonlinear Schrödinger equation which describes the evolution of optical wave at the transmission distance z is specified as (Agrawal; Govind).

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2} A = i\gamma |A|^2 A \tag{4.1}$$

Where A is assumed as normalized pulse amplitude such that $|A^2|$ represents optical power; γ is the nonlinearity coefficient; α is the attenuation constant; β_1 , β_2 are first and second order derivative of mode-propagation constant β about the reference wavelength λ_o which denote chromatic dispersion through linear delay; the effects of fiber loss is represented through α. Nonlinear effects are represented through Nonlinearity parameter γ and it relates with fiber parameters as:

$$\gamma = \frac{n_2 \omega_o}{c A_{eff}} \tag{4.2}$$

Here, n_2 and ω_o denote nonlinear refractive index and carrier frequency respectively. A_{eff} represents effective area of fiber core. Nonlinearity compensation is performed using a digital back propagation (DBP) method (Napoli; Antonio, et al.) (Yao; Haitao, et al.) (Arboleda-Alzate; Natalia; Ferney, Amaya-Fernández). The received signal can be digitally propagated through an inverse fiber model to compensate for CD and fiber nonlinearity as given by:

$$\frac{\partial A}{\partial(-z)} = (D + N)A \tag{4.3}$$

Where D is the differential operator accounting for linear effects (chromatic dispersion and attenuation) and N is the nonlinear operator, which are given by:

$$D = \frac{i\beta_2}{2}\frac{\partial^2}{\partial t^2} - \frac{\alpha}{2} \tag{4.4}$$

$$N = i\gamma |A|^2 \tag{4.5}$$

The linear section in DBP is same as that used for CD compensation. The nonlinear section of DBP is identical to the nonlinear section used in a single-step nonlinearity compensator.

The phase shifts for each step is defined as:

$$\Theta_{NL}(t) = k\gamma L_{eff} |A|^2 \tag{4.6}$$

Where k is a compensation factor and L_{eff} is the effective length of each step. If each DBP step only compensates for a fraction of a fiber span, then L_{eff} is represented as:

$$L_{eff} = \frac{1 - \exp(-\alpha L_{span})}{\alpha} \tag{4.7}$$

4.3 System Design

WDM optical communication system set up is shown in Figure 4.1. Transmitter section is formed using two CW lasers with centre frequencies of 193.1 THz and 193.2 THz, Wavelength division multiplexer, PRBS generator, PDM 16-QAM generator, Mach-zehnder modulator (MZM) and sine wave generator of 25 GHz frequency. Frequency Spectrum of WDM multiplexer is shown in Figure 4.2(a).

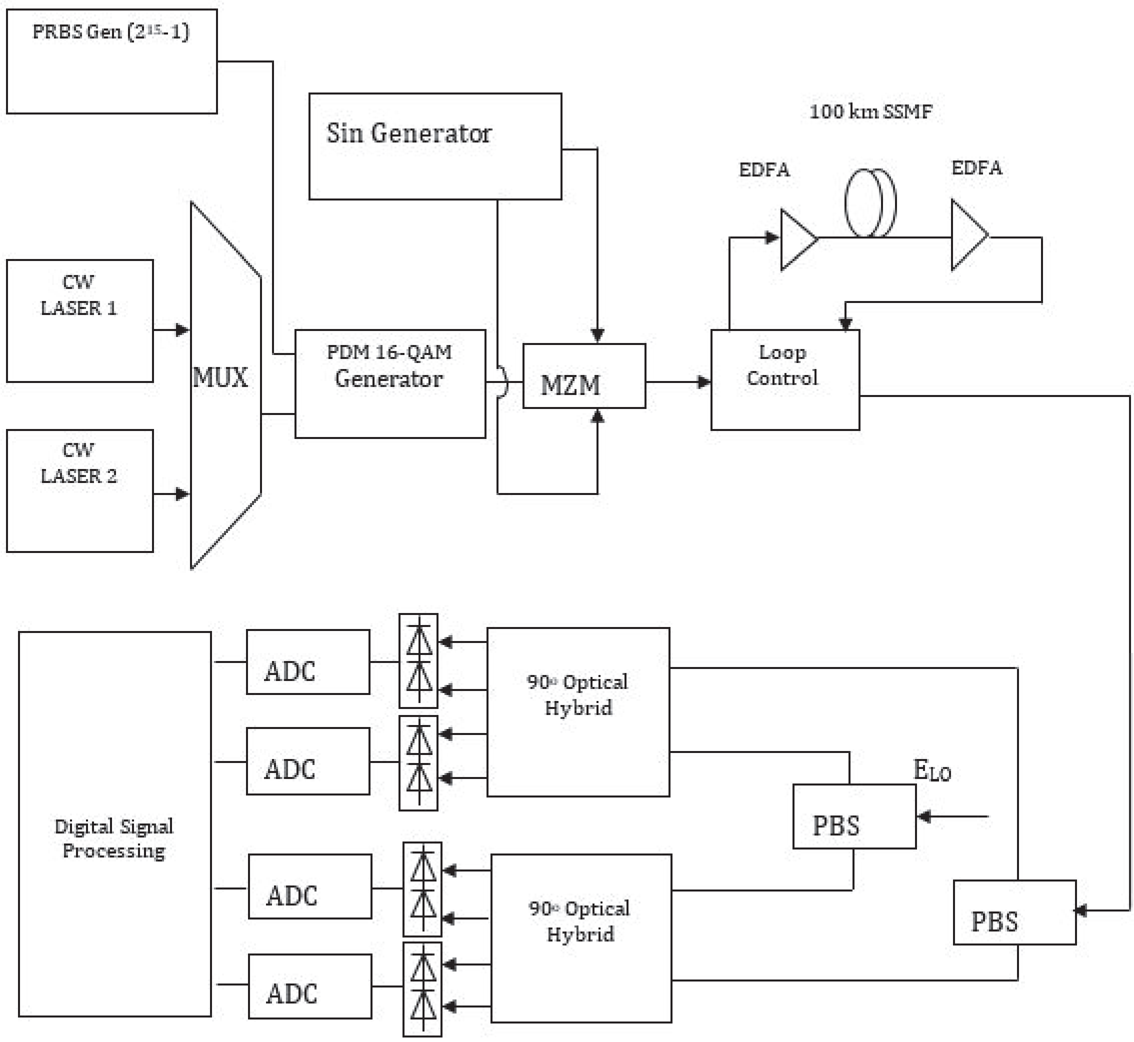
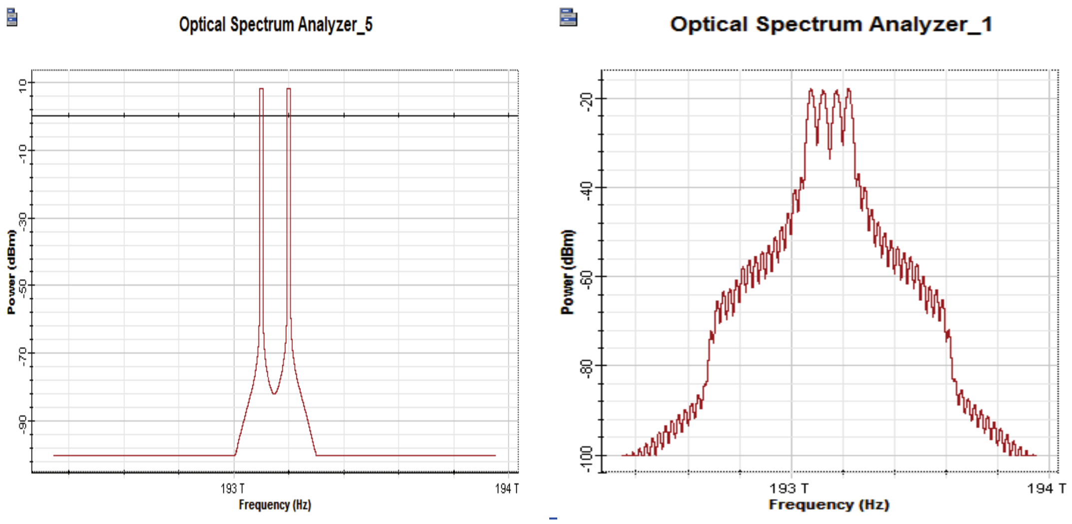


Figure 4.1 PDM 16-QAM WDM optical system set up using dual carrier generation

IQ modulator is created with two MZMs for single polarization, thus two pairs of IQ modulators are formed with four MZMs for PDM-16 QAM. π/2 phase shift is applied between I(In-phase) and Q(Quadrature) components. Two pairs of IQ modulators generate I and Q components for X and Y polarizations. 25 GHz frequency sinusoidal signal drives dual carrier generator. Each of laser frequency is converted into frequency shifted copies of ±25 GHz, which results into 50 GHz apart four channels (two sets of dual carriers). Spectrums of dual carrier generator using MZM is shown in Figure 4.2 (b). Dual-carriers for two lasers are found in the range of 193.075 THz to 193.225 THz frequencies.



(a) (b)

Figure 4.2 Spectrum of optical signal after (a) WDM Multiplexer (b) Dual carrier generator

Optical signal containing four carriers is propagating through single mode fiber as shown in Figure 4.1. Transmission of the signal is carried out for system with only EDFA as inline amplifier consisting of recirculating loop having span length of 100 km with ultra large effective area fiber (ULAF). Chromatic dispersion of 19.9 ps/nm/km, an attenuation of 0.185 dB/km, an effective area of 120 μm^2 and a nonlinearity coefficient γ of 0.878 W^{-1} km^{-1} are considered as simulation parameters at reference wavelength of 1550 nm. Optical signal loss in fiber is compensated with two EDFAs in WDM optical system. Recirculating loop is included in design to multiply 100 km fiber span length as per the requirement to establish long distance optical communication.

Rectangular band pass filter with bandwidth of 40 GHz is placed at receiver side to recover individual carrier. Figure 4.1 shows the structure of single channel PDM-16 QAM receiver with DSP (Chang; Sun, Hyok; Hwan, Seok Chung; Kwangjoon, Kim) (Lau; Alan, Pak Tao, et al) (Abdullah; M, F L; Bhagwan Das; Shah, Nor Shahida Mohd). Coherent PDM-16 QAM receiver contains four output optical signals. These signals are I and Q components of each polarization (X and Y), which contain full information of transmitted signal. Signal is further processed in DSP (Lau; Alan, Pak Tao; Chao, Lu).

4.4 Results and discussion

Extensive simulations were carried out for performance investigation of the proposed WDM optical systems with and without nonlinearity compensation. Variation of Q factor with transmission distance up to 1000 km at 6 dBm launch power is shown in Figure 4.3. It is seen from Figure 4.3 that as we increase the transmission distance between 200 km to 1000 km, correspondingly Q-factors vary between 15.79587 dB to 11.41145 dB for system without nonlinearity compensation and between 18.22134 dB to 13.36978 dB for system with nonlinearity compensation at receiver. It clearly indicates that the Q-factor is better for system with nonlinearity compensation than without nonlinear compensation in the range of 2.43 dB to 1.95 dB over 200 km – 1000 km.

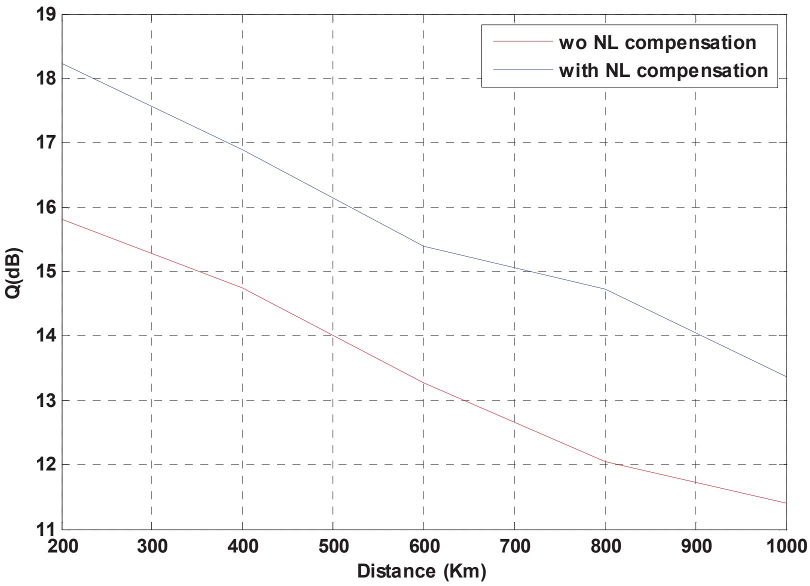


Figure 4.3 Q-factor vs. Transmission Distance for systems with and without Non linearity Compensation

Figure 4.4 shows variation in Log (ESE) values between -9.15634 to -3.90361 for system without nonlinearity compensation and between -13.43526 to -5.51895 for system with nonlinearity compensation for corresponding transmission distance of 200 km to 1000 km. It is observed that the values of Log (ESE) are 46.7% to 41.2% lower for system with nonlinearity compensation compared to system without nonlinearity compensation over 200 km – 1000 km.

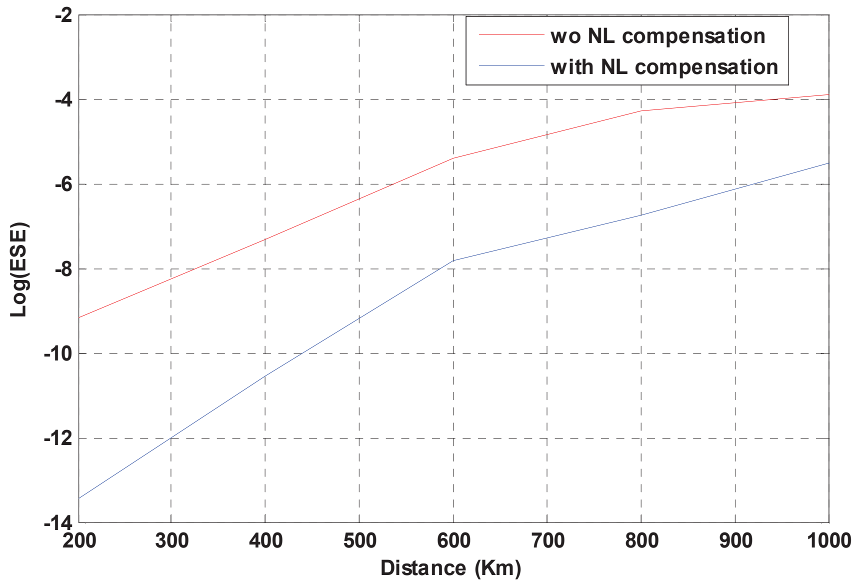


Figure 4.4 Log (ESE) vs. Transmission Distance for systems with and without Non linearity Compensation

It is evident from the Figure 4.5 that as we change the transmission distance in the range of 200 km to 1000 km, correspondingly the value of EVM varies in the range of 8.50449% to 11.16115% for system without nonlinearity compensation and 7.72018 to 9.83591 for system with nonlinearity compensation. It clearly indicates that the values of EVM are 0.78% to 1.33% lower for system with nonlinearity compensation compared to system without nonlinearity compensation over 200 km – 1000 km. Figure 4.6 shows the constellation of both the systems for transmission distance of 1000 km. The deviation of bits from exact position is more in system without nonlinearity compensation in comparison with system with nonlinearity compensation at receiver.

