# NON-LINEAR EFFECTS IN A DPSK SYSTEM

*A Dissertation submitted in the partial fulfillment of*

*requirements for the award of the Degree of*

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*Submitted by:*

Navpreet Kaur Waraich

Roll No: 801261013

*Under the guidance of:*

Dr. R.S. Kaler

Senior Professor

**DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING**

**THAPAR UNIVERSITY**

**(Established under the section 3 of UGC Act, 1956)**

**PATIALA – 147004 (PUNJAB)**

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# CERTIFICATE

I, Navpreet Kaur Waraich, hereby declare that the work which is being presented in this dissertation entitled, **"Non-linear Effects in a DPSK System"** in partial fulfillment of the requirements for the award of degree of Master of Engineering in Electronics and Communication Engineering from Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Dr. R.S. Kaler and refers other researchers' works which are duly listed in the reference section.

The matter presented in this dissertation has not been submitted in any other University/Institute for the award of any other degree.

Navpreet.

Date: 16th July, 14

Navpreet Kaur Waraich

Roll no: 801261013

It is certified that the above statement made by the student is correct to the best of our knowledge and belief.

Date: 16th July, 14.

Dr. R.S. Kaler

Senior Professor (ECED)

Thapar University, Patiala

Countersigned by:

Dr. Sanjay Sharma

Professor & Head

ECED, Thapar University

Patiala, 147004

Dr. S.K. Mahopatra

Dean of Academic Affairs

Thapar University

Patiala, 147004

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Navpreet Kaur Waraich

# ABSTRACT

Recently much interest has been shown in the advanced data modulation techniques in order to reduce the impairments in the system. Direct detection differential phase-shift-keying modulation has gained a lot of attraction in the recent past. This is accredited to the two main advantages provided by this modulation technique: improved immunity to the fiber nonlinear effects and better sensitivity at the receiver side. It has already been shown, through experiments and in theory, an optically pre-amplified DPSK-balanced receiver requires about half number of photons/bit compared to the ON–OFF-keying (OOK) technique. Thus, the required optical signal-to-noise ratio (OSNR) in DPSK systems is 3 dB less than the conventional OOK systems. Due to this improvement, the transmission distance is extended and the system margin is increased. It also allows lower fiber launch power to avoid the degradation of signals due to the fiber nonlinear effects. The DPSK system also has higher tolerance to fiber nonlinear effects such as cross-phase modulation besides the improved receiver sensitivity. The nonlinear impairment is reduced by the constant amplitude modulation which in turn reduces the nonlinear effects dependent on pattern.

In this thesis work, we have verified that DPSK performs better than other modulation techniques like NRZ for long distance communication. The main advantage of DPSK over NRZ is the constant transmission power in the channel due to which the DPSK technique can eliminate SPM and XPM effects. Further, we investigated the performance of two intensity modulators- Electro-absorption modulator (EAM) and Mach Zehnder modulator (MZM) used in the IM-DPSK technique. The high Q-factor and low BER for the system using MZM at all the transmission points proves that MZM is a better choice for intensity modulation in IM-DPSK technique. Finally, we proposed that using mid link spectral inverter in transmission link for IM-DPSK based transmission system makes the system more tolerant to the effects of nonlinearities and is convenient to use since it reduces the need of OEO conversion.

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| | |
|---|---|
| ASE | Amplified Spontaneous Emission |
| BER | Bit Error Rate |
| BPSK | Binary Phase shift Keying |
| CD | Chromatic Dispersion |
| CS-RZ | Suppressed Carrier Return-to-Zero |
| CW | Continuous Wave |
| DBPSK | Binary Differential Phase Shift Keying |
| DCF | Dispersion Compensating Fiber |
| DFB | Distributed Feed Back |
| DLI | Delay Line Interferometer |
| DPSK | Differential Phase Shift Keying |
| DQPSK | Quadrature Differential Phase Shift Keying |
| DSP | Digital Signal Processing |
| EAM | Electro Absorption Modulator |
| FBG | Fiber Bragg Grating |
| FK | Franz- Keldysh |
| FOM | Figure Of Merit |
| FSR | Free Spectral Range |
| FWM | Four-Wave Mixing |
| GM | Gordon–Mollenauer |
| GVD | Group Velocity Dispersion |
| IM-DPSK | Intensity Modulated Differential Phase Shift Keying |
| ISI | Inter Symbol Interference |
| LO | Local Oscillator |
| MLSI | Mid Link Spectral Inversion |
| MZM | Mach- Zehnder modulator |
| NALM | Nonlinear Amplifying Loop Mirror |
| NOLM | Nonlinear Optical Loop Mirror |
| NRZ | Non Return-to-Zero |

| | |
|---|---|
| NZDSF | Non Zero Dispersion Shifted Fiber |
| OEO | Optical to Electrical to Optical |
| OOK | On- Off Keying |
| OSNR | Optical Signal-to-Noise Ratio |
| OTDM | Optical Time Domain Multiplexing |
| PM | Phase Modulator |
| PMD | Polarization Mode Dispersion |
| PSK | Phase Shift Keying |
| QPSK | Quadrature Phase Shift Keying |
| QW | Quantum Well |
| RZ | Return-to-Zero |
| SBS | Stimulated Brillouin Scattering |
| SMF | Single-Mode Fiber |
| SNR | Signal-to-Noise Ratio |
| SOA | Semiconductor Optical Amplifier |
| SPM | Self Phase Modulation |
| SRS | Stimulated Raman Scattering |
| VOIP | Voice over Internet Protocol |
| WDM | Wavelength Division Multiplexing |
| WWW | World Wide Web |
| XPM | Cross Phase Modulation |

# CHAPTER -1

# INTRODUCION

## 1.1 IMPORTANCE OF OPTICAL NETWORK:

An optical network is a network that is used to transfer data from one place to another. The data usually lies in the computers which are connected by the optical fiber. An optical network also includes devices which are used to convert optical data to electrical data or vice-versa which are required for the propagation of signal inside the optical fiber and to restore the actual data. Basically, the main technology used in optical networks for the transportation of information is optical fiber. These fibers can be based on single-wavelength or multi-wavelength and can be single mode or multi mode.

Optical fiber networking is used because of its high potential and boundless capabilities. Some of the advantages are listed below [1]:

- It has a very high bandwidth i.e. of over 50 Tbps.
- In optical fiber communication, the attenuation of signal is very less, it can be as low as 0.2 dB/km, so it can be used for long haul communication minimizing the use of repeaters.
- It is resistant to the electromagnetic interference.
- The signal is highly secured. Since there is no electromagnetic radiation, so its difficult to snoop into the data carried by the fiber.
- no interference and crosstalk between fibers in the same cable,
- It is appropriate for carrying digital information since the distortion in signal is very low.
- The power required is also very low.
- The space required is small, is cost effective, non-flammable and very light in weight.
- It has high electrical resistance.

## 1.2 GENERAL INTRODUCTION:

The fiber optical communication era began in 1966 when Charles Kao, 2010 Nobel Prize winner in Physics, demonstrated the possibility of transmitting information through a dielectric medium with a performance that was far better than that of existing coaxial systems [2] . This demonstration led to the design of first optical network that became commercially available two decades later [3]. The network used an on/off keying (OOK) format as a modulation scheme and had a capacity of about 50 Mbps. Optical networks now a days still make use of the OOK format but further take advantage of various multiplexing techniques i.e., optical time division multiplexing and/or wavelength division multiplexing to boost the capacity. For instance, in networks using the WDM technique, by transmitting the information on 32 wavelengths, each operating at the bit-rate of 10 Gbps, the capacity can be increased to 320 Gbps [4]. However, these high-speed networks are not able to relieve the increasing demand of capacity that arises from revolutionary technologies, for example, the World Wide Web (WWW) and Voice over IP (VOIP).

Escalating the capacity of today's networks to meet such high demand is, therefore, crucial and can be realized in many ways. One of the ways is to expand the number of WDM channels into a Long band (L-band). Such a system with 432 wavelength channels was reported in [5]. However, a more attractive method to increase the capacity is the use of advanced modulation formats.

## 1.3 PHASE MODULATION TECHNIQUES:

These techniques, such as quadrature amplitude modulation and phase shift keying formats, modify an optical carrier phase and/or amplitude to carry the information and can transmit information at higher symbol-rates than that of the OOK format [2,3]. However, since the phase- entrenched information disappears after the detection of signal carrier by a photo detector; the receivers necessitate special detection techniques, i.e., coherent detection and differential detection to be implemented.

Coherent detection is based on the interference between a signal carrier and a local oscillator (LO) to detect the phase-embedded information. The local oscillator is usually a continuous wave (CW) laser, whose frequency is either identical to the signal carrier, called the intradyne detection or located at a difference from that of the signal carrier, called the heterodyne detection, depending on the frequency spacing between the two signals [6].

On the other hand, differential detection does not require a local oscillator. Instead, it makes use of an interferometric device such as a delay line interferometer (DLI) to extract the phase-embedded information. In the DLI, the input signal is split equally into two branches, with the signal in one delayed by one symbol-slot. Hence, an output signal of the DLI is essentially a beating product whose amplitude is determined by phase differences between two consecutive symbols of the input signal. However, this detection technique requires the input signal to be differentially encoded.

Compared with differential detection, the coherent detection achieves superior receiver sensitivity when detecting equivalent modulation formats because differential detection inevitably interprets one encoded-bit error into two decoded-bit errors [7]. Moreover, coherent detection provides higher tolerance towards transmission impairments, e.g., polarization mode dispersion, chromatic dispersion and filtering due to digital signal processing (DSP) capabilities [8].