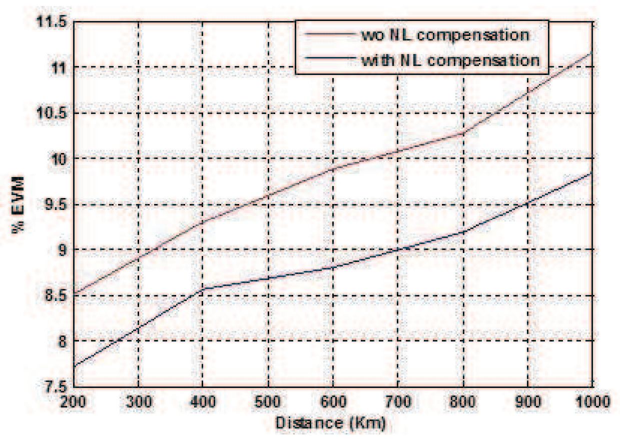


Figure 4.5 EVM vs. Transmission Distance for systems with and without Non linearity Compensation

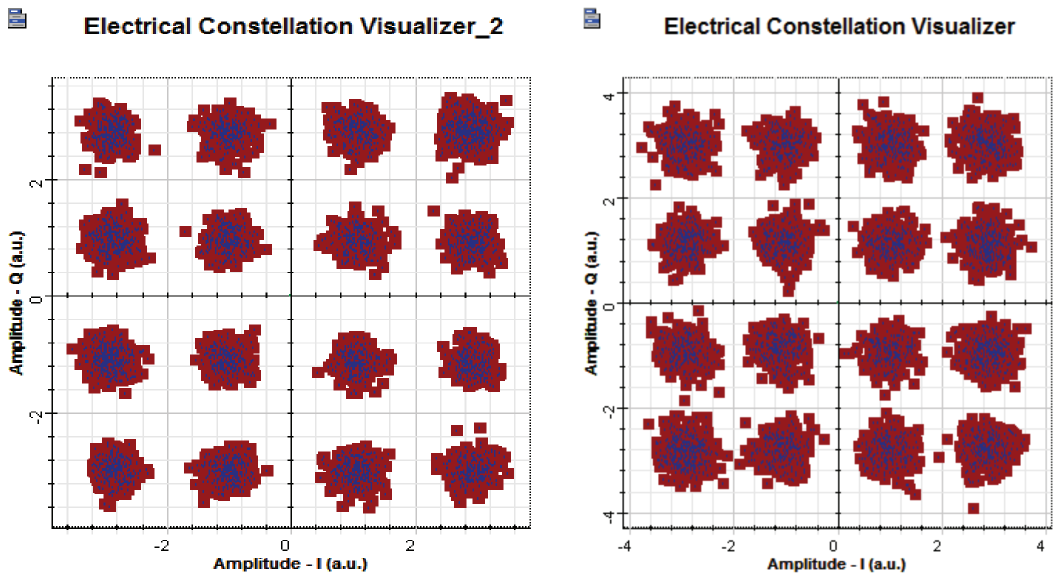


Figure 4.6 Constellation diagrams at 1000 km Transmission Distance for systems (a) with (b) without Nonlinearity Compensation

4.5 Performance Evaluation of 10 x 100 Gbps Coherent WDM Optical System Using Hybrid Modulation Approach

10 x 100 Gbps coherent WDM optical systems using hybrid modulation (polarization division multiplexed quadrature phase shift keying (PDM QPSK) and polarization division multiplexed 16-quadrature amplitude modulation (PDM 16 QAM)) is investigated and discussed in this section. Dual carrier concept is utilized in system design with 50 GHz spacing between channels. System is verified through simulation for ULAF fiber and SSMF fiber. Performance is verified through system parameters like Q-factor, symbol error rate and error vector magnitude (EVM). Q factor is improved about 2.85 dB to 2.98 dB for 500 km – 2500 km transmission distances using ULAF fiber in system. WDM optical system with ULAF fiber also outperforms than system with SSMF fiber in terms of symbol error rate and EVM.

4.5.1 Introduction

Transmission rate of 100 Gbps for each channel is in demand for current development of optical networks (Lach; Eugen; Wilfried, Idler). Kerr nonlinearity and dispersion are major limiting factors for reducing the capacity of fiber optic communication system (Savory; Seb, J., et al) (Carena; Andrea, et al.;) (Essiambre; René-Jean, et al.) (Agrawal; Govind). Coherent detection at the receiver side is a promising way to mitigate phase noise. Digital signal processing (DSP) is an effective way to compensate dispersion and nonlinear effects (Taylor; Michael, G) (Napoli; Antonio, et al.) (Chang; Sun, Hyok; Hwan, Seok Chung; Kwangjoon, Kim). The concept of dual carrier is useful to increase spectral density with tight spacing between channels. Higher data rate with tight channel spacing reduces the transmission distance of communication due to linear and nonlinear impairments. Higher order modulation formats like PDM-QPSK and PDM-16 QAM are attractive solution to reduce the symbol rate at transmission side (van, den Borne; Dirk, et al.) (Roberts; Kim, et al.) (Curri; Vittorio, et al.). In line dispersion compensation is avoided when electronic dispersion compensation is utilized at receiver end. Multilevel modulation format is more useful for WDM optical system at higher data rate (Savory; Seb, J). WDM system is designed using PDM QPSK and PDM 16-QAM modulation formats in combination with dual carrier concept. Results are reported for WDM hybrid optical system with ULAF fiber and SSMF fiber.

4.5.2 System Design

Figure 4.7 shows the WDM optical system set up with hybrid modulation. Three CW lasers are used with 193.3 THz, 193.4 THz and 193.5 THz centre frequencies for PDM QPSK transmitter. Modulated PDM QPSK signal is applied to dual carrier 1 for generation of six carriers ranges from 193.275 THz to 193.525 THz. Dual carrier generator is formed using Mach-zehnder modulator (MZM) and sine wave generator of 25 GHz frequency. Similarly, two CW lasers are used with 193.2 THz and 193.6 THz centre frequencies for PDM 16-QAM transmitter. Modulated PDM 16-QAM signal is applied to dual carrier 2 for generation of four carriers of 193.175 THz, 193.225 THz, 193.575THz and 193.625 THz. Six PDM QPSK channels and four PDM 16-QAM channels are combined through optical coupler. These ten channels are passed through optical span formed using EDFA amplifier and 100 km optical fiber. Long transmission distance is created using loop control mechanism.

Channels are separated at receiving end with optical band pass filter, which is followed by coherent detector as shown in Figure 4.7. Separate coherent detectors for PDM QPSK and PDM 16-QAM channels are utilized at receiving end. Digital signal processing block mitigates linear and nonlinear impairments at receiver. We used two different fibers ULAF and SSMF for simulation. ULAF has chromatic dispersion of 19.9 ps/nm/km, an attenuation of 0.185 dB/km and an effective area of 120 μm^2. Similarly, SSMF has chromatic dispersion of 16.5 ps/nm/km, an attenuation of 0.2 dB/km and an effective area of 80 μm^2. Simulation is carried out using optisystem software.

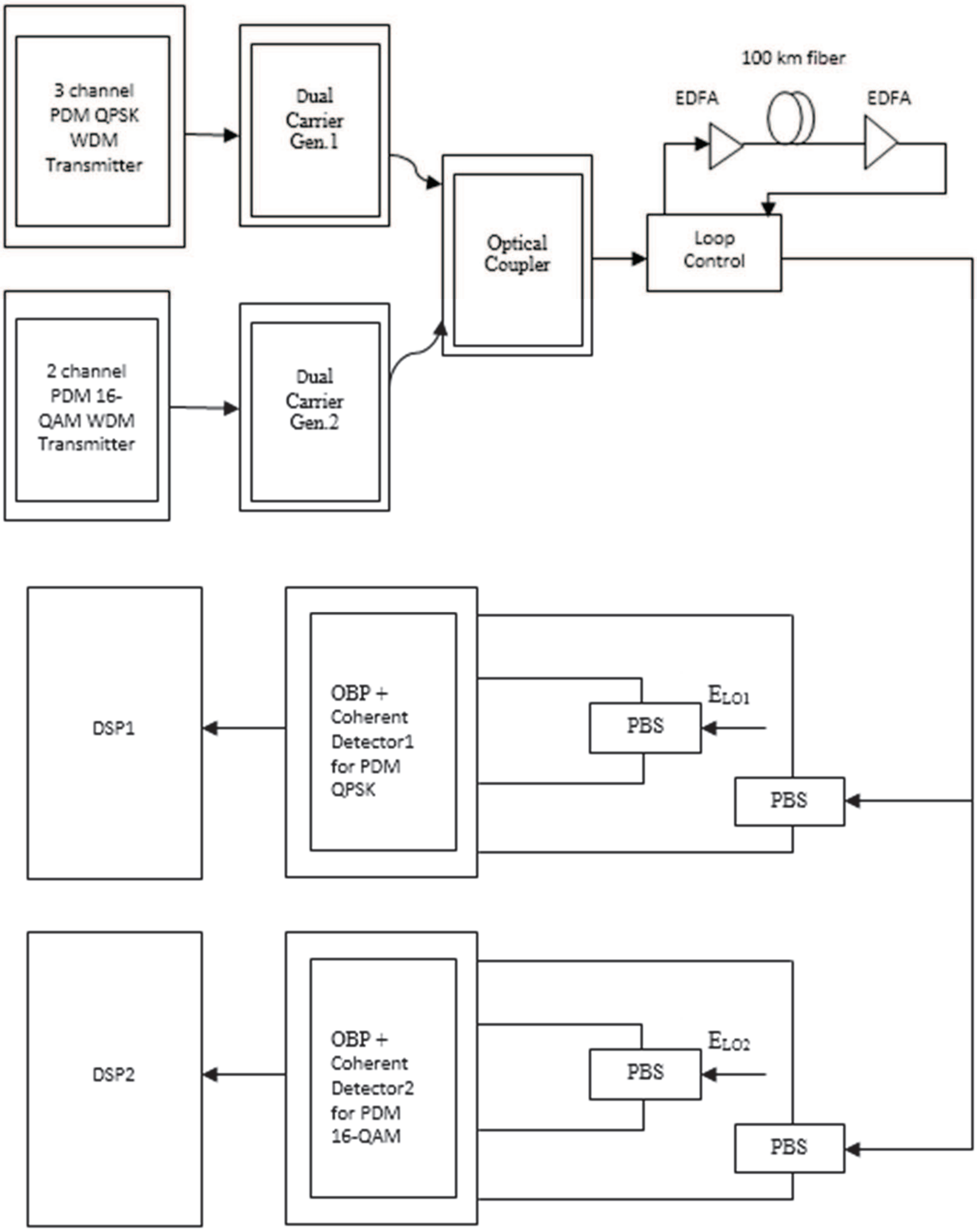


Figure 4.7 WDM Optical system set up with hybrid modulation

4.5.3 Results and discussion

Performance of hybrid modulation WDM optical system is verified for two different fibers e.g. standard single mode fiber (SSMF) and ultra large area fiber (ULAF) at 8 dBm transmission power per channel. System is simulated for distance up to 2500 km employing SSMF and ULAF fibers. Q factor vs. distance plot is shown in Figure 4.8 for 193.375 THz PDM QPSK modulation channel. It is observed that as distance varies from 500 km to 2500 km, Q factor changes from 19.11 dB to 8.93 dB for system with ULAF fiber and 16.26 dB to 5.95 dB for system with SSMF fiber for PDM-QPSK modulation. Better value of Q is obtained from 2.85 dB to 2.98 dB for 500 km – 2500 km transmission distances due to large effective area of ULAF fiber.

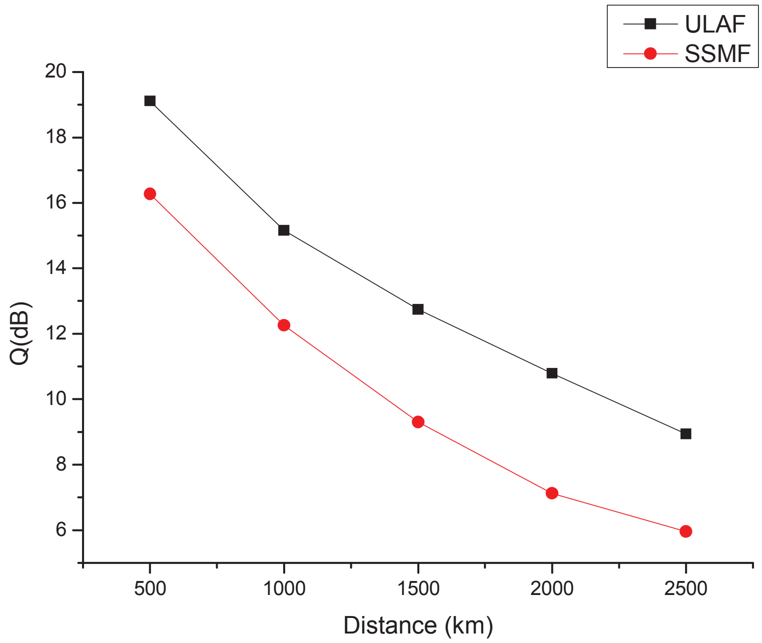


Figure 4.8 Q vs. Distance for 193.375 THz PDM QPSK modulation channel in hybrid modulation WDM optical system

Similar results are obtained for PDM 16-QAM modulation in system as shown in Figure 4.9. Q varies from 12.21 dB to 5.53 dB and 10.24 dB to 4.95 dB for system with ULAF and SSMF fibers respectively for 193.625 THz PDM 16-QAM modulation channel. 1.97 dB to 0.58 dB improvement in Q values are gained for 500 km – 2500 km distance for system with ULAF fiber.

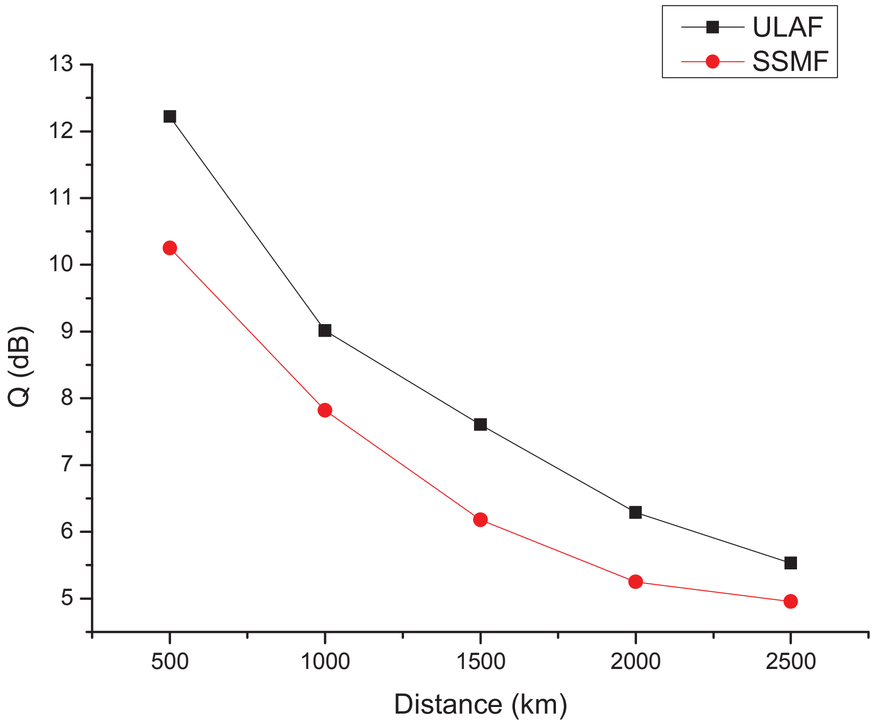


Figure 4.9 Q vs. Distance for 193.625 THz PDM 16-QAM modulation channel in hybrid modulation WDM optical system

Figure 4.10 shows deviation from -18.78 to -2.29 and -10.13 to -1.33 in Log (ESE) of 193.375 THz channel for hybrid optical system with ULAF fiber and SSMF fiber respectively for 500 km – 2500 km. It is seen that Log(ESE) values are lower for system using ULAF fiber with respect to SSMF fiber. Nonlinearity influence is more for system with SSMF fiber due to small effective area.

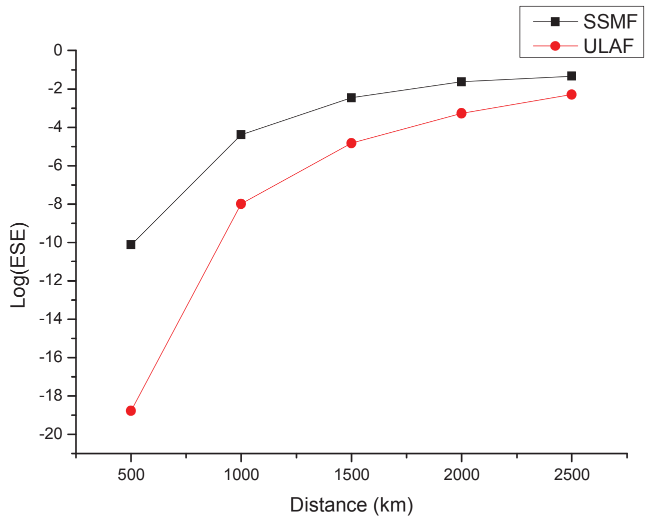


Figure 4.10 Log (ESE) vs. Distance of 193.375 THz channel for hybrid WDM optical system

Variation of EVM with respect to distance is shown in Figure 4.11 for 193.375 THz channel. EVM varies from 11.33% to 32.94% and 15.68% to 41.29% for system with ULAF fiber and SSMF fiber respectively for 500 km – 2500 km transmission distance. Lower values of EVM from 4.35% to 8.35% are obtained for system with ULAF fiber for 500 km – 2500 km.

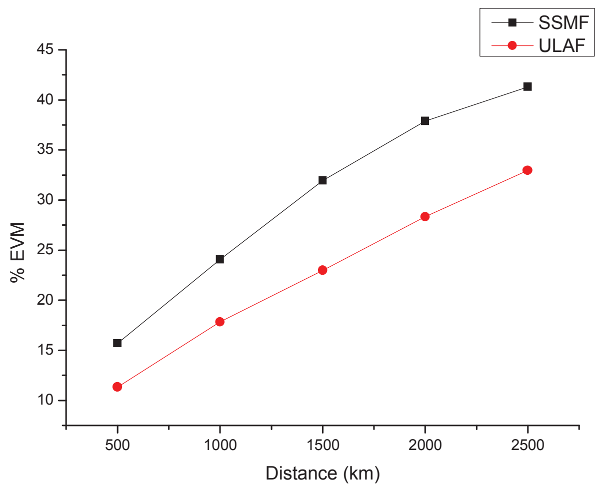


Figure 4.4.11 EVM vs. Distance of 193.375 THz channel for hybrid WDM optical system

Plots of Q factor vs. PDM QPSK channels and PDM 16 QAM channels are shown in Figure 4.12 and Figure 4.13 respectively for WDM optical system with ULAF fiber and SSMF fiber. Figure 4.12 shows the six channels with PDM QPSK modulation for

500 km and 2500 km transmission distance. System with ULAF fiber shows about 2-3 dB higher Q factor. Similarly Figure 4.13 shows the four channels with PDM 16 QAM modulation for 500 km and 2500 km transmission distance. Around 0.5-1.5 dB improvement in Q factor is obtained for system with ULAF fiber.

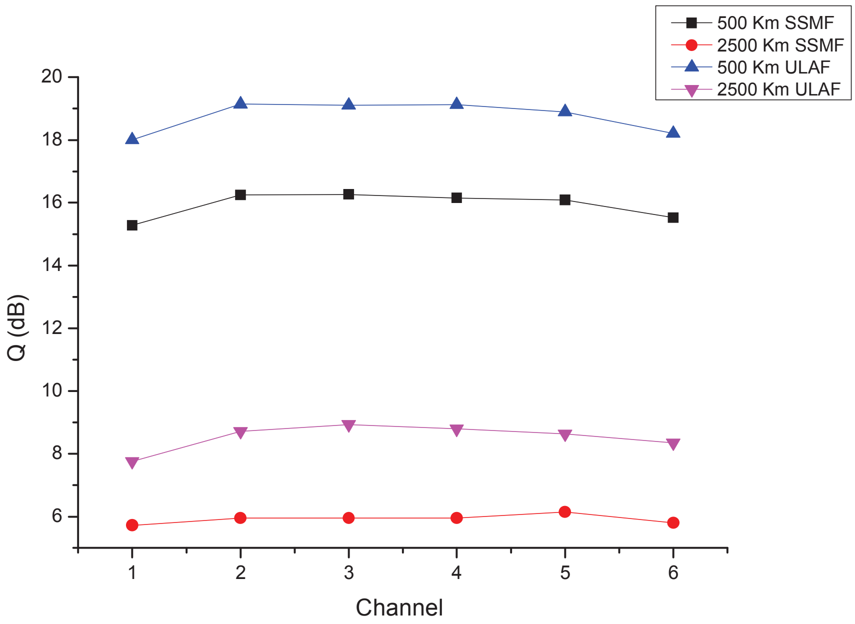


Figure 4.12 Q vs. Channel for PDM QPSK modulation in hybrid modulation WDM optical system

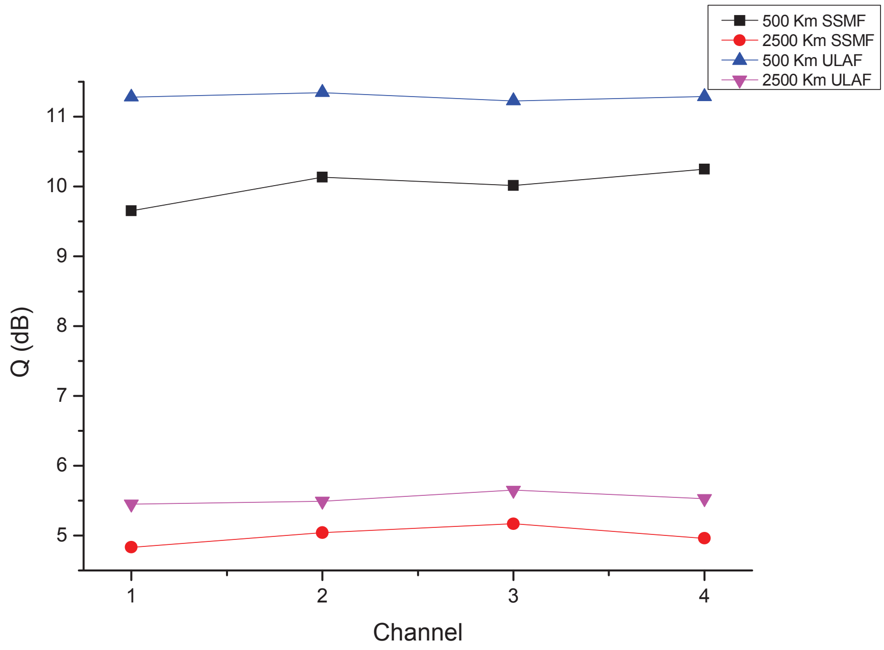


Figure 4.13 Q vs.channel for PDM 16 QAM modulation in hybrid modulation WDM optical system

Table 4.1 Brief comparison between proposed technique and earlier reported work

Dispersion compensation technique	Modulation	Q factor / BER	Transmission Distance
Direct detection with DSP (Erkılınc, M; Zhe, Li et al.;)	16-QAM	8.7 dB	323 km
DCF (Neheeda, P; Pradeep, M; Shaija, P J;)	RZ	11 dB	320 km
FBG (Valts, Dilendorfs; Sandis, Spolitis; Vjaceslavs, Bobrovs;)	NRZ	$< 10^{-12}$	50 km
Pre compensation (Jasvir Singh; Vivekanand, Mishra Smieee; P, N Patel; Pushpa, Gilawat)	PDM-OFDM	12.373 dB	1200 km
Coherent detection with DSP **(Proposed Work)**	Hybrid PDM-QPSK and PDM 16-QAM employing dual carrier	8.93 dB	2500 km

Direct detection with DSP is used for WDM optical system employing 16-QAM modulation format, which reflects the Q factor of 8.7 dB for 323 km transmission distance (Erkılınc, M; Zhe, Li et al.;). However, direct detection system is suitable for data rate below 100 Gb/s at short reach due to the receiver sensitivity. Dispersion compensating fiber is deployed for RZ WDM optical system for transmission reach of 320 km to compensate fiber chromatic dispersion. Transmission power per channel is limited with the use of DCF (Neheeda, P; Pradeep, M; Shaija, P J;). Moreover, it enhances the fiber nonlinear effects due to the small effective area of fiber core, which limits it’s use for long haul WDM optical communication.

Inline fiber Bragg grating technique is utilize for optical system in case of BER < 10^{-12} (Valts, Dilendorfs; Sandis, Spolitis; Vjaceslavs, Bobrovs;). FBG exhibits lower insertion loss with respect to DCF. However, fabrication of complex FBG structure is difficult for WDM system. Pre-dispersion compensation technique using DCF is employed for 1200 km transmission reach (Jasvir Singh; Vivekanand, Mishra Smieee; P, N Patel; Pushpa, Gilawat). However, deployment of DCF is limited for long haul WDM optical communication systems due to the promotion of fiber nonlinear effects. Multilevel modulation formats with polarization division multiplexing approach using coherent detection with DSP at receiver end performs better at high data rate for long haul WDM optical systems. Our proposed technique for WDM optical system employing dual carrier shows enhancement in Q factor at long transmission distance compared to earlier reported work as illustrated in Table 4.1.

4.6 Conclusion

In this chapter design of 4 x 200 Gb/s (800 Gb/s) Dual Carrier PDM 16-QAM WDM optical systems for 1000 km transmission distance is investigated. The performance is evaluated for systems with nonlinearity compensation and without nonlinearity compensation at receiver from 200 km to 1000 km. Q factor is almost 2.43 dB to 1.95 dB higher for system with nonlinearity compensation than system without nonlinearity compensation at 6 dBm power per channel for 200 km to 1000 km transmission reach. EVM values are reduced from 0.78% to 1.33% in system with nonlinearity compensation. Log of Estimated symbol error (ESE) is 41.2% lower in system with nonlinearity compensation at 1000 km. Spectral efficiency of 4 b/s/Hz is achieved by keeping 50 GHz channel spacing at the data rate of 200 Gb/s of each sub-carrier. Dual Carrier PDM 16-QAM WDM optical system with nonlinearity compensation outperforms than the system without nonlinearity compensation.

Another design of 10 x 100 Gbps WDM Optical systems using hybrid modulation employing dual carrier concept for WDM optical system up to 2500 km transmission distance is also investigated in this chapter. Due to higher effective area, nonlinearity influence is low in case of system with ULAF fiber. The performance of WDM optical system is assessed with utilization of ULAF and SSMF fibers. Improvement of Q factor is observed around 2.85 dB to 2.98 dB for 500 km – 2500 km transmission distances using ULAF fiber in system. Lower values of EVM from 4.35% to 8.35% are obtained for system with ULAF fiber for 500 km – 2500 km. estimated symbol error is reduced in case of design with ULAF. WDM optical system with ULAF fiber outperforms in comparison with system with SSMF fiber.

Chapter 5 WDM Coherent PDM-QPSK 2.3 Tb/s (23 ch.x100 Gb/s) Multi-carrier WDM Optical Transmission Systems

5.1 Introduction

The current traffic scenario in optical transport network requires data rate as high as 100 Gb/s and beyond. This has given rise to efficient modulation formats with high symbol rate such as two or more bits per symbol. Phase modulation methods like QPSK and DQPSK are better options to accomplish current and future need of such optical transport network. Multilevel phase modulation set-up with polarization division multiplexed (PDM) schemes are preferred for future WDM systems (Curri; Vittorio, et al). For such high data rate network, fiber nonlinearity and chromatic dispersion presents key challenges for realizing long distance WDM optical communication systems. To enhance the capacity of such multi-channel optical systems, dispersion and nonlinearity management becomes essential. Dispersion compensating fiber (DCF), Digital back propagation (DBP) and pre-equalization techniques are used to minimize dispersion and fiber nonlinearity. Coherent detection contributes to mitigate fiber nonlinearity at the receiver side. The optical communication system with multilevel modulation format for high data rate and long distance communication with coherent detection at the receiver side is widely considered to address the current traffic requirement. The use is made of digital signal processing (DSP) with coherent detection as an emerging technology to mitigate the effects of such impairments (Savory and Seb) (Ip, Ezra and Joseph) (Savory; Seb, J;). Fiber nonlinearities compensation using DSP is presented in (Ip; Ezra; Joseph, M Kahn) (Millar; David, S., et al).

Recently WDM optical system with PDM-QPSK modulation is reported in the literature to carry data rate of the order of Tb/s for 4800 km (Raybon; Gregory, et al.;). Higher Spacing between sub carriers can improve performance by reduction in Q-penalty at the expense of spectral efficiency (Rahman; Talha, et al.). Coherent optical communication systems with PDM-QPSK are used using dispersion managed links for 4000 km transmission reach at 112

Gb/s data rate (Zhang; Fangzheng, et al). WDM optical system with PM-DQPSK signals containing single mode fiber (SMF), DCF and EDFA for 100 Gb/s data rate at the transmission distance of 2700 km is reported in (Chen; Xiaoyong; José, A Martín Pereda; Paloma, R Horche). Dual carrier differential quadrature phase shift keying (DC-DQPSK) / Dual polarization quadrature phase shift keying (DP-QPSK) signal is transmitted upto 1000 km at a data rate of 112 Gb/s with co-propagating 10.7 Gb/s OOK signals in long distance WDM optical systems (Chang; Sun, Hyok, et al.).

The main goal of this work is, to explore design and performance of 23 x 100 Gbps (2.3 Tb/s) WDM Optical systems employing multicarrier generation concept. Each sub carrier transmits at a transmission rate of 100 Gbps using Polarization division multiplexed quadrature phase shift keying (PDM-QPSK) modulation format with spacing of 25 GHz between sub carriers. The analysis is carried out for 23 x 100 Gb/s (2.3 Tb/s) PDM-QPSK WDM optical systems with ultra large area fiber (ULAF), standard single mode fiber (SSMF) and large effective area fiber (LEAF) at transmission reach from 600 km to 5000 km. Coherent detection with DSP is used for all the systems at receiving end. Systems are verified with parameters like symbol error rate, error vector magnitude (EVM) and Q-factor using analytical and simulation results. Improvement of 1.66 dB to 3.21 dB and 2.08 dB to 4.63 dB is noted in Q-factor for system with ULAF in comparison with system using SSMF and LEAF respectively over 600 km to 5000 km transmission reach. EVM values are found 2.24% to 2.68% and 2.68% to 12.43% lower in system with ULAF than system with SSMF and LEAF respectively. Log of Estimated symbol error (ESE) is observed less for system with ULAF than systems with SSMF and LEAF fibers, respectively, at transmission distance of 5000 km. The results clearly show that WDM optical system with ULAF fiber gives better performance.