Although it has several encouraging advantages, coherent detection requires such a narrow LO line width that the system becomes considerably costly to realize. Furthermore, the scheme intensively relies on the DSP, which is currently unavailable at high baud-rates. Differential detection, on the other hand, provides cost-effective systems because of its simple receiver structure, which can also be customized for any baud-rate. These advantages, indeed, make the scheme more attractive for near-term commercialization.

A common modulation technique that is detectable by differential detection is the multi-level PSK format, which is typically referred to as the differential multi-level PSK (DPSK) format. Its simplest form is known as a binary DPSK (DBPSK) format, which was found to be superior to the OOK format with respect to receiver sensitivity and robustness toward fiber nonlinearities [9]. The DBPSK format currently reaches a record baud-rate of 42.7 Gbaud on a single wavelength [10].

The Quadrature DPSK (DQPSK) format has also drawn much attention as it can carry 2 bits per symbol. This relaxes the electronic bandwidth requirement by half at the same bit rate as that of the DBPSK format. The format was demonstrated at a bit-rate of 111 Gbit/s in an OOK WDM environment having 10.7Gbps bit rate, showing the feasibility of upgrading existing infrastructures for higher capacities [11]. Moreover, it achieved a very high spectral efficiency of 3.2 bit/s/Hz in the dense WDM system [12]. The DQPSK signal was also demonstrated in OTDM systems, reaching the bit- rates of 1.07 Tbit/s over a 480 km transmission link and 5.1 Tbit/s in back-to- back transmission [13, 14].

## 1.4 BACKGROUND:

1. In around 1990 the early experiments performed were[15]
    - For the improvement of receiver sensitivity (At BER $10^{-9}$, 1000 photons/bit in OOK v.s. < 100 photons/bit in DPSK)
    - Low bit rate: ~ 1 Gb/s
2. Then in the early 90's after the advent of optical amplifiers
    - High sensitivity OOK receiver (<100 photons/bit) can be realized with the aid of optical amplifier (Ex. Erbium-Doped Fiber Amplifier)
    - Complicated DPSK transmitter and receiver
    - Stringent requirements on laser linewidth (< 1% of data rate)
3. Recent Revival around 2002
    - For the improvement of receiver sensitivity (< 50 photons/bit), reduction of fiber nonlinearity and increase of spectrum efficiency
    - Interferometric demodulation + direct detection
    - Data rates of 10 Gb/s and 40 Gb/s → relaxed linewidth requirements

## 1.5 NON LINEAR EFFECTS:

Nonlinearities in an optical fiber greatly affect the transmission of signal in an optical communication system. The non linear effects in a fiber cause cross-channel interference, distortion, and attenuation of the signal carried by the fiber. These effects restrain various properties of a DPSK system like the spacing between adjacent wavelength channels, and they also limit the maximum bit rate, the maximum power per channel and the system reach.

### Nonlinear Refraction [1]

In an optical fiber, the varying optical intensity of signals propagating through the fiber causes changes in the refractive index of the fiber. Thus, the optical intensity, the length of the fiber and the phase of the light sent by the transmitter will determine the phase of light received at the receiver. This phenomenon causes two main types of non linear effects- cross-phase modulation and self-phase modulation which are explained below.

### Self Phase Modulation (SPM):

In self phase modulation, the phase of the signal changes due to the variations in the power of an optical signal. The amount by which the phase of the signal shifts is given by the following equation:

$$\emptyset_{NL} = n_2 k_0 L|E|^2$$

Where, $k_0$= 2π/X, $n_2$ is the nonlinear coefficient for the index of refraction, $|E|^2$ is the optical intensity and $\boldsymbol{L}$ is the length of the fiber. In phase shift- keying systems, the receiver depends on the phase information and due to the change in the phase of the received signal, the performance of this system is degraded. SPM also causes the spectral broadening of pulses, as explained below. The instantaneous variations caused in the phase of the signal by the changing intensity of the signal results in instantaneous variations of frequency of the signal around its central frequency. The effects of material dispersion combined with the effects of self phase modulation lead to the generation of additional frequency components which causes the spreading or compression of the pulse in the time domain and affects the bit error rate and the maximum bit rate.

### Cross Phase Modulation (XPM):

In cross-phase modulation, the phase of the signal is changed due to the change in the intensity of a signal traversing at a neighboring wavelength. It causes the asymmetric spectral broadening of the signal. The cross-phase modulation combined with dispersion may also cause changes in the pulse shape of the signal in time domain. Despite of its limitations, the cross phase modulation can have advantageous applications as well. It can be used to modulate a pump signal at one wavelength from a modulated signal on a different wavelength.

**Stimulated Raman Scattering (SRS):**

Stimulated Raman Scattering is caused by the interaction of light with molecular vibrations. When light is incident on the molecules, it is scattered at a longer wavelength as compared to that of the incident light. Each frequency component of a portion of light traveling in the fiber is then downshifted across a region of lower frequencies. This light which is generated at the lower frequencies is called the Stokes wave. The Stokes wave occupies a range of frequencies which is determined by the *Raman Gain spectrum* that covers a range of around 40 THz below the frequency of the input signal. In silica fiber, the maximum gain of Stokes wave is at a frequency of around 13.2 THz less than the input signal. As the power of the input signal is increased, the fraction of power transferred to the Stokes wave grows rapidly. Stimulated Raman Scattering causes almost all of the power in the input signal to be transferred to the Stokes wave under very high input power.

In multi-wavelength systems, the higher-wavelength channels gain some power within the Raman gain spectrum from the shorter-wavelength channels. The power on each channel is required to be below a certain level to reduce this loss of power.

**Stimulated Brillouin Scattering (SBS):**

In Stimulated Brillouin scattering, the shift in frequency is caused by sound waves unlike Stimulated Raman Scattering where this shift is caused by molecular vibrations. In SBS the Stokes wave propagates in a direction opposite to that of the input light. Also, it occurs at relatively low input powers for wide pulses (greater than 1 ps), but has negligible effect for short pulses (less than 10 ns). The frequency range of SBS, on the order of 10 GHz, is much lower than that of SRS, but the intensity of the scattered light is much greater in SBS than in SRS. The gain bandwidth of SBS is only on the order of 100 MHz.

The input power must be below a certain threshold to oppose the effects of SBS. It may also induce crosstalk between channels in multi wavelength systems. In SBS, crosstalk occurs when two channels propagating in opposing directions differ in frequency of around 11 GHz for wavelengths at 1550 nm. However, if we keep the gain bandwidth of SBS narrow, the crosstalk can be avoided easily.

**Four-Wave Mixing (FWM):**

Four-wave mixing becomes a principal effect when the bit rate of optical data streams in fibers is increased. FWM is worst-case for the case in which WDM channels are equally-spaced. It also causes inter-channel crosstalk. FWM penalty can be reduced by unequally spaced channels or by using fiber with high local dispersion (SMF, NZDSF).

Though using unequally spaced channels reduces the effect of four wave mixing, but there is a lower limit on the minimum channel spacing. However, there are some other significant advantages of FWM which are being used in WDM networks. For example, it can be used for conversion of wavelength.

## 1.6 LINEAR EFFECTS [1]:

### 1.6.1 Attenuation in Fibers:

As the signal propagates over some distance, its power starts to reduce and this effect is known as attenuation. One must consider attenuation while determining the maximum distance to which a signal can be transmitted for a given receiver sensitivity and transmitter power. Receiver sensitivity can be defined as the minimum power required by a receiver for the detection of the signal. Let P(L) be the power of the optical pulse at distance L km from the transmitter and A be the attenuation constant of the fiber (in dB/km). Attenuation is characterized by:

$$P(L) = 10^{\frac{-AL}{10}} P(0)$$

where P(0) is the optical power at the transmitter. For a link length of L km, *P(L)* must be greater than or equal to Pr, the receiver sensitivity. The above equation can also be written as:

$$L_{max} = \frac{10}{A} log_{10} \frac{P(0)}{P_r}$$

The maximum distance at which the receiver can be placed from the transmitter (or the distance between amplifiers) is ruled by the constant A than by the optical power launched by the transmitter.

### 1.6.2 Dispersion in Fibers:

As the signal travels through the fiber, it gets widened and this widening of pulse duration is known as Dispersion. This widening of a pulse becomes a cause of it’s interfere with neighboring pulses (bits), which causes intersymbol interference. Thus, dispersion limits the maximum transmission rate and the bit rate on a fiber-optic channel. One type of dispersion is *intermodal dispersion.* It occurs when multiple modes of the same signal propagate at different velocities along the fiber. It does not occur in a single mode fiber.

Another form of dispersion is *chromatic dispersion*. Chromatic dispersion arises from the fact that even within the same mode, different wavelengths or colors travel at different speeds. The refractive index is a function of the wavelength in a dispersive medium. Thus, certain wavelengths will propagate faster than other wavelengths, if the transmitted signal consists of more than one wavelength. Chromatic dispersion is the result of *material dispersion, waveguide dispersion,* and/or *profile dispersion.*

*Profile dispersion* is caused by the variation of index of refraction with respect to wavelength. The dependence of the propagation of different wavelengths on waveguide characteristics, such as shape of the fiber core and cladding and on the indices leads to another type of dispersion known as *Waveguide dispersion*. *Material dispersion* is caused due to the difference in velocities of each wavelength in a material. Since any signal carrying information will have a nonzero spectral width (range of wavelengths/frequencies in the signal) or since, no laser can make a signal consisting of only a single wavelength, material dispersion will occur in most systems. The last two forms of dispersion are very common in optical fibers. Although the single-mode fiber (SMF) can perfectly eliminate several types of dispersion (which the multimode fiber cannot), *chromatic dispersion* and *polarization mode dispersion,* (PMD) still need to be dealt with.