5.2 System Design

5.2.1 Transmitter section

Transmitter section of multichannel WDM optical communication system is shown in Figure 5.1. This set up is developed for 23 x 100 Gbps (2.3Tb/s) WDM system. Three CW lasers are used with optical carriers centered at 193.1 THz, 193.3 THz and 193.5 THz respectively. Optical frequency multicarrier is generated by phase modulation of CW lasers. 25 GHz frequency sinusoidal signal is phase shifted and applied to drive one intensity MZM modulator and two phase modulators, due to which multi-carrier of 23 frequency channels is obtained.

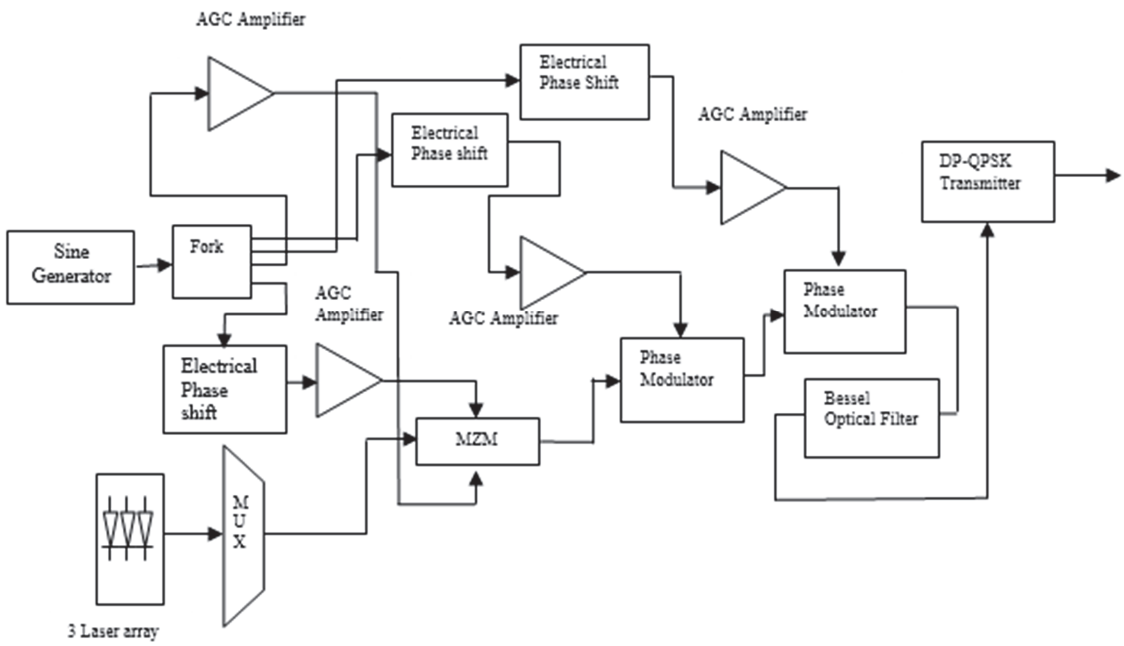


Figure 5.1 Transmitter section

Intensity modulator is used with two phase modulators in cascading manner to generate multi-carrier as shown in Figure 5.1 and can be expressed as (Dou; Yujie; Hongming, Zhang; Minyu, Yao).

$$E_{out} = E_{int}\, exp[i\, (\pi Vp_1/V\pi_1)\, cos(w_m t + \Delta\phi_2) + i\, (\pi Vp_2/V\pi_2)\, cos(w_m t + \Delta\phi_3)] \qquad (5.1)$$

Here E_{int} is output of the intensity modulator. Sinusoidal waveform amplitudes Vp_1 and Vp_2 are applied on first phase modulator and second phase modulator respectively. Half-wave voltages are denoted as $V\pi_1$ and $V\pi_2$. Phase shifts $\Delta\phi_2$ and $\Delta\phi_3$ of sinusoidal waveform are applied on phase modulator1 and phase modulator 2, respectively.

$$E_{out} = E_{int}\ exp[i\ \Delta\theta_1\ cos(w_m t + \Delta\phi_2) + i\ \Delta\theta_2\ cos(w_m t + \Delta\phi_3)] \tag{5.2}$$

Where, $\Delta\theta_1 = \pi Vp_1/V\pi_1$ and $\Delta\theta_2 = \pi Vp_2/V\pi_2$, are representing phase modulation indices.
The output of intensity modulator, Eint is represented as:

$$E_{int} = E_{in}\ exp(i\ (wc_1+wc_2+wc_3)t)\ sin^2[1/2(\Gamma_B\pi + \Gamma_m\pi\ cos(w_m t + \Delta\phi_1))] \tag{5.3}$$

Here E_{int} is output of the intensity modulator. Sinusoidal waveform amplitudes Vp_1 and Vp_2 are applied on first phase modulator and second phase modulator respectively. Half-wave voltages are denoted as $V\pi_1$ and $V\pi_2$. Phase shifts $\Delta\phi_2$ and $\Delta\phi_3$ of sinusoidal waveform are applied on phase modulator 1 and phase modulator 2, respectively. Here, E_{in} is input optical amplitude and wc_1, wc_2 and wc_3 are angular frequencies of three lasers at transmitter. $\Gamma_m = V_A/V_\pi$ represents normalized amplitude and $\Gamma_B = V_{DC}/V_\pi$ denotes normalized DC bias, where VA signifies sinusoidal waveform amplitude , VDC denotes applied DC bias to intensity modulator and half-wave voltage is represented by $V\pi$ of intensity modulator . Besides Γ_m and Γ_B the flatness of multi-carriers depends upon phase shifts of sinusoidal waveform applied on intensity modulator and two phase modulators.

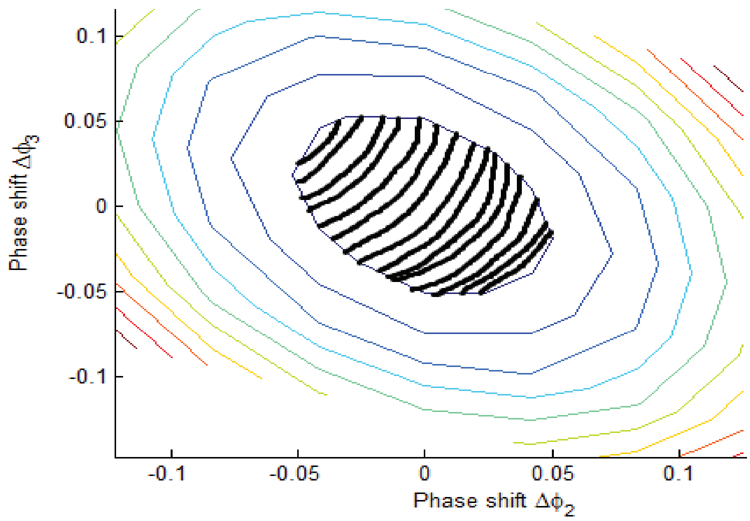
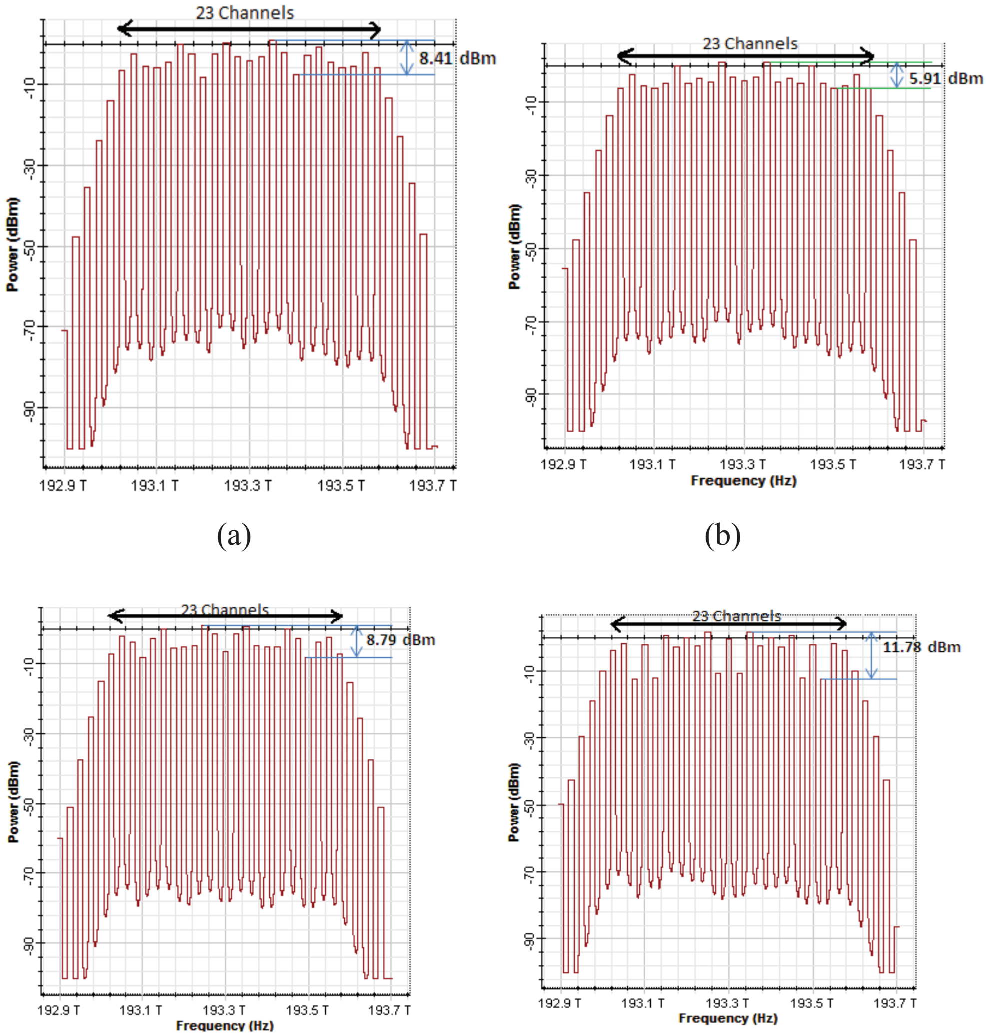


Figure 5.2 Contour plot as a function of parameters $\Delta\phi2$ and $\Delta\phi3$ for $\Delta\phi1 = \pi$, $\Gamma m = 0.5\ \pi$, $\Gamma B = 0.35\ \pi$ and $\Delta\theta1 = 8$, $\Delta\theta2 = 8$

IQ modulator is created with two MZMs for single polarization, thus two pairs of IQ modulators are formed with four MZMs for PDM-QPSK. $\pi/2$ phase shift is applied between I (In-phase) and Q (Quadrature) components. I and Q components for X and Y polarizations are generated through two pairs of IQ modulators.



(a) (b)

(c) (d)

Figure 5.3 Spectrum of Multi-carriers for (a) $\Delta\phi1 = \pi$, $\Delta\phi2=0.05\pi$, $\Delta\phi3=0.1\pi$; (b) $\Delta\phi1 = \pi$, $\Delta\phi2=0$, $\Delta\phi3=0$; (c) $\Delta\phi1 = \pi$, $\Delta\phi2=-0.15\pi$, $\Delta\phi3= 0.1\pi$; (d) $\Delta\phi1 =0$, $\Delta\phi2=0$, $\Delta\phi3= 0$

Figure 5.2 shows the contour plot as a function of parameters $\Delta\phi_2$ and $\Delta\phi_3$ with Γ_m and Γ_B set to 0.5 π and 0.35 π respectively. The values of $\Delta\theta_1$ and $\Delta\theta_2$ are set equal to 8.The multi-carriers for different values of phase shifters are shown in Figure 5.3. Maximum flatness with variation of 5.91 dBm is obtained for the values of $\Delta\phi_1 = \pi$, $\Delta\phi_2=0$, $\Delta\phi_3=0$ as shown in Figure 5.3 (b), which is also indicated in contour plot by shaded area. Frequency separation between each optical sub-carrier is 25 GHz. Multi-carrier signal is passed through Bessel optical filter with centre frequency of 193.1 THz and bandwidth of 500 GHz to reduce out of band noise. Spectrum of optical multi-carrier is shown in Figure 5.3 (b). Finally, multi-carrier signal is applied to PDM-QPSK modulator. Four $LiNbO_3$ (Lithium Niobate) MZMs are utilized in PDM-QPSK modulator. Multi-carrier optical signal drives MZMs modulator. The PRBS generator generates 2^{15}-1 data sequence length.

5.2.2 Optical Fiber Link

Optical signal containing twenty three sub-carriers is propagating through single mode fiber as shown in Figure 5.4. Optical signal is transmitted through four fibers of 50km each with total fiber span of 200 km with effective area of 120 μm^2 for ULAF, 80 μm^2 for SSMF and 72 μm^2 for LEAF fibers.

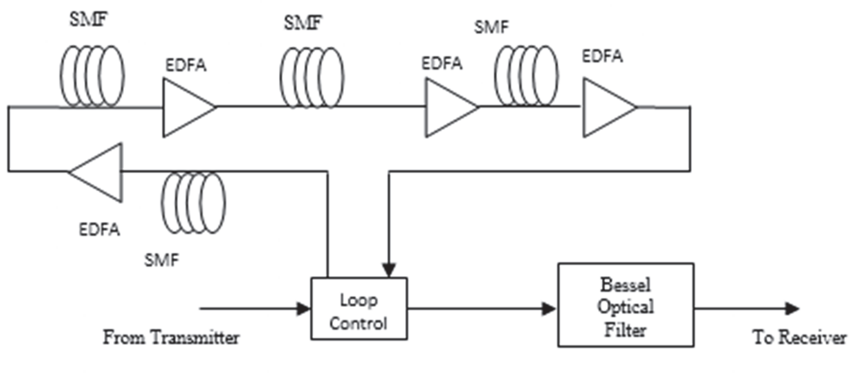


Figure 5.4 Fiber Span

Optical signal loss in single mode fiber is compensated with Erbium doped fiber amplifiers (EDFAs) followed by 50 km length of fiber as shown in Figure 5. 4. Recirculating loop is included in design to multiply 200 km fiber span length as per the requirement to establish long distance optical length communication. Bessel optical filter is placed after recirculating loop to remove out of band noise similar to that used at transmission end.

5.2.3 Receiver Section

Rectangular band pass filter with bandwidth of 40 GHz is placed at receiver side to recover individual subcarrier. PDM-QPSK single channel receiver with DSP is same as Figure 3.5 of chapter 3. Coherent detection recovers signal phase information, which is distorted due to impairments in fiber (Zhang; Fangzheng, et al). Coherent PDM-QPSK receiver contains four output optical signals. I and Q components of each polarization contain full information of transmitted signals. Signal is further processed using DSP. The Digital back propagation (DBP) is used to compensate dispersion and nonlinearity in electric domain in system.

5.3 Theoretical Background

Nonlinear distortions induced by propagation of signal over link without optical dispersion management with PDM-QPSK format are assumed as Gaussian distribution (Vacondio; Francesco, et al.). Each optical amplifier adds amplified spontaneous emission (ASE) noise field which is assumed as zero-mean circular complex Gaussian noise process. In non-dispersion managed system, Gaussian nature of total received ASE field conserves after non-linear propagation (Grellier; Edouard; Alberto, Bononi). We have considered PDM-QPSK modulation with coherent detection for multichannel propagation. OSNR is calculated using equation (1) (Forysiak; Wladek, et al).

$$OSNR = P_{TX} / (P_{ASE} + P_{NLI}) \tag{5.4}$$

Here, P_{TX}, P_{ASE} and P_{NLI} denote the launch power per WDM channel, noise power due to amplified spontaneous emission and noise power due to nonlinear interference respectively. Noise power due to amplified spontaneous emission is expressed as:

$$P_{ASE} = N_S N_F (G-1) h\upsilon B_N \tag{5.5}$$

In equation (5.5) N_S and B_N signify number of fiber spans (each of length L) and noise bandwidth, respectively, NF and G are noise figure and amplifier gain, respectively. The nonlinear interference power is approximated as:

$$P_{NLI} = N_S\, a_{NLI}\, \gamma^2 P_{TX}^3 \tag{5.6}$$

Where a_{NLI} is nonlinear interference parameter and defined as :

$$a_{NLI} = (2/3)^3\, L_{eff}\, [\log (\pi^2\, |\beta_2| L_{eff}\, N_{ch}^2\, R^2)/(\pi|\beta_2|\, R^3)]\, B_N \tag{5.7}$$

In equation (5.7) L_{eff} is effective length of fiber span and defined as:

$$L_{eff} = [(1-e^{-\alpha L})/\alpha] \tag{5.8}$$

Here, L and α represents fiber length per span and fiber attenuation per km respectively. β_2 is the fiber group velocity dispersion coefficient in equation (5.8) and defined as:

$$\beta_2 = -D\lambda^2/2\pi C \tag{5.9}$$

Where D is dispersion coefficient, γ is nonlinearity coefficient in (1/W.km) and represented as:

$$\gamma = 2\pi n_2/\lambda A_{eff} \tag{5.10}$$

By putting the values of Leff and β_2 into the equation (7) and rearranging as:

$$\alpha_{NLI} = (8/27)\ (1-e^{-\alpha L}/\alpha)[(\log(\pi D\lambda^2/2C)(1-e^{-\alpha L}/\alpha)N_{ch}^2 R^2)B_N]\ /\ (D\lambda^2 R^3/2C) \tag{5.11}$$

Here, R is the symbol rate and N_{ch} is the number of channels.

SNR can be calculated from OSNR as:

$$SNR = OSNR\ (B_N/R) \tag{5.12}$$

Finally, BER is obtained from SNR (Carena; Andrea, et al.) :

$$BER = 0.5 erfc\ (\sqrt{(SNR/2)}) \tag{5.13}$$

Quality parameter depends on BER as:

$$Q_{dB} = 20\log_{10} (\sqrt{2}\ erfc^{-1}(2BER)) \tag{5.14}$$

5.4 Results and Discussion

Performance investigation of the proposed WDM optical systems using ULAF, SSMF and LEAF fibers were carried out using theoretical analysis and extensive simulations. The system with ULAF fiber consisting of re-circulating loop having span length of 200 km with chromatic dispersion of 19.9 ps/nm/km, effective area of 120 μm^2, attenuation of 0.185 dB/km, and nonlinearity coefficient γ of 0.878 W^{-1} m^{-1} are considered as simulation parameters at 1550 nm of wavelength. Similarly, system with SSMF has chromatic dispersion of 16.5 ps/nm/km, attenuation of 0.2 dB/km, effective area of 80 μm^2 and nonlinearity coefficient γ of 1.31 W^{-1} m^{-1} and LEAF has chromatic dispersion of 4 ps/nm/km, attenuation of 0.22 dB/km, effective area of 72 μm^2 and nonlinearity coefficient γ of 1.46 W^{-1} m^{-1}. These parameters are used for theoretical analysis and simulation for WDM systems using ULAF, SSMF and LEAF. The theoretical results obtained from section 3 and simulation results obtained from section 2 are plotted and discussed in this section.

5.4.1 Investigation of Q, Log (ESE) and EVM for different transmission distances

Investigation of the variation of Q factor, Log (ESE) and EVM with different transmission lengths at 8 dBm launch power is carried out in this section. Results from theoretical computations and simulation of Q factor for WDM systems using ULAF, SSMF and LEAF are plotted in Figure 5.5. Theoretical results are calculated using equation (5.14) of section 5.3. Q factor is found to vary between 21.38 to 12.18 dB, 17.44 to 8.23 dB and 16.41 to 7.20 dB for transmission reach of 600 km to 5000 km in systems using ULAF, SSMF and LEAF fibers respectively. Simulation result shows the variation of 19.87 dB to 10.43 dB, 18.22 dB to 7.22 dB and 17.81 dB to 5.80 dB in Q factor for systems for the same fibers respectively from 600 km to 5000 km transmission reach. Q factor improvement of 3.95 dB and 4.98 dB is observed from theoretical analysis for system with ULAF in comparison with system using SSMF and LEAF at transmission reach of 5000 km. Simulation results also presents improvement of 3.21

dB and 4.63 dB in Q factor for system using ULAF than systems using SSMF and ULAF at 5000 km. Theoretical and simulation results show almost similar improvement in Q factor for system using ULAF than other two systems at 5000 km transmission reach.

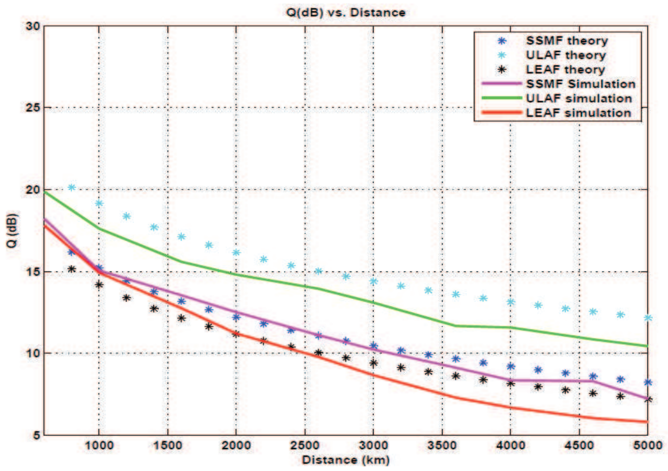


Figure 5.5 Q factor vs. Transmission Distance for WDM optical systems with ULAF,SSMF and LEAF fibers

Log (ESE) is calculated theoretically from BER mentioned in equation (5.13) of section 5.3 and both the results from theoretical computation and simulations are plotted in Figure 5.6. Theoretical analysis shows that Log (ESE) varies from -30.7705 to -4.0173, -12.7344 to -1.7059 and -10.1293 to -1.3579 in systems using ULAF, SSMF and LEAF fibers respectively for 600 km to 5000 km transmission reach. Similarly, variation in Log (ESE) from -22.22 to -3.06, -15.44048 to -1.66479 and -14.10434 to -1.29324 is obtained with simulation results for systems using ULAF, SSMF and LEAF fibers respectively for 600 km to 5000 km transmission reach. Results show lower values of Log (ESE) for system using ULAF than other two systems at long transmission reach. Theoretical and simulation results clearly indicate better performance for system using ULAF than systems using SSMF and LEAF for transmission reach up to 5000 km.

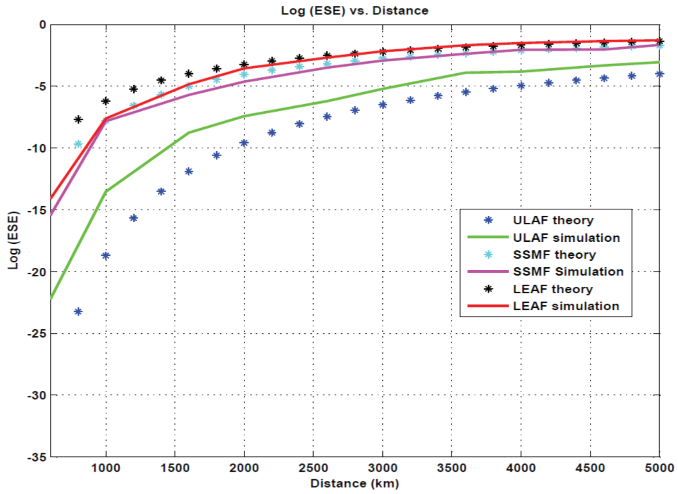


Figure 5.6 Log (ESE) vs. Transmission Distance for WDM optical systems with ULAF, SSMF and LEAF fibers

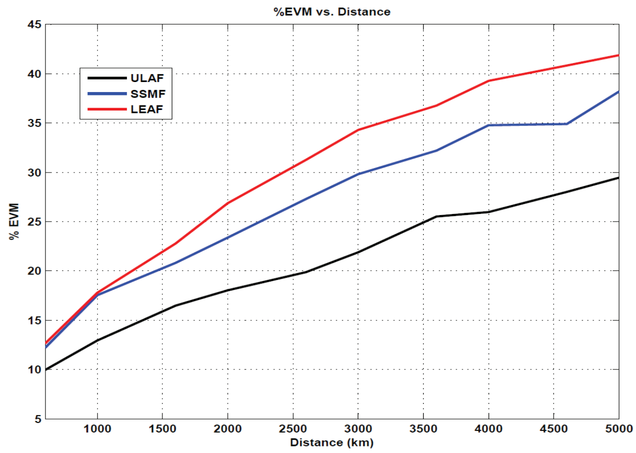


Figure 5.7 EVM vs. Transmission Distance for WDM optical systems with ULAF, SSMF and LEAF fibers

It is evident from the Figure 5.7 that as we change the transmission distance in the range of 600 km to 5000 km, correspondingly the values of EVM varies in the range of 9.96 % - 29.44% for ULAF, 12.20% - 38.18% for SSMF and 12.64% - 41.87% for LEAF. It clearly indicates that the values of EVM for ULAF system are 2.24% to 8.74% and 2.68% to 12.43% lower in comparison with systems with SSMF and LEAF respectively, over 600 km – 5000 km.

5.4.2 Analysis of Q for various channels at fixed transmission distances

Further we have investigated the variation of Q factor of different transmission channels for systems with ULAF, SSMF and LEAF fiber over transmission distances of 600 km and 5000 km as shown in Figure 5.8. Channels 1,2,5,12,16 and 23 indicate carrier frequencies of 193.025 THz, 193.05 THz, 193.125 THz, 193.3 THz, 193.4 THz and 193.575 THz respectively. Fig. 9 shows that as we change the transmission distance between 600 km to 5000 km, correspondingly higher values of Q-factors around 2-3 dB in comparison with SSMF and around 3.5 dB in comparison for LEAF fibers obtained. Q factor varies from channel to channel due to non-uniform gain of EDFA amplifier used in fiber loop.

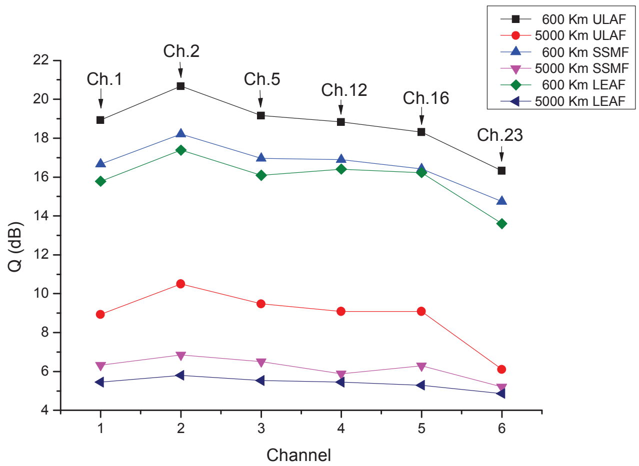


Figure 5.8 Q factor vs. channel for WDM optical systems with ULAF, SSMF and LEAF fibers

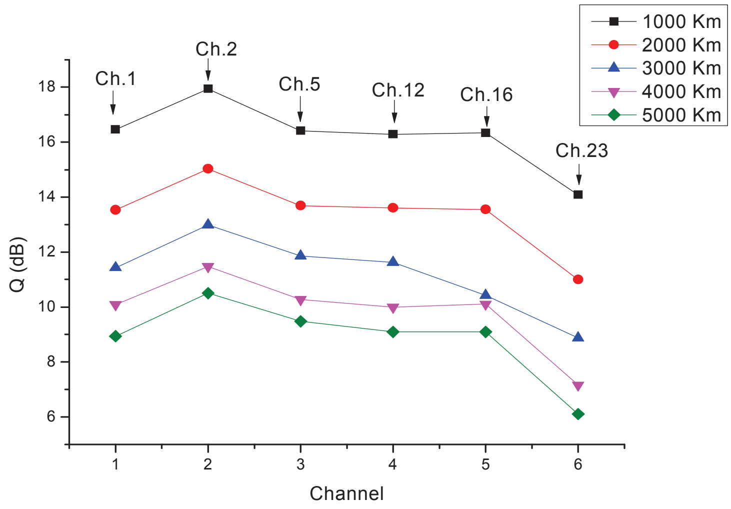


Figure 5.9 Q factor vs. channel for WDM optical system with ULAF fiber

Figure 5.9 shows the variation of Q factor with transmission distance in the range of 1000 km to 5000 km for system with ULAF fiber. For long transmission distances performance of system is degraded due to fiber nonlinear effects and dispersion. Q factor varies 17.94 dB to 10.49 dB from 1000 km to 5000 km for channel no. 2.

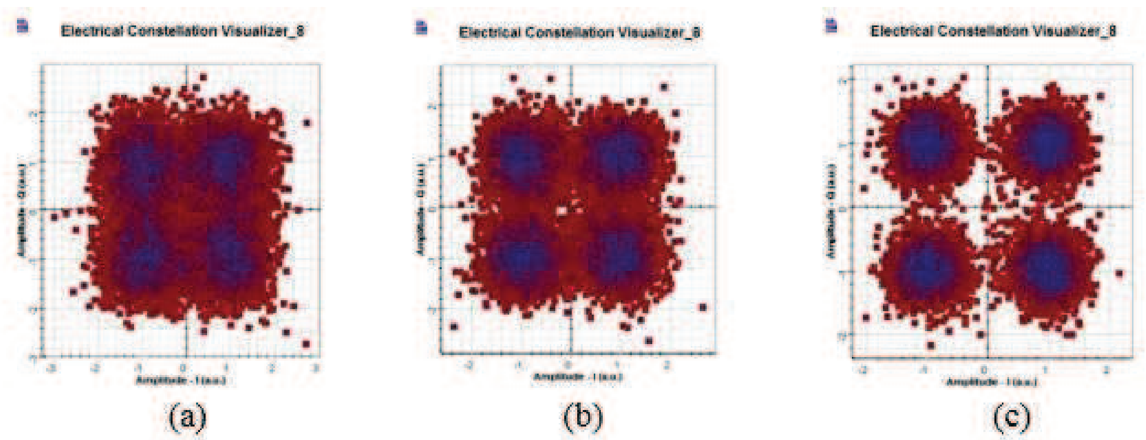


Figure 5.10 Constellation diagram of channel 2 (193.050 THz) at 5000 km for (a) LEAF; (b) SSMF ; (c) ULAF

Figure 5.10 shows the constellation of all the three systems for transmission distance of 5000 km. The deviation of bits from exact centre position of ([1,1],[1,-1],[-1,-1],[-1,1]) is more in systems with LEAF and SSMF than ULAF. System with ULAF performs comparatively better than other two systems at long haul communication of 5000 km transmission.