In single-mode optical fibers, another complex optical effect that occurs is called *Polarization mode dispersion (PMD)*. Single-mode fibers support two perpendicular polarizations of the original transmitted signal. Both the polarization modes would propagate at exactly same speed if a fiber were perfectly round and free from all stresses which would result in zero PMD. However, practical fibers are not perfect. These two polarization modes may travel at different speeds and, hence, arrive at different times at the end of the fiber (one perpendicular polarization direction is the slow axis, and the other one is the fast axis). The difference in arrival times between the axes is known as PMD. Like chromatic dispersion, Due to PMD, the spreading of digitally transmitted pulses occurs because different polarization rnodes arrive at their destination at different times. For digital transmissions, where the bit-rate is high, it limits the receiver sensitivity and can cause bit errors at the receiver. Although, in case of low optical attenuation, a system can tolerate large dispersion, the maximum acceptable dispersion penalty is mostly 2 dB.

## 1.7 DIFFERENTIAL PHASE SHIFT KEYING:

The on/off keying modulation format has been used in optical communication since its beginning. It encodes the information by manipulating the optical carrier's intensity, that is, the presence and the absence of light represent bits "1" and "0", respectively. This leads to a symbol-rate of 1 bit per symbol. Advanced optical modulation formats, on the other hand, are capable of transmitting more bit per symbol than that of the OOK format. Among these formats, multi-level PSK format is regarded as one of the potential candidates because of its robustness towards fiber nonlinearities and its simple modulator implementation, which utilizes only common modulators, for instance, a phase modulator (PM) and a Mach-Zehnder modulator (MZM) [9]. Moreover, the format can make use of differential detection, providing low receiver complexity and costs, which is attractive for near-term commercialization.

### 1.7.1 Multi-level phase shift keying:

Multi-level PSK formats embed the information on an absolute phase of the optical carrier, and each phase state (typically referred to as a symbol) corresponds to a unique bit pattern. The simplest form of such formats is known as the binary PSK (BPSK) format, whose phase states 0 and π symbolize the bit "0" and "1", respectively. Higher-order PSK formats such as quadrature PSK (QPSK) or 8-level PSK (8PSK) formats utilize 4 or 8 phase states to carry 2 and 3 bits per symbol. The PSK formats can exploit Gray coding to minimize the bit error rate, that is, neighboring symbols differ only in a single bit, leading to one bit error from wrong symbol detection, assuming the signal having high signal-to-noise ratio (SNR) [16]. Fig. 1 depicts the constellation diagram of BPSK, QPSK, and 8PSK signals with the Gray coded bit patterns assigned in each symbol. The constellation diagram is a representation of the modulated signal, which is plotted as a two-dimensional scatter diagram in the complex plane. The diagram is typically used to recognize signal distortion and intersymbol interference by observing the symbol positions and the transitions between the symbols (commonly referred to as a trajectory). The PSK formats are detectable by coherent detection. However, a reference signal is required in the receivers.

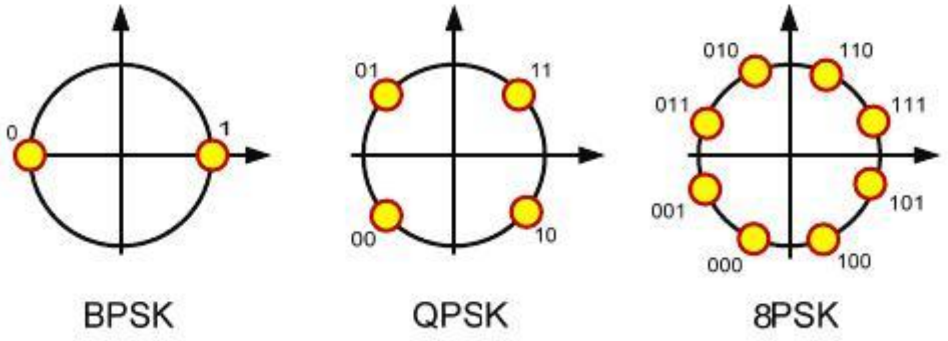
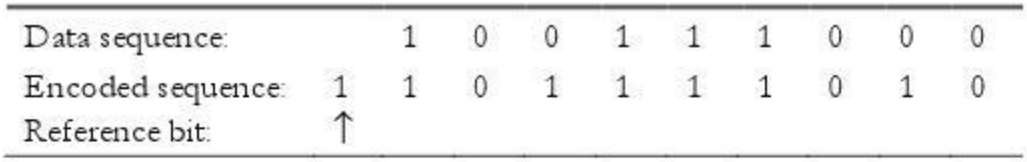


Fig. 1: The constellation diagrams of 2-, 4-, and 8-level PSK formats with the Gray coded bit mapping. [21]

### 1.7.2 Differential encoding and decoding

Differential coding was invented to eliminate the need of the reference signal in the receiver. The coding is designed such that the information can be recovered by detecting phase changes (instead of an absolute phase) between two consecutive symbols. Table 1 demonstrates the differential coding example in the case of the binary differential phase shift keying (DBPSK) signal where the data and encoded sequences represent the original and the differentially encoded information [7].



| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Data sequence: | | 1 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| Encoded sequence: | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 1 | 0 |
| Reference bit: | ↑ | | | | | | | | | |

Table 1.1: Differential coding example for DBPSK. [21]

The encoding operation can be described as follows. A current bit of the encoded sequence is compared with a following bit of the data sequence to generate a successive encoded bit. The new encoded bit is marked “1” when the two bits under comparison are identical or marked “0” when otherwise. This operation also requires an initial flag as a reference bit for the encoded sequence, which is “1” in this case. Fig. 2(a) illustrates the block diagram of the differential encoder that performs the operation described above. At the differential decoder, the two adjacent bits of the encoded sequence are compared. The decision is made in the way that bit “1” is given when the two bits under comparison are identical. Otherwise, bit “0” is given. As a result, the original data sequence is recovered. Fig. 2(b) illustrates the differential decoder block diagrams.

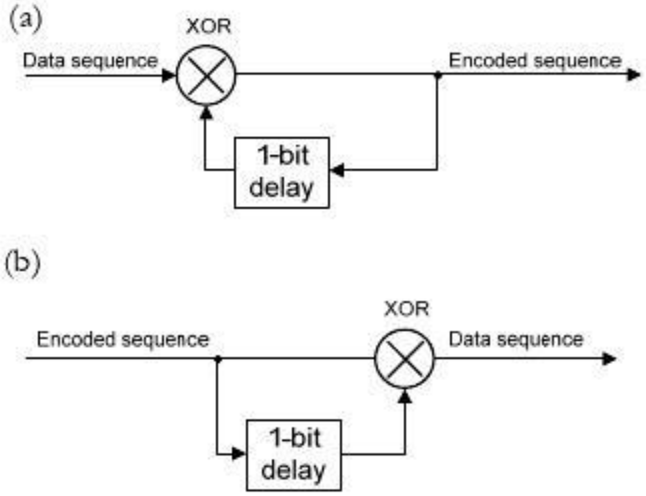


Fig. 1.2: (a) The encoder and (b) the decoder block diagrams of DBPSK. [21]

### 1.7.3 Optical DPSK implementations

Optical DPSK communication systems can be divided into three parts: a differential encoder, a DPSK transmitter, and a DPSK receiver, as illustrated in Fig. 3. The variables A, B, and C represent the original data sequences while the variables I, Q, and D correspond to the differentially encoded sequences. It is not essential that all variables be used. This depends on the order of DPSK formats. For instance, the DBPSK format requires only variables A and I whereas all are needed for the D8PSK format. The differential encoder, as discussed in preceding sections, can be easily made by logic circuits such as OR and XOR. Its complexity, however, increases with the order of the formats and also depends on how the transmitter is implemented.

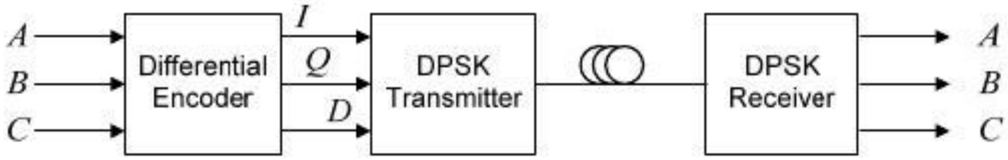


Fig 1.3: The block diagram of an optical DPSK communication system. {A, B, C} and {I, Q, D} represent the original data sequences and the encoded sequences, respectively. [21]

The DPSK transmitter consists of a laser and an optical modulator. There currently exist three classical modulators: phase modulators, electro-absorption modulators (EAMs), and Mach-Zehnder modulators. The phase modulators are typically based on the Pockels effect where the refractive indexes of their waveguides are altered in proportion to the applied electric field strength [17]. Since the refractive index determines the speed of light, the phase of an optical carrier can be controlled by the driving voltage while its amplitude remains unchanged. These modulators are typically a few cm long, requires roughly 4– 8V to create a π phase shift (which is defined as Vπ), and are usually made of Lithium Niobate (LiNbO3) [18].

In contrast, electro-absorption modulators take advantage of the Franz- Keldysh (FK) effect in bulk or quantum well (QW) materials. Such an effect alters the material absorbing coefficient by varying the applied electric field strength [19, 20]. The modulators require a relatively low driving voltage (~1 V) to achieve 10-dB extinction ratio and can be monolithically integrated with the CW light source such as a distributed feedback (DFB) laser in a single chip (sub-centimeter long).