5.5 3.9 Tb/s (39 ch.x100 Gb/s) Hybrid Transmission Multi-carrier WDM Optical System

5.5.1 Introduction

The current traffic scenario in optical transport network requires data rate as high as 100 Gb/s and beyond. This has given rise to efficient modulation formats with high symbol rate such as two or more bits per symbol. Phase modulation methods like QPSK and DQPSK are better options to accomplish current and future need of such optical transport network. Multilevel phase modulation set-up with polarization division multiplexed (PDM) schemes are preferred for future WDM systems (Curri; Vittorio, et al.).For such high data rate networks, fiber nonlinearity and chromatic dispersion presents key challenges for realizing long distance WDM optical communication systems. To enhance the capacity of such multi-channel optical systems, dispersion and nonlinearity management becomes essential. Dispersion compensating fiber (DCF), Digital back propagation (DBP) and pre-equalization techniques are used to minimize dispersion and fiber nonlinearity. Coherent detection contributes to mitigate fiber nonlinearity at the receiver side. The optical communication system with multilevel modulation format for high data rate and long distance communication with coherent detection at the receiver side is widely considered to address the current traffic requirement. The use is made of digital signal processing (DSP) with coherent detection as an emerging technology to mitigate the effects of such impairments (Savory and Seb) (Ip, Ezra and Joseph) (Savory; Seb, J;). Fiber nonlinearities compensation using DSP is presented in (Ip; Ezra; Joseph, M Kahn) (Millar; David, S., et al).

The commercial system available today supports 100-Gb/s polarization-division multiplexed quadrature-phase-shift keying (PDM-QPSK) on a 50-GHz wavelength-division-multiplexing (WDM) grid and at a spectral efficiency (SE) of 2 b/s/Hz. Higher SE of 3 b/s/Hz is demonstrated on a commercial all-Raman optical transport platform (Fishman, Daniel and William) (Raybon; Gregory, et al.) (C, Xie; G, Raybon; S, Chandrasekhar) using a widely deployed optical fiber type and dispersion map. Higher Spacing between sub-carriers can improve performance by reduction in Q-penalty at the expense of spectral efficiency (Rahman; Talha, et al.). Channels of different modulation formats may co-exist due to up gradation of optical networks at higher bit rates (Chongjin, Xie; Gregory, Raybon). Therefore it is important to investigate the transmission performance of optical systems where PDM QPSK co-propagates with PDM 16-QAM modulation format.

The main goal of this work is, to explore co-existence of multilevel phase and amplitude modulation formats to enable a new generation of high speed optical transport platform. 39 x 100 Gbps (3.9 Tb/s) hybrid transmission WDM optical system is employing multicarrier generation concept. 20 sub-carriers utilize polarization division multiplexed quadrature phase shift keying (PDM-QPSK) modulation format and 19 sub-carriers use polarization division multiplexed 16-ary quadrature amplitude modulation (PDM 16-QAM) out of 39 sub-carriers. Each sub-carrier transmits at a transmission rate of 100 Gbps with frequency spacing of 25 GHz between sub-carriers to achieve spectral efficiency of 4 b/s/Hz. The analysis is carried out for 39 x 100 Gb/s (3.9 Tb/s) hybrid WDM optical system with ultra large area fiber (ULAF) and large effective area fiber (LEAF) at transmission reach from 600 km to 4000 km. Systems are verified with parameters like Q-factor, estimated symbol error and error vector magnitude (EVM). Analytical and simulation results are presented. Results show that hybrid WDM optical system with ULAF fiber outperforms than LEAF fiber at long transmission reach.

5.5.2 System design

Multi-channel hybrid WDM optical system set up is shown in Figure 5.11. This set up is developed for 39 x 100 Gbps (3.9 Tb/s) WDM system. Five CW lasers are used with optical carriers centered at 193.1 THz, 193.3 THz , 193.5 THz, 193.7 THz and 193.9 THz respectively. Optical frequency multi-carrier is generated by phase modulation of

CW lasers. 25 GHz frequency sinusoidal signal is phase shifted and applied to drive one intensity MZM modulator and two phase modulators, due to which multi-carrier spectrum of 39 frequency channels is obtained. Multicarrier generator contains one intensity modulator and two phase modulators. Intensity modulator is used with two phase modulators in cascading manner to generate multi-carriers and can be expressed as (Dou; Yujie; Hongming, Zhang; Minyu, Yao) .

$$E_{out} = E_{int} \exp[i\,(\pi Vp_1/V\pi_1)\cos(w_m t + \Delta\phi_2) + \; i\,(\pi Vp_2/V\pi_2)\cos(w_m t + \Delta\phi_3)] \tag{5.15}$$

Here E_{int} is output of the intensity modulator. Sinusoidal waveform amplitudes Vp_1 and Vp_2 are applied on first phase modulator and second phase modulator respectively. Half-wave voltages are denoted as $V\pi_1$ and $V\pi_2$. Phase shifts $\Delta\phi_2$ and $\Delta\phi_3$ of sinusoidal waveform are applied on phase modulator 1 and phase modulator 2, respectively.

$$E_{out} = E_{int} \exp[i\,\Delta\theta_1 \cos(w_m t + \Delta\phi_2) + i\,\Delta\theta_2 \cos(w_m t + \Delta\phi_3)] \tag{5.16}$$

Where, $\Delta\theta_1 = \pi Vp_1/V\pi_1$ and $\Delta\theta_2 = \pi Vp_2/V\pi_2$, are representing phase modulation indices.

The output of intensity modulator, E_{int} is represented as:

$$E_{int} = E_{in} \exp(i\,(wc_1 + wc_2 + wc_3 + wc_4 + wc_5)t)\,\sin^2[1/2(\Gamma_B\pi + \Gamma_m\pi\cos(w_m t + \Delta\phi_1))] \tag{5.17}$$

Here, E_{in} is input optical amplitude and wc_1, wc_2, wc_3, wc_4 and wc_5 are angular frequencies of five lasers at transmitter. $\Gamma_m = V_A/V_\pi$ represents normalized amplitude and $\Gamma_B = V_{DC}/\,V_\pi$ denotes normalized DC bias, where V_A signifies sinusoidal waveform amplitude , V_{DC} denotes applied DC bias to intensity modulator and half-wave voltage is represented by V_π of intensity modulator . Besides Γ_m and Γ_B , the flatness of multi-carriers depend upon phase shifts of sinusoidal waveform applied on intensity modulator and two phase modulators. Optical spectrum outputs of WDM multiplexer and Multi-carrier generator are shown in Figure 5.12(a) and Figure 5.12(b) respectively.

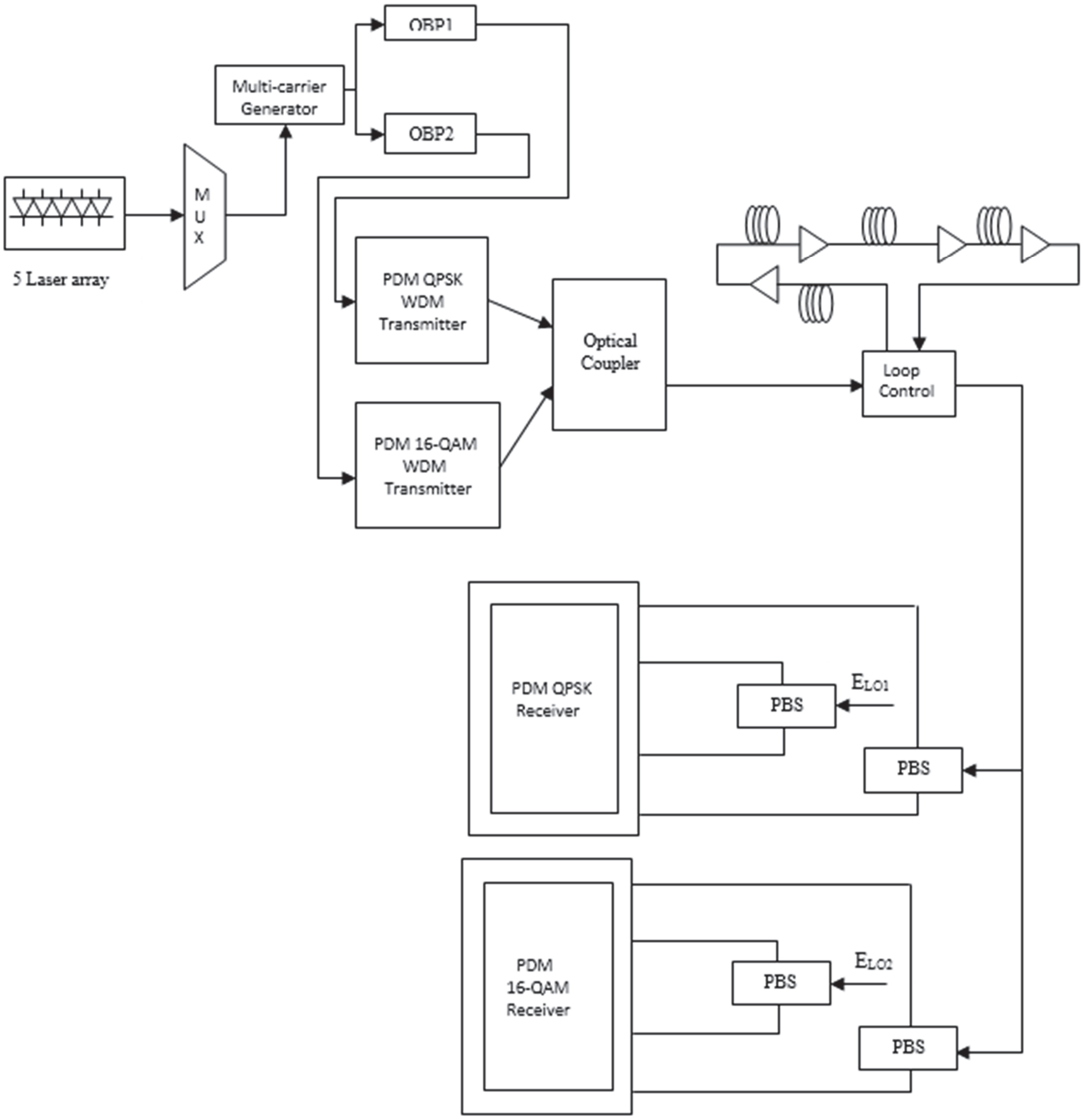
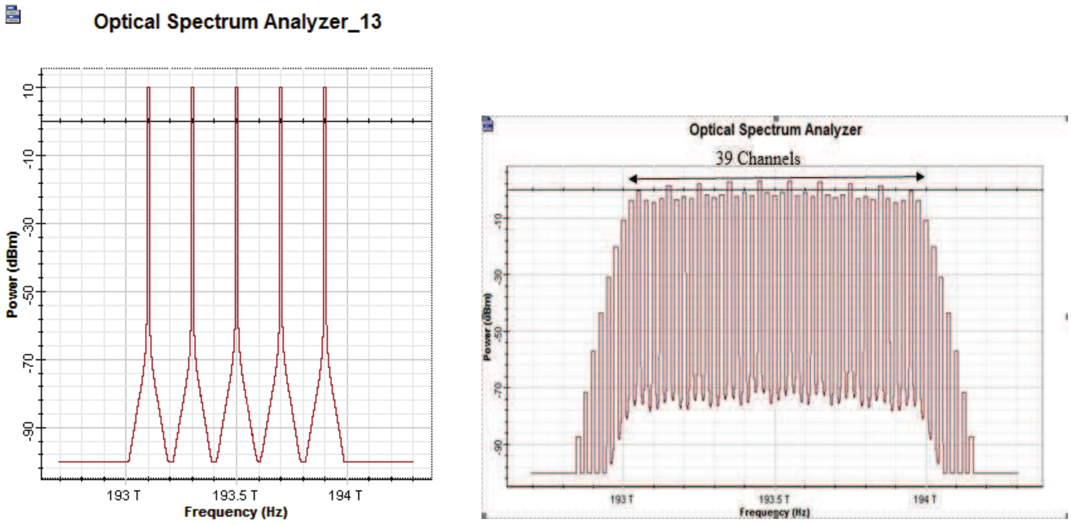


Figure 5.11 System Setup



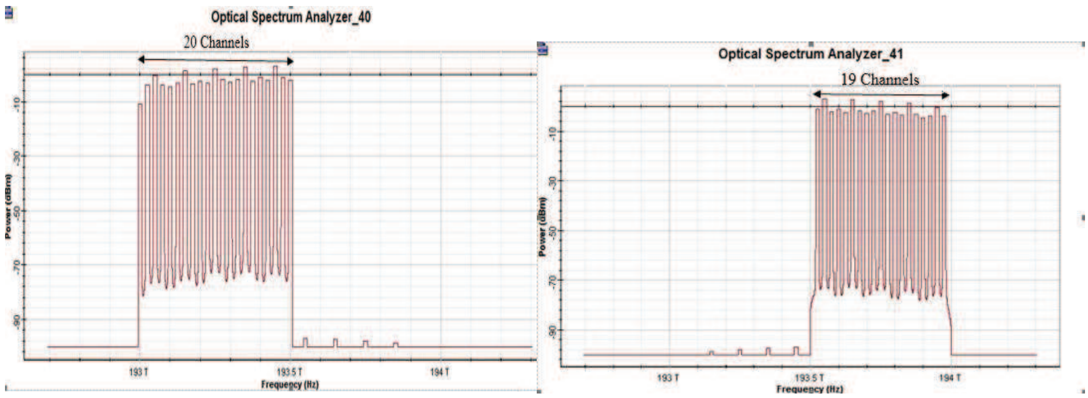
(a) (b)

Figure 5.12 Spectrum after (a) WDM Multiplexer and (b) Multi-carrier generator with parameters $\Delta\phi1 = \pi$, $\Delta\phi2=0$, $\Delta\phi3=0$

Frequency separation between each optical sub-carrier is 25 GHz. Multi-carrier signal is passed through optical band pass filter 1 (OBP1) and optical band pass filter 2 (OBP2). OBP1 is centered with 193.25 THz and bandwidth of 500 GHz to separate 20 channels for PDM QPSK transmission as shown in Figure 5.13(a). OBP2 is centered at 193.75 THz with 490 THz bandwidth to separate 19 channels for PDM 16-QAM transmission as shown in Figure 5.13(b). 20 PDM QPSK and 19 PDM 16- QAM channels are coupled together for transmission through common optical fiber loop. 2^{15}-1 data sequence length is generated with PRBS generator in transmitter.

Table 5.1 Fiber Parameters

Parameter	ULAF Fiber	LEAF Fiber
Span Length	200 km	200 km
Attenuation	0.185 dB/km	0.22 dB/km
Dispersion	19.9 ps/nm/km	4 ps/nm/km
A_{eff}	120 μm^2	72 μm^2
Nonlinearity coefficient γ	0.878 $W^{-1}km^{-1}$	1.46 $W^{-1}km^{-1}$



(a) (b)

Figure 5.13 Spectrum after (a) OBP1 and (b) OBP2

Optical signal containing thirty nine sub-carriers is propagating through single mode fiber as shown in Figure 5.12. Optical signal is transmitted through four fibers of 50 km each with total fiber span of 200 km. Parameters of fibers are illustrated in Table 5.1. Erbium doped fiber amplifier (EDFA) with gain of 10 dB and noise figure of 4 dB, compensates the optical signal loss in single mode fiber. Recirculating loop is included in design to multiply 200 km fiber span length as per the requirement to establish long distance optical length communication. Bessel optical filter is placed after recirculating loop to remove out of band noise similar to that used at transmission end. Rectangular band pass filter with bandwidth of 40 GHz is placed at receiver side to recover individual sub-carrier for PDM-QPSK and PDM 16-QAM receiver. Coherent detection recovers signal phase information, which is distorted due to impairments in fiber (Zhang; Fangzheng, et al). Coherent PDM-QPSK and PDM 16-QAM receivers contain four output optical signals. I and Q components of each polarization contain full information of transmitted signals. Signal is further processed using DSP in receiver. The Digital back propagation (DBP) is used to compensate dispersion and nonlinearity in electric domain in system.