The last type of modulator, the Mach-Zehnder modulator, makes use of an interferometric structure with the phase control section similar to that in the PMs in both interferometric arms. These modulators can vary both phase and intensity of the optical carrier, depending on driving conditions. Moreover, they provide superior signal quality due to the cosine-characteristic electrical/optical transfer function, which helps reduce imperfections such as overshoots and ripples of the driving signals. Nevertheless, all modulators mentioned above can be used to generate multi-level Differential Phase Shift Keying signals.

To differentially decode the signals, the DPSK receivers utilize a delay line interferometer and (preferably) a balanced detector. At the DLI, the modulated signal is split equally into two arms with the signal in one delayed by one symbol-slot. A phase shift can also be applied into either arm, which helps demodulate higher-order DPSK signals. The signals from the two arms later interfere with each other, transforming the phase difference between the two consecutive symbols into the varying amplitude. Lastly, the demodulated signals are detected by the balanced detectors.

## 1.8 OBJECTIVES OF DISSERTATION:

1. To investigate BER performance for DPSK modulation for different channel spacing.

2. To reduce the effects of fiber non linearities by using DPSK and other techniques.

3. To improve spectrum efficiency using phase modulation techniques.

## 1.9 ORGANIZATION OF DISSERTATION:

Chapter 2 gives literature survey about the topic of the dissertation. In order to start the dissertation, the first step is to study the papers that have already been published by researchers. Paper related to this work are chosen and studied. With the help of literature review, it becomes easier to perform this work.

Chapter 3 presents an investigation of impact of non-linear effects on various modulation techniques at different channel spacing.

Chapter 4 presents the investigation of different intensity modulators used in IM-DPSK technique.

Chapter 5 explains the Use of Mid-link Spectral Inversion to reduce the effect of nonlinearities in IM-DPSK transmission system

Chapter 6 includes the Conclusion, Recommendations and Future Scope of the work.

# CHAPTER 2

# LITERATURE SURVEY

Recently much interest has been shown in the advanced data modulation techniques in order to reduce the impairments in the system. Direct detection differential phase-shift-keying modulation has gained a lot of attraction in the recent past. The literature survey of non linear effects in DPSK system by various researchers in past years is shown below:

**Takeshi Hoshida** *et al.* [22]

In this paper, the authors presented the performance comparison of different modulation formats in 75GHz spaced long-haul transmission. Using the numerical simulations, Q-factor was evaluated for the three modulation techniques namely, NRZ, CS-RZ, IM-DPSK. The NRZ technique performed better for shorter distances i.e., for less than 1000km and therefore is considered attractive for its less cost and simple circuitry. The CS-RZ technique suffers severely from four wave mixing crosstalk considering lower dispersion coefficient of the transmission fiber. Thus, in highly spectral efficient systems it is considered unsuitable. The IM-DPSK technique provides better nonlinear tolerance and shows 3dB higher tolerance to the optical noise. Thus, it is considered an optimum modulation technique for spectrally efficient ultra long-haul transmission systems.

**Hoon Kim** *et al.* [23]

Differential phase shift keying is being widely used because of its two main advantages- enhanced immunity to the nonlinear effects in an optical fiber and the improved receiver sensitivity. It has a number of advantages over OOK technique. It requires only half the number of photons/bit as compared to the OOK format and thus the OSNR required by the DPSK system is 3dB less than the OOK systems. This advantage not only allows us to extend the transmission distance but also to lower the launch power in a fiber which lowers the effect of nonlinearities in the fiber. In this paper, the authors observed and studied the performance degradation of DPSK systems in the presence of non linear phase noise. It was observed that the amplified spontaneous emission (ASE) noise converts the intensity fluctuations into phase noise through Kerr nonlinearity. The pdf of nonlinear phase noise was found to be similar to an exponential distribution, rather than a Gaussian distribution.

**Hoon Kim** [24]

In this paper, the author investigated the degradation of performance due to cross phase modulation (XPM) induced nonlinear phase noise in DPSK systems. In addition to the self phase modulation induced nonlinear phase noise, the cross phase modulation induced phase noise deteriorates the performance of the DPSK systems even further. The theoretical analysis done in this paper shows that when the channel spacing is less than 100GHz, the noise induced by cross phase modulation becomes as large as that induced by self phase modulation in a NZ-DSF link. This has also been experimentally verified by using a 600-km nonzero-dispersion-shifted-fiber link.

**Keang-Po Ho** [25]

In this paper, the authors derived closed-form formulas for calculating the error probability of DPSK signals in the presence of non linear phase noise with and without using received intensity compensation. The phase of amplifier noise was assumed to be independent of both the residual non linear phase noise after compensation and the non linear phase noise without compensation. The error probability formulas turned out to be very accurate as shown by the simulations. Keeping the SNR constant, the mean non linear phase shift was found to be double on doubling the transmission distance considering non linear phase noise as the dominant impairment.

**S. L. Jansen** *et al.* [26]

In this paper, the authors showed that inserting a mid-link spectral inversion reduces the effect of nonlinear phase noise for phase encoded modulation techniques like DPSK. This was proved by using an 800km standard single mode fiber in the channel. The results showed that when the transmitted OSNR was low, where the phase noise affects the signal strongly, the system showed a BER improvement of about 2dB. Therefore, by using this technology the impairments due to nonlinear phase noise are reduced which can be advantageous for long-haul transmission of data, since the need of optical to electrical to optical (OEO) is reduced.

**Yannick Keith Lize** *et al.* [27]

In this paper, the authors presented the bit delay mismatch in the presence of chromatic dispersion in DPSK demodulation scheme. It was shown that if the FSR of the DLI was offset in order to obtain partial bit delay in the demodulator, the tolerance to chromatic dispersion increased without affecting the frequency offset penalty or the polarization mode dispersion tolerance. It was found that the receiver sensitivity could be increased by 1dB and that the chromatic dispersion tolerance could be increased by 12.5%. However, in this paper only an increase of 0.25dB was shown in receiver sensitivity to demonstrate that the PMD does not negatively affect the mismatch. The optimum delay mismatch scales with PMD and CD.

**Wei Hong** *et al.* [28]

In this paper, the authors investigated and numerically simulated the non linear phase noise for optical amplification using Semiconductor Optical Amplifier (SOA) for RZ-DPSK signal, considering both finite input OSNR and broadband ASE. The probability distribution and standard deviation of differential phase noise was obtained from the statistics of the same for different signal OSNR and average input power. It was found that the nonlinear phase noise contributed to the total phase noise in case of a noisy signal and this contribution was found to be larger if the SOA carrier lifetime is shorter. It was concluded that the SOA proved to be suitable for processing of DPSK signals and optical amplification if the signal input power is taken not too low.

**Xiaolin Li** *et al.* [29]

In this paper, the authors studied the optimization of FSR in the presence of Kerr nonlinearities in an optical fiber. The numerical results showed that in case of serious Kerr nonlinearities, the one bit-period is longer than the delay time of an optimal Delay Line Interferometer (DLI). As the strength of Kerr nonlinearities increases, it also increases the optimal FSR which can further increase the nonlinear tolerance of a DPSK system. However, this effect of FSR optimization is limited due to less cross phase modulation (XPM) effects in a DPSK system as compared to that of the multi-format WDM systems. The choice of optimal delay time is not affected by the nonlinear phase noise. Thus, it has been concluded that optimizing FSR along with optical filter bandwidth further enhances the tolerance of a system to the fiber Kerr nonlinearities.

**Anu sheetal** *et al.* [30]

In this paper, the authors investigated the systems for 10Gbps and 40Gbps bit rate by using in-line DCF for maximizing the transmission distance by considering ASE noise. By varying the input powers, the impact of different modulation techniques, namely, CS-RZ, RZ, NRZ and RZ-DPSK has been shown. For each of these data formats, figure of merit (FOM) $P_{max}$ has been calculated. It was found that RZ-DPSK gives minimum value of $P_{max}$ at 10Gbps and gives the highest at 40Gbps. The best performance was given by CS-RZ at 10Gbps. However, the maximum tolerance to SPM-induced non linear distortion was shown by RZ-DPSK at 40 Gbps. It has also been shown that the non linear phase noise limits the transmission distance but still RZ-DPSK proved to be the best choice for transmission at 40Gbps.

**Sub Hur** *et al.* [31]

In this paper, the authors, while considering the FWM effect with a modified TMM, designed a complete dynamic model of SOAs. Using model, they evaluated the SOA-induced crosstalk and phase error. The investigations were done on the effect of a reservoir channel injection into SOAs on the FWM and phase-error. It was found that by shortening gain recovery time with a reservoir channel could reduce the SOA induced phase-error. Introducing a reservoir channel into SOAs improved the transmission performance of SOA-boosted DPSK signals. However, due to the increased crosstalk by four-wave mixing an additional power penalty occurred in WDM transmission systems. The transmission performance of NRZ-DPSK signals could be improved with a reservoir channel injection into SOAs because the SOA-induced phase-error was more predominant than the crosstalk by FWM.

**C. Y. Lin** *et al.* [32]

In this paper, the nonlinear phase noise caused by Gordon-Mollenauer effect was analyzed in single-channel RZ-DPSK transmission system for various bit-rates. dispersion schemes and fiber types also have a great influence on the Q-factor. The Q-factor was found to increase with the increasing bit-rate and the system was more tolerant to non-linear phase noise when bit rates higher than 20Gbps were chosen. It was also shown that the pre-compensation techniques give better results than the post-compensation techniques.

**C. Stephan** *et al.* [33]

In this paper, the authors used a nonlinear optical loop mirror (NOLM) to suppress the nonlinear phase noise which is one of the major impairments in a differential phase shift keying (DPSK) transmission system. The NOLM helps in preserving the phase of the transmitted signal as required in the advanced modulation techniques like DPSK. The nonlinear phase noise originates when the amplitude fluctuations are transferred into phase fluctuations. This phenomenon is known as Gordon-Mollenauer effect. It was shown that an NALM provides suppression of amplitude noise while preserving the phase of the DPSK signal. Due to this, the generation of nonlinear phase noise is suppressed which originates by these amplitude fluctuations. It has been shown that a system's performance can be improved by using a single regenerator. An in-line optical amplifier can be replaced by an NALM-based regenerator as it provides both suppression of amplitude noise and intrinsic signal amplification at the cost of an increase in noise figure compared to a conventional in-line amplifier and slightly lower gain.

The authors investigated the use of recirculating fiber loop in improving the efficiency of cascaded, phase preserving amplitude regeneration in RZ-DPSK transmission. The results show that the accumulation of nonlinear phase noise is lesser as the use of regenerators makes the system more tolerant to phase noise. The eye diagrams show an improvement of about 2dB by the use of these regenerators.

**Monika** *et al.* [34]

In this paper, the authors presented the design, implementation and performance analysis of FWM in optical communication system. The system has been designed for different number of input channels like 2,4,6,8,12 input channels and for various values of channel spacing i.e., 6.25GHz, 12.3GHz, 25GHz, 40GHz, 50GHz. The results show that as the number of users/channels is increased, the interference also increases and thus, the four wave mixing effect also increases. The eye diagram becomes less clear with the increase in number of input channels. Also, it increases the BER and decreases the Q-factor. The authors thus concluded that the effect of FWM is minimum when there is least number of users.

**Xiadong He** *et al.* [35]

In this paper, the authors studied the channel capacity of the transmission system by using the Finite State Machine (FSM) approach for different modulation techniques. The NRZ-DPSK shows an improvement of at least 48% as compared to NRZ-OOK technique which makes it clear the NRZ-DPSK is more suitable for long haul transmission. When the nonlinearity is compensated, the increase in input power leads to the increase in channel capacity. The authors used Wiener filtering to further reduce the noise and to increase the channel capacity especially at lower power arrangement. The channel performs similar to linear Shannon system after Wiener filtering and compensating non linearity.

Table 2.1 Literature Survey

| TYPE | AUTHORS | WORK DONE | RESULTS |
|---|---|---|---|
| Suppression of non-linear phase noise | Takeshi Hoshida et al. | Use of intensity modulator at 75GHz spacing and 40Gbps bit-rate | Can transmit beyond 1000km as it has superior noise tolerance as compared to NRZ and CS-RZ |
| Suppression of non-linear phase noise | Keang-Po Ho | Compensation of nonlinear phase noise by received intensity | The transmission distance is doubled |
| Suppression of non-linear phase noise | S.L. Jensen et al. | Using mid-link spectral inversion (MLSI) | BER is improved by over two decades |
| Suppression of non-linear phase noise | Yufeng Shao et al. | Superimposing DPSK signals on dark RZ signals | Higher spectral efficiency, extinction ratio, reduced bandwidth |
| Suppression of non-linear phase noise | C. Stephan et al | Use of nonlinear optical loop mirror (NOLM) to suppress the nonlinear phase noise | Reduction in eye opening penalty of about 2dB |
| Suppression of non-linear phase noise | Xiaodong He et al. | Use of self adapting Wiener filtering | Increase of 48% in channel capacity as compared to OOK systems |
| Kerr nonlinearity | Hoon Kim et al. | Experimental study of performance degradation in DPSK system | PDF of nonlinear phase noise deviates from Gaussian distribution |
| Kerr nonlinearity | Yannick Keith Lize et al. | Use of Karkunen-Loeve expansion simulation | Offsetting FSR increases tolerance to chromatic dispersion without affecting the frequency offset penalty or the polarization mode |

| | | | |
|---|---|---|---|
| | | | dispersion tolerance |
| Kerr nonlinearity | Xiaolin Li et al. | Using Delay line interferometer with a free spectral range equal to the transmitted bit-rate | optimizing FSR along with optical filter bandwidth further enhances the tolerance of a system to the fiber Kerr nonlinearities |
| Using SOA | Wei Hong et al. | Investigation of the non linear phase noise for optical amplification using Semiconductor Optical Amplifier (SOA) for RZ-DPSK signal, considering both finite input OSNR and broadband ASE. | nonlinear phase noise contributed to the total phase noise in case of a noisy signal and this contribution was found to be larger if the SOA carrier lifetime is shorter |
| Using SOA | Sub Hur et al. | Designed a complete dynamic model of SOAs while considering the FWM effect with a modified TMM for evaluating the SOA-induced crosstalk and phase error. | The transmission performance of NRZ-DPSK signals was improved with a reservoir channel injection into SOAs because the SOA-induced phase-error was more predominant than the crosstalk by FWM. |

# CHAPTER-3

# INVESTIGATION OF IMPACT OF NON-LINEAR EFFECTS ON VARIOUS MODULATION TECHNIQUES AT DIFFERENT CHANNEL SPACING

Non return-to-zero (NRZ) technique is spectrally compact and has a very simple transmitter and receiver configuration. It turns out to be a good scheme for shorter transmission distances. Bit synchronous differential phase shift keying (DPSK) format has superior tolerance to fiber non-linear effects and optical noise. The main advantage of DPSK over NRZ is the constant transmission power in the channel when using DPSK as opposed to NRZ. The DPSK technique can eliminate SPM and XPM effects by taking advantage of this constant transmission power. The results show that the NRZ performs better for shorter system lengths but for long haul systems, DPSK is the better choice.

## 3.1 Introduction

An optical modulation technique is a method used to impose data signal on a carrier signal for transmission over optical fiber. A simple modulation technique is the on-off-keying (OOK) format that is of two types: return-to-zero (RZ) and non-return-to-zero (NRZ). Out of these two, NRZ modulation technique has been widely used in various communications systems because it is easy to generate, less costly and the signal bandwidth required is about 50% smaller than the RZ technique.

Chris Xu *et al.* [36] presented that the DPSK is being widely used for its high spectral efficiency in optical transmission. The DPSK has higher receiver sensitivity and is more tolerant to fiber nonlinearities. They explained a simple technique for estimation of the performance of phase-shift keying. They have also presented the techniques for further improving the performance of PSK in long distance transmissions.

Hoon Kim *et al.* [37] have experimentally reviewed the nonlinear phase noise in phase-coded transmission systems. They have described the measurements of nonlinear phase noise as well as its impact on 10-Gbps and 40-Gbps transmission systems.

J. P. Gordon et al. [38] explained that the conversion of amplitude to phase noise occurs due to the nonlinear Kerr effect in the transmitting fiber, which results in optimal phase noise performance. This limits the range of phase detection techniques to a few thousand kilometers at multi gigabit rates.

The main advantage of DPSK over NRZ is the constant transmission power in the channel when using DPSK as opposed to NRZ. The DPSK technique can eliminate SPM and XPM effects by taking advantage of this constant transmission power. The limitation of DPSK compared to NRZ is that the extra sensitivity due to phase modulation instability is being generated throughout the system.

The evolution of advanced modulation schemes like Differential Phase Shift Keying has engrossed significant importance as new alternatives to improve the capacity of fiber optical communication systems. But with every new alternative come new limitations. Fiber optical communication channels are limited by linear and nonlinear effects. Linear effects include polarization mode dispersion (PMD) and chromatic dispersion (CD). The variation in index of refraction of the optical fiber causes nonlinear impairments due to its dependence on the launched power. This phenomenon is called Kerr effect. Nonlinear impairments include self phase modulation (SPM), cross phase modulation (XPM) and four wave mixing (FWM).

In addition to these, due to the nonlinear interaction between the signal and the amplified spontaneous emission (ASE) emitted by the inline amplifiers the phase modulation also suffers the nonlinear phase noise, called Gordon–Mollenauer (GM) noise. Self-phase modulation converts the amplitude noise into phase noise due to the linear addition of ASE to the signal.

Another effect that aggravates the performance of a system is the combined SPM-GVD effect. The index of refraction depends on wavelength which leads to the Group Velocity Dispersion (GVD) which causes broadening of pulse and thus restricts the transmission distance because of inter-symbol interference (ISI). The index of refraction also depends on the intensity, causing SPM, i.e., it introduces chirp that causes pulse spectrum broadening. These phenomena limit the overall performance and the transmission rate of the optical communications; therefore it is very important to lessen these effects in fiber optic communications.

This chapter is divided into four sections. Section 3.2 describes the simulation model used to investigate the performance of two modulation techniques. Section 3.3 reports the results of the transmission performance for the two formats at different channel spacing and finally in section 3.4, conclusions are made.

## 3.2 Simulation Model

Fig.3.1 shows the simulation setup for investigating the performance of DPSK and NRZ formats in the presence of non linear phase noise caused by the Gorden-Mollenauer effect.
In case of NRZ, the continuous-wave (CW) OOK laser source is used to generate the optical signal and the source is driven by the amplitude modulator for 43-GHz NRZ data signal, while in the case of DPSK format, a phase modulator is used to modulate the phase of the original carrier derived from a CW laser source. NRZ data stream encoded differentially is used to drive this modulator. For differential encoding we use an exclusive-OR gate and one bit delay feedback loop. The two modulated signals are then passed through a channel consisting of five loops. Each loop has an SSMF followed by a DCF and an amplifier.