5.5.3 Theoretical background

Nonlinear distortions induced by propagation of signal over link without optical dispersion management with PDM-QPSK and PDM 16-QAM formats are assumed as

Gaussian distribution (Vacondio; Francesco, et al.). Each optical amplifier adds amplified spontaneous emission (ASE) noise field which is assumed as zero-mean circular complex Gaussian noise process. In non- dispersion managed system, Gaussian nature of total received ASE field conserves after non-linear propagation (Edouard, Grellier; Alberto, Bononi). We have considered PDM-QPSK and PDM 16-QAM modulation with coherent detection for multichannel propagation. OSNR is calculated using equation (5.18) (Forysiak, W; D, S Govan; I, McClean; B, K Nayar; O, A Olubodun; N, J Doran).

$$OSNR = P_{TX} / (P_{ASE} + P_{NLI}) \tag{5.18}$$

Here, P_{TX}, P_{ASE} and P_{NLI} denote the launch power per WDM channel, noise power due to amplified spontaneous emission and noise power due to nonlinear interference respectively. Noise power due to amplified spontaneous emission is expressed as:

$$P_{ASE} = N_S N_F (G-1) h\upsilon B_N \tag{5.19}$$

In equation (5.19) N_S and B_N signify number of fiber spans (each of length L) and noise bandwidth, respectively, N_F and G are noise figure and amplifier gain, respectively. The nonlinear interference power is approximated as:

$$P_{NLI} = N_S\, a_{NLI}\, \gamma^2 P_{TX}^3 \tag{5.20}$$

γ is nonlinearity coefficient in (1/W.km) and represented as :

$$\gamma = 2\pi n_2/\lambda A_{eff} \tag{5.21}$$

Where a_{NLI} is nonlinear interference parameter and defined as :

$$a_{NLI} = (2/3)^3\, L_{eff}\, [\log (\pi^2\, |\beta_2| L_{eff}\, N_{ch}^2 R^2)/ (\pi|\beta_2|\, R^3)]\, B_N \tag{5.22}$$

Equation (5.22) and rearranging as :

$$\alpha_{NLI} = (8/27)\, (1\text{-}e^{-\alpha L}/\alpha)[(\log(\pi D\lambda^2/2C)(1\text{-}e^{\alpha L}/\alpha)N_{ch}^2R^2)B_N] \,/\, (D\lambda^2R^3/2C) \tag{5.23}$$

Here, R is the symbol rate and N_{ch} is the number of channels. SNR can be calculated from OSNR as:

$$SNR = OSNR\ (B_N/R) \tag{5.24}$$

Finally, BER is obtained from SNR for PDM QPSK channel and PDM 16-QAM (Carena; Andrea, et al.).

$$BER_{\textbf{PDM QPSK}} = 0.5\text{erfc}\ (\sqrt{(SNR/2)}) \tag{5.25}$$

$$BER_{\textbf{PDM 16-QAM}} = (3/8)\text{erfc}\ (\sqrt{(SNR/10)}) \tag{5.26}$$

Quality parameter depends on BER as:

$$Q_{dB} = 20\log_{10}\ (\sqrt{2}\ erfc^{-1}(2BER)) \tag{5.27}$$

5.5.4 Results and discussion

Performance investigation of the proposed WDM hybrid optical systems using ULAF and LEAF fibers were carried out using theoretical analysis and extensive simulations.

5.5.4.1 Investigation of Q, Log (ESE) and EVM for different transmission distances

Investigation of the variation of Q factor, Log (ESE) and EVM with different transmission lengths at 10 dBm launch power is carried out in this section. Results from theoretical computation and simulation of Q factor for hybrid WDM systems with PDM QPSK modulation and with PDM 16-QAM using ULAF and LEAF are plotted in Figure 5.14 and Figure 5.15, respectively. Theoretical results are calculated using equations (5.25),(5.26) and (5.27) of section 5.5.3. Q factor for PDM QPSK channel is found to vary between 21.38 to 13.15 dB and 16.41 to 8.17 dB using theoretical analysis for transmission reach of 600 km to 4000 km in systems using ULAF and LEAF fibers respectively. Simulation results show the variation of 21.82 to 14.39 and 14.89 to 7.34 in Q factor for systems for the same fibers respectively from 600 km to 4000 km transmission reach. Variations of 0.44 to 1.24 dB and 1.52 to 0.83 dB in Q are found in between theoretical and simulation results. Q factor improvement of 6.93 dB and 7.05 dB is observed from proposed design for system with ULAF in comparison with system using LEAF at transmission reach from 600 km to 4000 km.

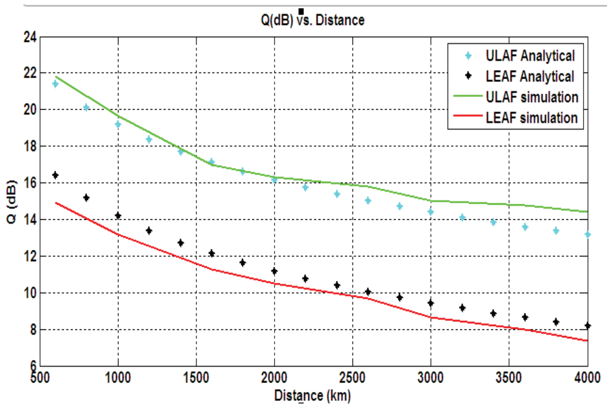


Figure 5.14 Q factor vs. Transmission Distance for hybrid WDM optical system for PDM-QPSK channel

Q factor for PDM 16-QAM channel is found to vary between 14.48 to 6.64 dB and 9.67 to 2.37 dB using theoretical analysis for transmission reach of 600 km to 4000 km in systems using ULAF and LEAF fibers respectively. Simulation results show the variation of 13.59 to 6.32 and 8.87 to 2.78 in Q factor for systems for the same fibers respectively from 600 km to 4000 km transmission reach. Variations of 0.89 dB to 0.32 dB and 0.8 to 0.41 dB in Q are found in between theoretical and simulation results. Q factor improvement of 4.72 dB and 3.54 dB is observed from proposed design for system with ULAF in comparison with system using LEAF at transmission reach from 600 km to 4000 km.

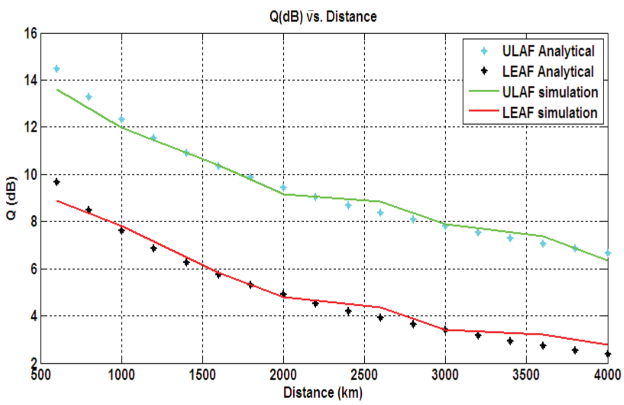


Figure 5.15 Q factor vs. Transmission Distance for hybrid WDM optical system for PDM 16-QAM channel

Log (ESE) is calculated theoretically from BER mentioned in equations (5.25),(5.26) of section 5.5.3 and both the results from theoretical computation and simulations are plotted in Figure 5.16 for PDM QPSK channel and in Figure 5.17 for PDM 16-QAM channel respectively. Analytical result of Log (ESE) varies for PDM QPSK channel from -31.0715 to -5.2596 and -10.4304 to -1.9827 in systems using ULAF and LEAF fibers respectively for 600 km to 4000 km transmission reach. Similarly, simulation result variation of Log (ESE) from -34.28809 to -7.26661 and -10.95428 to -2.61383 is obtained for WDM hybrid systems using ULAF and LEAF fibers respectively for 600 km to 4000 km transmission reach.

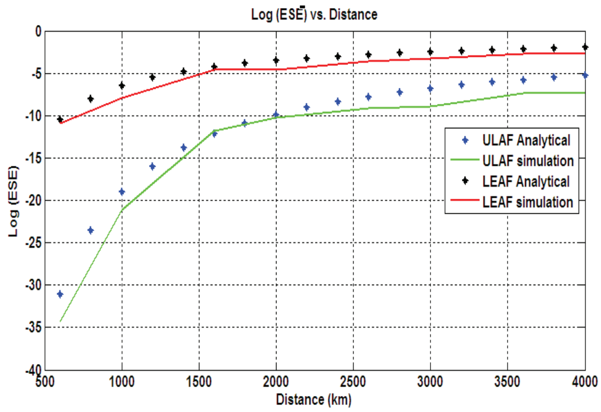


Figure 5.16 Log (ESE) vs. Transmission Distance for hybrid WDM optical system for PDM-QPSK channel

Analytical result of Log (ESE) varies for PDM 16-QAM channel from -6.6367 to -1.1996 and -2.3336 to -0.4227 in systems using ULAF and LEAF fibers respectively for 600 km to 4000 km transmission reach. Similarly, simulation result variation of Log (ESE) from -5.38248 to -1.02197 and -2.295228 to -0.12041 is obtained for WDM hybrid systems using ULAF and LEAF fibers respectively for 600 km to 4000 km transmission reach. Results show lower values of Log (ESE) for system using ULAF than LEAF system at long transmission reach. Theoretical and simulation results clearly indicate better performance for system using ULAF than system using LEAF for transmission reach up to 4000 km

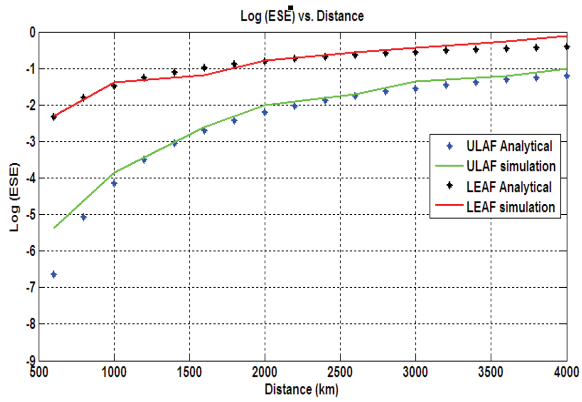


Figure 5.17 Log (ESE) vs. Transmission Distance for hybrid WDM optical system for PDM 16-QAM channel

It is evident from the Figure 5.18 that as we change the transmission distance in the range of 600 km to 4000 km, correspondingly the values of EVM varies in the range of 10.62% to 24.32% for ULAF and 18.04 % to 37.11% for LEAF with PDM QPSK channel. EVM variation of 11.02% to 18.97 for ULAF and 16.34% to 21.84% for LEAF with PDM 16-QAM channel is observed in Figure 5.19. It clearly indicates that EVM for ULAF system is 7.42% to 12.79% and 5.32% to 2.87% lower in comparison with system with LEAF for PDM QPSK and PDM 16-QAM channel respectively, over 600 km to 4000 km.

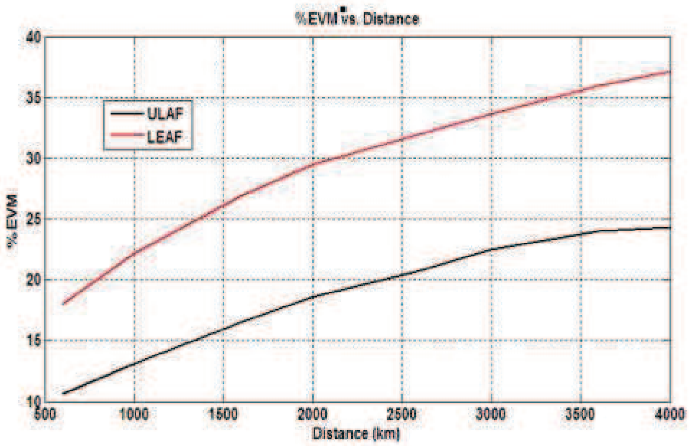


Figure 5.18 EVM vs. Transmission Distance for hybrid WDM optical system for PDM-QPSK channel

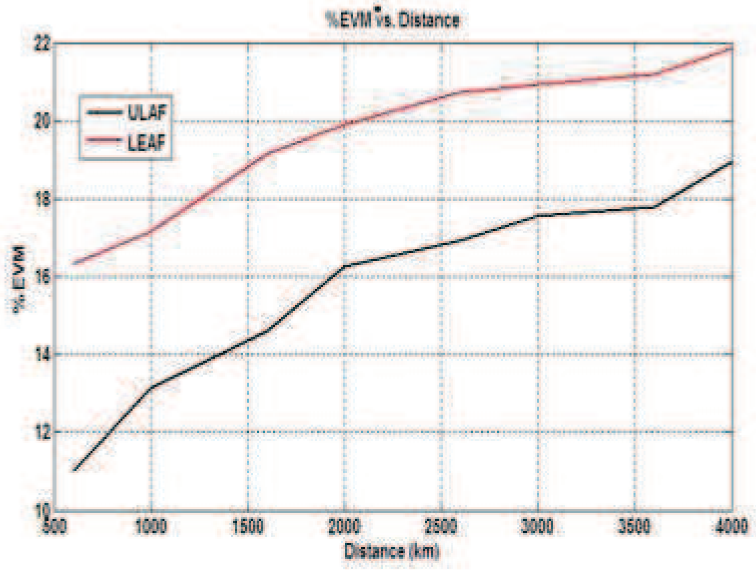


Figure 5.19 EVM vs. Transmission Distance for hybrid WDM optical system for PDM 16-QAM channel

5.5.4.2 Analysis of Q for various channels at fixed transmission distances

Further we have investigated the variation of Q factor of different transmission channels for WDM hybrid systems with ULAF and LEAF fibers over transmission distances of 600 km and 4000 km for PDM QPSK channels and PDM 16-QAM channels as shown in Figure 5.20 and Figure 5.21 respectively. Channels 2,4,7,9,12,14,17 and 19 in Figure 5.20 indicate carrier frequencies of 193.05 THz, 193.1 THz, 193.175 THz, 193.225 THz, 193.3 THz, 193.35 THz, 193.425 THz and 193.475 THz respectively for PDM QPSK modulated channels. Similarly, Channels 23,25,28,30,32,33,36 and 38 in Figure 5.21 indicate carrier frequencies of 193.575 THz, 193.625 THz, 193.7 THz, 193.75 THz, 193.8 THz, 193.825 THz, 193.9 THz and 193.95 THz respectively for PDM 16-QAM modulated channels. Q-factor is found higher for different channels in case of WDM system with ULAF fiber for long reach as shown in Figure 5.20 and Figure 5.21. Q-factor varies from channel to channel due to non-uniform gain of EDFA amplifier used in fiber loop. Figure 5.22 shows the constellation of hybrid WDM optical systems for transmission distance of 4000 km. System using LEAF exhibits more distortion for PDM QPSK and PDM 16-QAM channels at 4000 km. System with ULAF performs comparatively better than other system at long haul communication of 4000 km transmission.