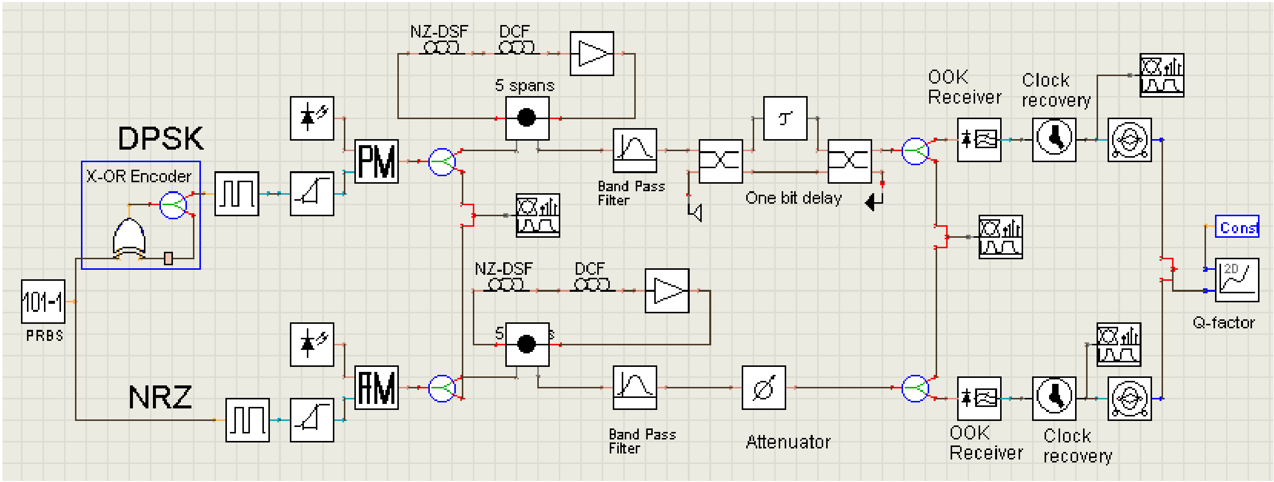


Fig 3.1. Simulation setup

The detection of NRZ is modest which requires a band pass filter and an OOK receiver as mentioned above in transmitter. For the detection of IM-DPSK signal, a Mach–Zehnder interferometer based delayed detector based is required at the receiver side. For conventional direct detection, this detector converts the phase information into the intensity information and then the signal can be retrieved by any usual receiver. In the MZI, the incoming signal is divided into two parts and one of them is allowed to pass as it is and the other one is delayed by one bit period, and then interference is done such that the bit is 1 if there is no phase difference and is zero otherwise.

Table 3.1. Fiber Parameters

| **Parameters** | **Value(universal fiber)** | **Value(DCF)** |
|---|---|---|
| Length | 90km | 4.6651 m |
| Group refractive index | 1.47 | 1.47 |
| Attenuation | 0.2dB/km | 0.6dB/km |
| Dispersion | 4.66*$10^{-6}$ s/$m^2$ | -90*$10^{-6}$ s/$m^2$ |
| Dispersion slope | 0.0114*$10^3$ s/$m^3$ | 0.21993*$10^3$ s/$m^3$ |
| Core area | 72*$10^{-12}$ $m^2$ | 80*$10^{-12}$ $m^2$ |

### 3.3 Results and discussion

Fig. 3.2 shows simulated optical spectra from the two transmitters. NRZ signal spectrum is compressed in its first order and pedestal sideband. This causes in a relatively small eye-opening penalty due to pass-band effect and neighboring channel crosstalk in 80-GHz-spaced WDM. Due to the inclusion of a residual carrier component, NRZ spectrum may suffer from FWM crosstalk generation with lower dispersion fibers.

DPSK signal spectrum does not have any line spectral components within the first-order sideband according to the nature of phase shift keying. This is beneficial in suppressing fiber nonlinear effects such as FWM and stimulated Brillouin scattering. Though having a broader first sideband, it suffers more from the optical filtering penalty in 80-GHz-spaced WDM.

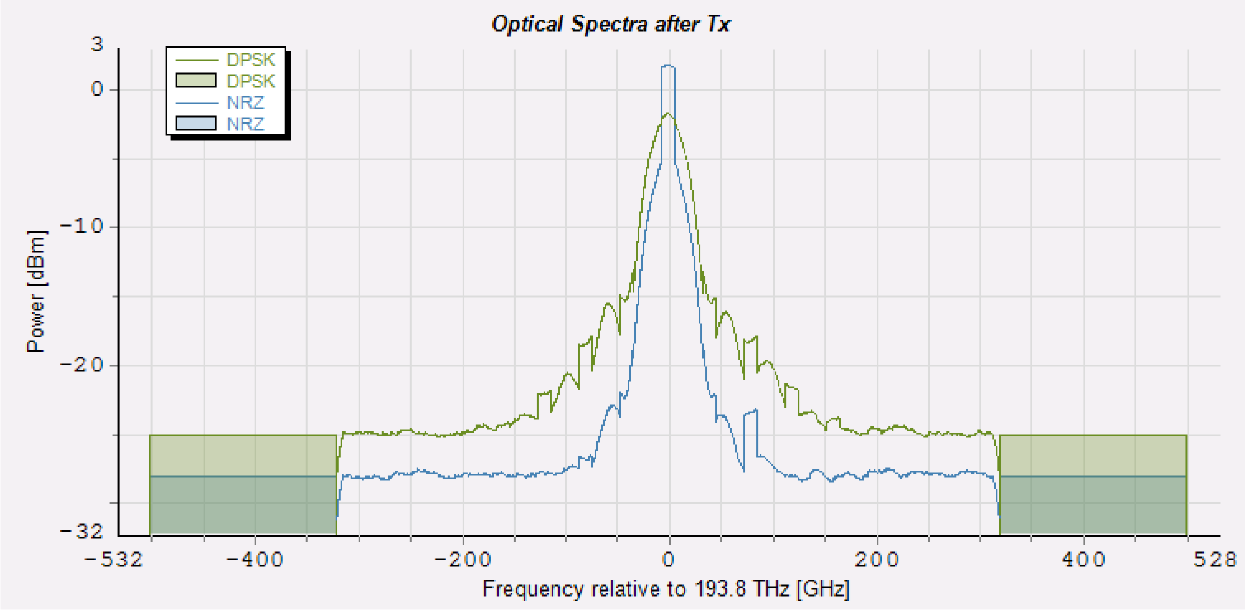


Fig 3.2. Simulated output spectra of NRZ and DPSK transmitters.

The eye diagrams of NRZ and DPSK format are shown in fig. 3.3(a) and 3.3(b) respectively. The eye diagram of NRZ technique is relatively less wide and open which shows its poor tolerance to the effects of nonlinearities. The main reason behind it being less wide and open is the existence of SPM-GVD effects in the fiber. Reducing the fiber input power to -2 dBm/ch, we can reduce the eye-opening penalty. According to the previous studies, this penalty is expected to be smaller in DPSK technique. We find that the results are in consistence with this expectation: DPSK format shows better nonlinear tolerance indicating its higher tolerance to both FWM and SPM-GVD effects.

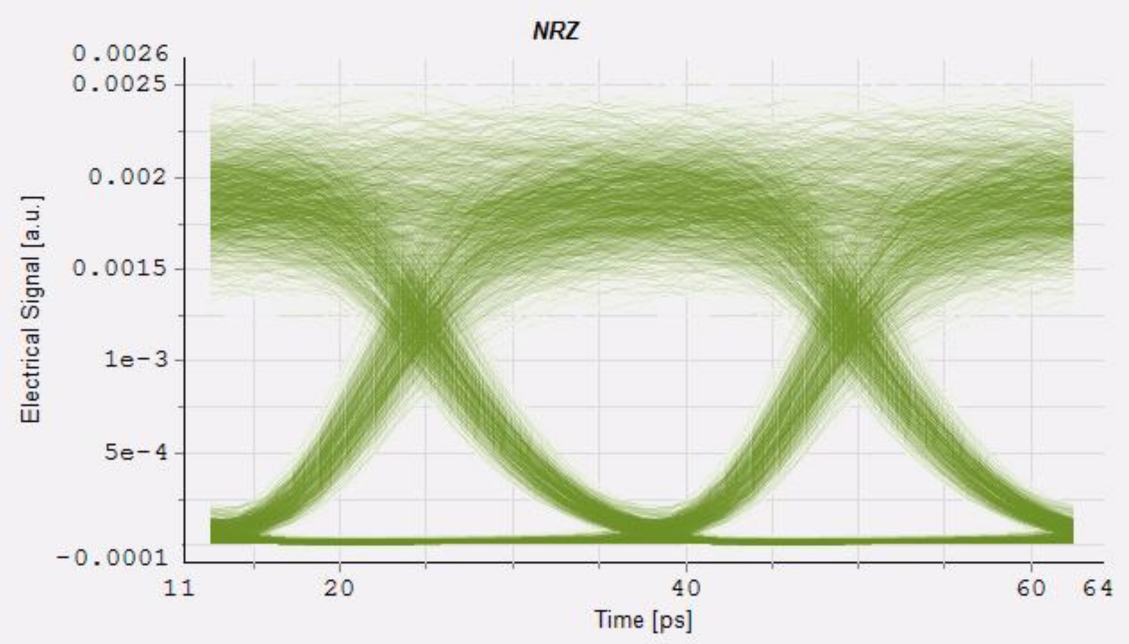


Fig. 3.3(a) Received eye diagram of NRZ format

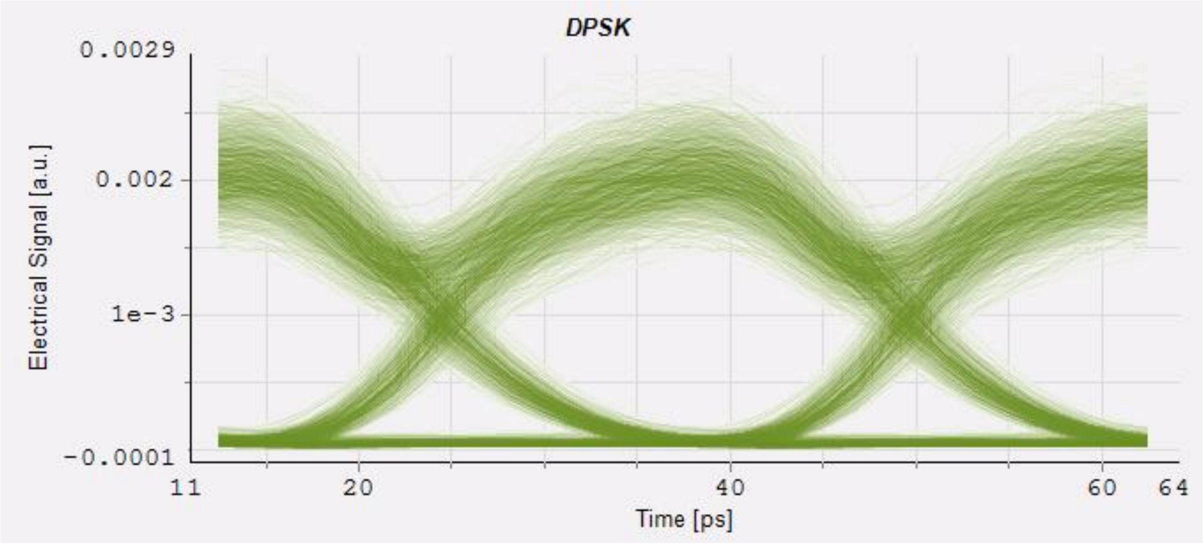


Fig. 3.3(b) Received eye diagram of IM-DPSK format

The BER and Q factor have been analyzed for various channel spacing, i.e., 20GHz, 40GHz, 60GHz, 80GHz. The results shown in fig. 3.4 and 3.5 depict that NRZ performs better for shorter system lengths. However, as the system length increases the Q factor for NRZ falls below that for DPSK. Similarly, the BER of DPSK is less than that of NRZ for higher transmission distance. This is a direct result of NRZ's higher sensitivity to non linear effects. This shows that the differential phase shift keying (DPSK) format has superior tolerance to fiber non-linear effects and optical noise. Hence, it can be considered as a better choice for long haul transmission systems.

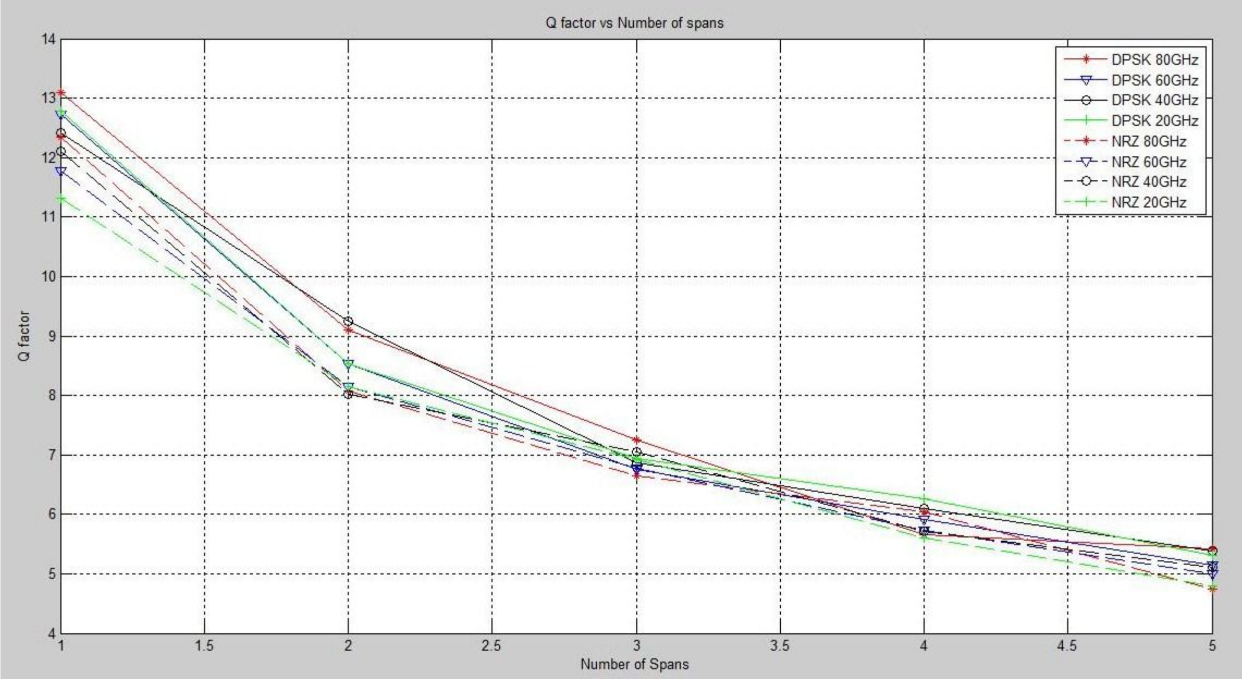


Fig 3.4. Q factor versus number of spans

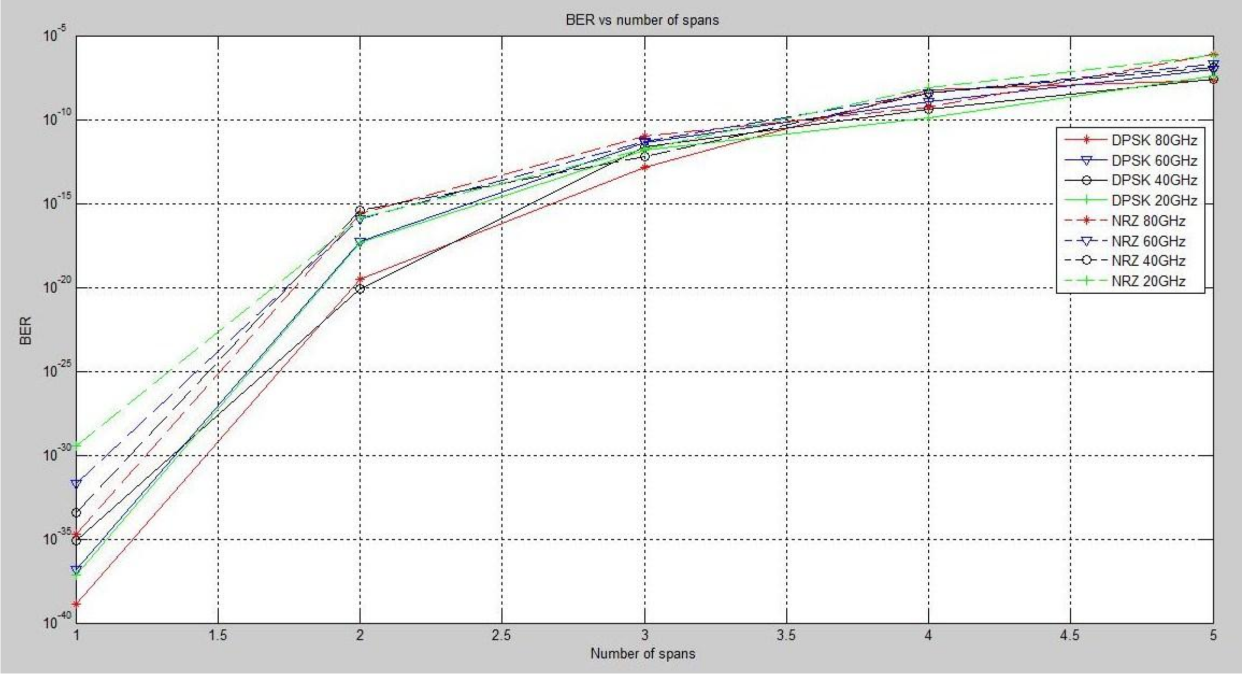


Fig 3.5. BER versus number of spans

### 3.4 Conclusion

This chapter has presented overall performance comparison of NRZ and DPSK modulation techniques in long-haul transmission. For the evaluation of Q-factor and BER a number of factors have been considered e.g. neighboring channel crosstalk, pass-band effects in optical filters, tolerances to optical noise and fiber nonlinear effects. Further, results divulge that NRZ performed better for shorter system lengths and made it attractive due to the advantages it offers like low-cost configuration, simple design. DPSK technique, in which SPM-GVD penalty was smaller as compared to the previous studies, in addition it had approximately 3 dB higher optical noise tolerance. Above results proved it an optimum modulation technique and thus it is one of the key enabling technologies for spectrally efficient ultralong-haul 40 Gb/s DWDM transmission systems.

# CHAPTER-4

# INVESTIGATION OF DIFFERENT INTENSITY MODULATORS USED IN IM-DPSK TECHNIQUE

In this chapter, the performance of two intensity modulators namely, Electro-absorption modulator (EAM) and Mach Zehnder modulator (MZM) used in the IM-DPSK technique has been investigated. The results have been reported by simulating IM-DPSK signals for 5*90km, by taking into account the penalties caused by non-linear effects in Q-factor. The Q-factor has been evaluated for three different kinds of fibers namely, SMF, NZ-DSF A, NZ-DSF B. The two systems using these modulators have been compared for different channel spacing. The plots of BER and Q-factor show that MZM performs better than EAM.