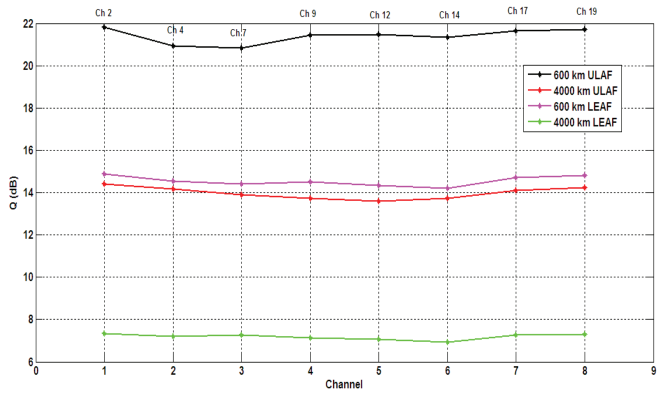


Figure 5.20 factor vs. PDM QPSK channels for hybrid WDM optical system with ULAF and LEAF fibers

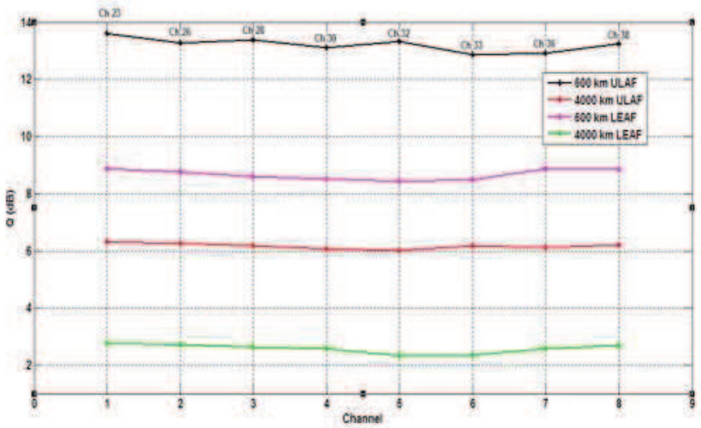
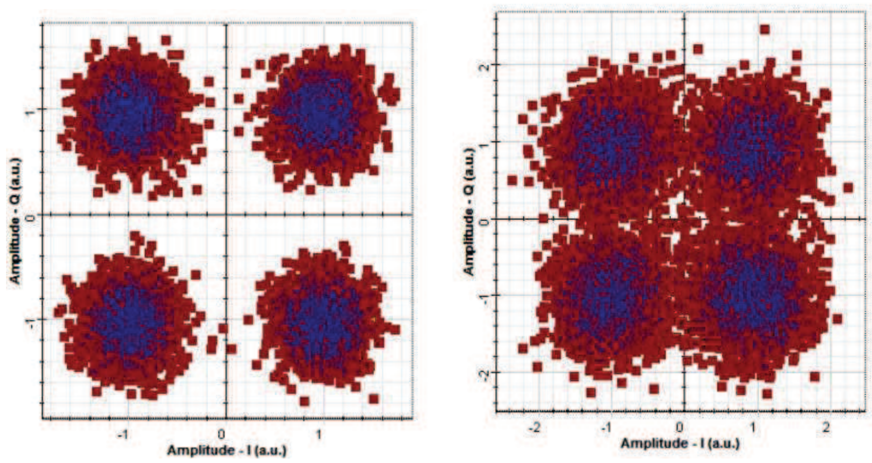
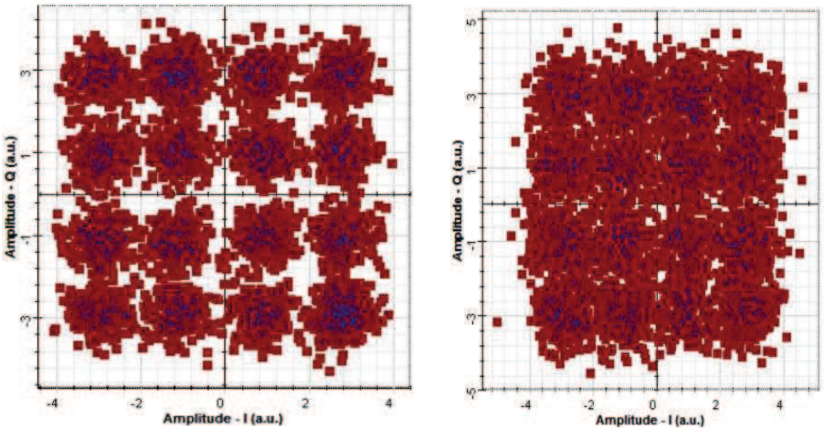


Figure 5.21 Q factor vs. PDM 16-QAM channels for hybrid WDM optical system with ULAF and LEAF fibers



(a) (b)



(c) (d)

Figure 5.22 Constellation diagram at 4000 km for PDM QPSK channel with (a) ULAF, (b) LEAF and for PDM 16-QAM channel (c) ULAF, (d) LEAF

Q factor of pre-dispersion compensation technique is observed 12.373 dB at 1200 km (Jasvir Singh; Vivekanand, Mishra Smieee; P, N Patel; Pushpa, Gilawat) as shown in Table 5.2. In line dispersion compensation technique is used to compensate dispersion of fiber, but at the same time dispersion compensating fiber is responsible for increasing the fiber nonlinearities. In (Deepak Malik; Kuldip, Pahwa; Amit, Wason) hybrid optical amplification (SOA + EDFA) used to amplify the signal. Amplifiers contribute to ASE noise, which degrades the performance at shorter distances in absence of nonlinearity and dispersion compensation technique. Direct detection method is employed with in line dispersion compensating fibers in (Fadil, Paloi; Taimur, Mirza; Shyqyri, Haxha). Dual carrier DQPSK transmission with DCF is used to compensate dispersion in link (Sun, Hyok Chang; Hwan, Seok Chung; Jyung, Chan Lee; Kwangjoon, Kim; Jong Hyun, Lee). Dispersion compensating fibers along with optical amplifier contributes to fiber nonlinearities, which degrades system performance at shorter distances.

Table 5.2 Brief comparison between proposed technique and earlier reported work

Dispersion compensation technique	Modulation	Max. Q factor	Transmission Distance
Pre compensation (Jasvir Singh; Vivekanand, Mishra Smieee; P, N Patel; Pushpa, Gilawat)	PDM-OFDM	12.373 dB	1200 km

Hybrid optical amplifier (Deepak Malik; Kuldip, Pahwa; Amit, Wason)	NRZ	≈ 8 dB	100 km
Dispersion Compensating Fiber (DCF) (Fadil, Paloi; Taimur, Mirza; Shyqyri, Haxha)	RZ	6.07 dB	840 km
DCF (Sun, Hyok Chang; Hwan, Seok Chung; Jyung, Chan Lee; Kwangjoon, Kim; Jong Hyun, Lee)	Dual Carrier – DQPSK	12.5 dB	1000 km
Coherent detection with DSP **(Proposed Work)**	Hybrid PDM-QPSK and PDM 16-QAM	14.39 dB	4000 km

Table 5.2 shows that, using our proposed technique of coherent detection technique with DSP at the receiving end, we obtained maximum Q factor of 14.39 dB at 4000 km transmission reach for PDM QPSK channel. Our proposed technique gives higher Q factor at long distance as compared to earlier reported work as shown in Table 5.2.

5.6 Conclusion

In this chapter, designs of PDM-QPSK long haul WDM optical systems for 23 x 100 Gb/s (2.3 Tb/s) are investigated. The performance is evaluated for systems with ULAF,SSMF and LEAF fibers at transmission reach from 600 km to 5000 km. Q factor is almost 1.66 dB to 3.21 dB and 2.08 dB to 4.63 dB higher for system with ULAF fiber than system with SSMF and LEAF fibers respectively for 600 km to 5000 km transmission reach. EVM values are found 2.24% to 2.68% and 2.68% to 12.43% lower in system with ULAF than other two systems using SSMF and LEAF fibers respectively. Log of Estimated symbol error (ESE) of system with ULAF is lower than systems with SSMF and LEAF at 5000 km. 25 GHz channel spacing is kept between sub-carriers to achieve spectral efficiency of 4 b/s/Hz at the data rate of 100 Gb/s of each sub carrier. PDM-QPSK WDM optical system with ULAF outperforms than the systems with SSMF and LEAF fibers at long transmission reach.

In this chapter the design of hybrid transmission of PDM-QPSK and PDM 16-QAM formats in WDM optical system for 39 x 100 Gb/s (3.9 Tb/s) is also investigated. 25 GHz channel spacing is kept between sub-carriers to achieve spectral efficiency of 4 b/s/Hz at the data rate of 100 Gb/s of each sub-carrier. 20 channels carry data with PDM QPSK format and 19 channels carry data with PDM 16-QAM format. The performance is evaluated for hybrid system with ULAF and LEAF fibers at transmission reach from 600 km to 4000 km. Q factor is almost 6.93 dB and 7.05 dB higher for PDM QPSK modulation and 4.72 dB and 3.54 dB higher for PDM 16-QAM modulation in hybrid system using ULAF fiber than system with LEAF fiber respectively for 600 km to 4000 km transmission reach. EVM is 7.42% to 12.79% and 5.32% to 2.87% lower for hybrid system with ULAF in comparison with hybrid system using LEAF for PDM QPSK and PDM 16-QAM respectively. Log of Estimated symbol error (ESE) of hybrid system with ULAF is lower than system with LEAF at 4000 km. Hybrid transmission WDM optical system with ULAF outperforms than the system with LEAF fiber at long transmission reach. Reported results of Q factors are also compared with the published results for long reach.

Chapter 6 Conclusion and Future Scope

6.1 Conclusion

The performance improvement of 12 x 160 Gb/s (1.92 Tb/s) PDM-QPSK WDM optical system employing dual carrier generation at transmitter side and coherent detection with digital signal processing at receiver end is investigated. This technique is applied and compared for three different cases by considering no coding, with gray coding and with differential coding for 100 km transmission distance by extensive simulation. The results are compared for parameters like Q-factor, Log of estimated symbol error and Error vector magnitude. 12 x 160 Gb/s (1.92 Tb/s) PDM-QPSK WDM system with differential coding performs better than system with gray coding and no coding. Burst error possibilities are minimized due to cycle slips in a system with differential coding. Q factor of WDM optical system with differential coding is improved in the range of 2 to 5 dB. Differential coding shrinks EVM around 26% to 35% in comparison with other two cases. Log of estimated symbol is also found lower in case of WDM system with differential coding. Transmission reach for the system is extended for the system up to 8000 km by maintaining the Q factor above the FEC limit (BER value 3.8×10^{-3}) with the technique.

The performance of 4 x 200 Gb/s (800 Gb/s) Dual Carrier PDM 16-QAM WDM optical systems is investigated for 1000 km transmission distance. The results are obtained and presented for WDM optical systems with nonlinearity compensation and without nonlinearity compensation at receiver from 200 km to 1000 km. It is observed that Q factor is improved by 2.43 dB to 1.95 dB for system with nonlinearity compensation than the system without nonlinearity compensation for 200 km to 1000 km transmission reach, respectively. System performance is also verified with other parameters like Error vector magnitude and Log of Estimated symbol error. EVM values and Log of Estimated symbol error (ESE) are reduced 1.33% and 41.2% in system with nonlinearity compensation in comparison with system with nonlinearity compensation at 1000 km reach, respectively. Spacing between channels are kept 50 GHz with individual channel data rate of 200 Gb/s to achieve the spectral efficiency of 4 b/s/Hz. Dual Carrier PDM 16-QAM WDM optical system with nonlinearity compensation outperforms than the system without nonlinearity compensation. A comparison of 10 x 100 Gbps WDM Optical systems using hybrid modulation employing dual carrier concept with ULAF and SSMF fibers is investigated up to the transmission reach of 2500 km. Polarization division multiplexed quadrature phase shift keying (PDM QPSK) and polarization division multiplexed 16-quadrature amplitude shift keying (PDM 16-QAM) are utilized for hybrid modulation WDM system. Optical system with ULAF fiber achieves improvement of Q factor around 2.85 dB to 2.98 dB for 500 km – 2500 km transmission distances. Performance improvement is also reflected with obtained lower values of Error vector magnitude (EVM) from 4.35% to 8.35% for system with ULAF fiber for 500 km – 2500 km transmission reach. WDM optical system with ULAF fiber outperforms in comparison with system with SSMF fiber.

The performance of coherent detection with DSP based multi-carrier generated PDM-QPSK long haul WDM optical systems for 23 x 100 Gb/s (2.3 Tb/s) is investigated. The obtained results are compared for systems with ULAF,SSMF and LEAF fibers at transmission reach from 600 km to 5000 km. Improvement in Q factor of almost 1.66 dB to 3.21 dB and 2.08 dB to 4.63 dB is noted for the system with ULAF fiber than systems with SSMF and LEAF fibers, respectively for 600 km to 5000 km transmission reach. Performance improvement in the system using ULAF fiber employing coherent detection with DSP at receiver end is also observed with lower values of EVM and Log(ESE) at long transmission distance for higher data rates. Higher spectral efficiency of 4 b/s/Hz is achieved by keeping 25 GHz channel spacing between sub-carriers at the data rate of 100 Gb/s of each sub carrier. PDM-QPSK WDM optical system with ULAF outperforms than the systems with SSMF and LEAF fibers at long transmission reach. The performance is also evaluated for the design of hybrid transmission of PDM-QPSK and PDM 16-QAM formats in 39 x 100 Gb/s (3.9 Tb/s) WDM optical system. 25 GHz channel spacing is kept between sub-carriers to achieve spectral efficiency of 4 b/s/Hz at the data rate of 100 Gb/s of each sub-carrier. 20 channels carry data with PDM QPSK format and 19 channels carry data with PDM 16-QAM format. The performance is evaluated for hybrid system with ULAF and LEAF fibers at transmission reach from 600 km to 4000 km. Q factor is almost 6.93 dB and 7.05 dB higher for PDM QPSK modulation and 4.72 dB and 3.54 dB higher for PDM 16-QAM modulation in hybrid system using ULAF fiber than system with LEAF fiber respectively for 600 km to 4000 km transmission reach. EVM is 7.42% to 12.79% and 5.32% to 2.87% lower for hybrid system with ULAF in comparison with hybrid system using LEAF for PDM QPSK and PDM 16-QAM respectively. Log of Estimated symbol error (ESE) of hybrid system with ULAF is lower than system with LEAF at 4000 km. Hybrid transmission WDM optical system with ULAF outperforms than the system with LEAF fiber at long transmission reach.

From this work, it is established that dual carrier and multi carrier generation require less number of CW LASERs at the transmitter end. Multi carrier generation concept also improves spectral efficiency of the WDM optical systems. Coherent detection with DSP enhances the system performance of WDM optical communication at high transmission rates for long reach due to the ability of mitigation of fiber dispersion and nonlinear effects efficiently.

6.2 Future scope of work

The work presented in this thesis has considered PDM QPSK and PDM 16-QAM modulation schemes employing multi-carrier concept with the deployment of coherent detection with DSP at receiver end. Looking at the spectral efficiency provided with PDM 32-QAM and PDM 64-QAM schemes, the performance of multi-carrier WDM optical system can also be investigated for long transmission reach. Further, the approach presented in this thesis can also be expanded by deployment of super channel concept for hybrid modulation multi-carrier transmission. The concept of reduced-guard-interval coherent orthogonal frequency division multiplexing (RGI-CO-OFDM) can also be explored with PDM 16-QAM to achieve still higher spectral efficiency with ultra large area fiber for long haul WDM optical communication

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