## 4.1 Introduction

Recently much interest has been shown in the advanced data modulation techniques in order to reduce the impairments in the system. Direct detection differential phase-shift-keying modulation has gained a lot of attraction in the recent past. This is accredited to the two main advantages provided by this modulation technique: improved immunity to the fiber nonlinear effects and better sensitivity at the receiver side. It has already been shown, through experiments and in theory, an optically pre-amplified DPSK-balanced receiver requires about half number of photons/bit compared to the ON–OFF-keying (OOK) technique [39], [40]. Thus, the required optical signal-to-noise ratio (OSNR) in DPSK systems is 3 dB less than the conventional OOK systems. Due to this improvement, the transmission distance is extended and the system margin is increased. It also allows lower fiber launch power to avoid the degradation of signals due to the fiber nonlinear effects. The DPSK system also has higher tolerance to fiber nonlinear effects such as cross-phase modulation besides the improved receiver sensitivity [41], [42]. The nonlinear impairment is reduced by the constant amplitude modulation which in turn reduces the nonlinear effects dependent on pattern.

To further improve the robustness of this transmission system, we can use the intensity modulation technique at the transmitter. In this technique, the intensity modulator is used to re-modulate the signal to be transmitted. This modulator is driven by clock signal which is synchronized with the data signal to curb the waveform degradation which is caused due to SPM-GVD effect. By using this technique, the optical intensity is attenuated at the bit transition points, which significantly reduces the effects of the frequency chirping [22].

Takeshi Hoshida *et al.* [22] compared three modulation techniques- CS-RZ, NRZ, IM-DPSK. The NRZ technique had a very simple transmitter and receiver design and was proved to be capable only for shoter distances i.e. less than 1000 km. the CS-RZ technique performed better than the NRZ counterpart but its transmission distance was bounded due to the four-wave mixing (FWM) effect. The Intensity-modulated DPSK (IM-DPSK) seemed to be the better option for long haul transmission i.e. for a distance beyond 1000 km.

Different intensity modulators have their own level of tolerating the optical noise and non linear effects. The two intensity modulators whose performance has been investigated in this paper are electro-absorption modulator (EAM) and Mach-Zehnder modulator (MZM). An electro-absorption modulator is a device made up of semiconductor material and uses an electric voltage modulate the intensity of a laser beam. The principle of operation of this modulator is based on the Franz–Keldysh effect which says that an applied electric field causes change in the absorption spectrum, which changes the band gap energy. These modulators can operate at very high speed with much lower voltages and are considered very useful in optical fiber communications because a very high modulation bandwidth (of tens of gigahertz) can achieved by using them. The Mach–Zehnder modulator splits the signal coming from a single source to determine the relative phase shift variations between these two collimated beams.

This chapter is divided into four sections. Section 4.2 describes the simulation model used to examine the performance of two modulators. Section 4.3 reports the results of the transmission performance for the two systems at different channel spacing and finally in section 4.4, conclusions are made.

### 4.2 Simulation Model

Fig.4.1 shows the simulation setup for investigating the performance of EAM and MZM in IM-DPSK technique in the presence of noise caused by nonlinear effects which is defined by the Gorden-Mollenauer effect. A phase modulator is used to modulate the phase of the original carrier derived from a CW laser source. NRZ data stream encoded differentially is used to drive this modulator. For differential encoding we use an exclusive-OR gate and one bit delay feedback loop.

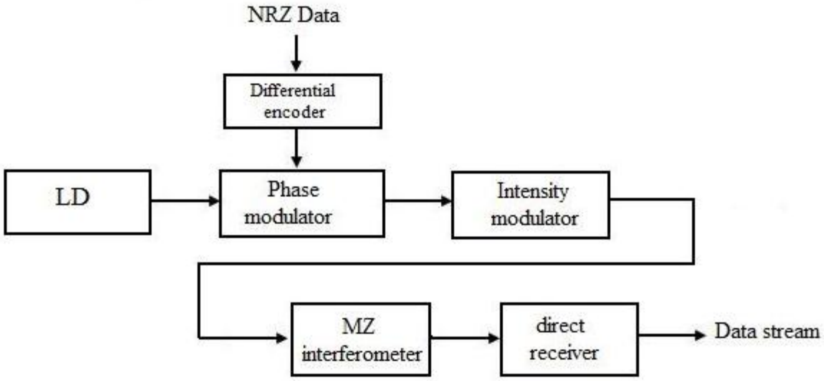


Fig 4.1. Simulation Setup

The modulated signal used here is a regular DPSK signal which is shown in Fig. 4.2. As shown in the figure, the phase of DPSK signal, at the transition point from 0 to 1, changes rapidly from 0 to π. This swift phase change, known as frequency chirping, is responsible for the appearance of intensity ripples due to CD. Chromatic dispersion in turn induces pattern-dependent SPM-GVD effect in the optical fiber used for transmission. This reduces the tolerance of nonlinear effects in a DPSK system.

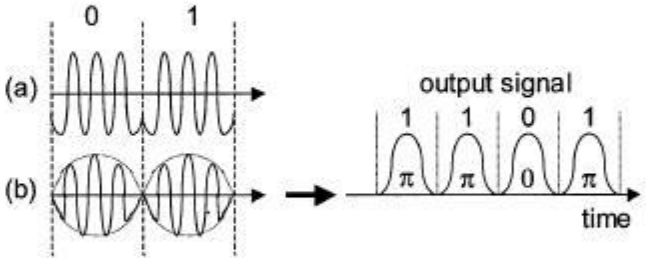


Fig 4.2. Data Signal

In IM-DPSK modulation technique, the intensity modulator is used to re-modulate the signal to be transmitted. This modulator is driven by clock signal which is synchronized with the data signal to curb the waveform degradation which is caused due to SPM-GVD effect. By using this technique, the optical intensity is attenuated at the bit transition points, which significantly reduces the effects of the frequency chirping.

For the detection of IM-DPSK signal, a Mach–Zehnder interferometer based delayed detector based is required at the receiver side. For conventional direct detection, this detector converts the phase information into the intensity information. In the MZI, the incoming signal is divided into two parts and one of them is allowed to pass as it is and the other one is delayed by one bit period, and then interference is done such that the bit is 1 if there is no phase difference and is zero otherwise.

### 4.3 Results and discussion

Eye diagram shows the width and height of the eye opening. When the received signal is clear, then width and height of the eye opening is large. The noise margin is represented by the height of the eye opening whereas time interval over which distortion-less received signal can be sampled is represented by the width of the eye opening. It is very much clear from fig. 4.3(a) and 4.3(b) that MZM performs better than the EAM modulator indicating its higher sensitivity and low thermal phase noise.

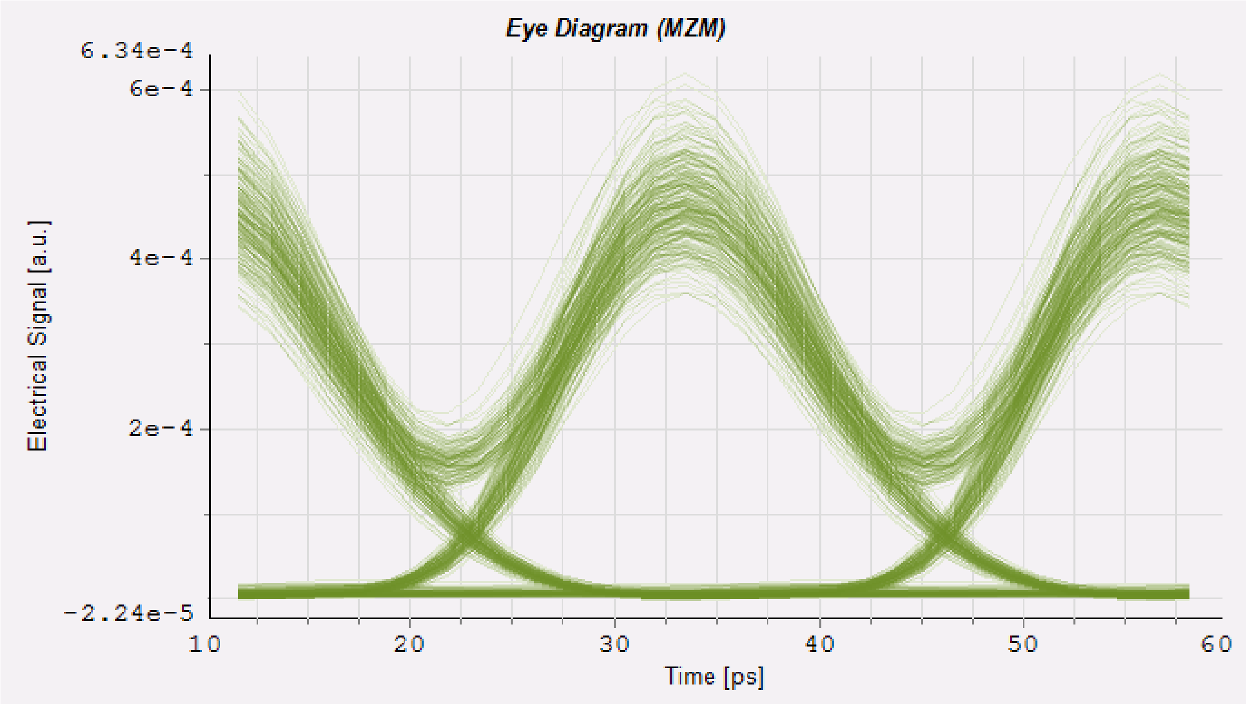


Fig. 4.3(a) Received eye diagram (using MZM)

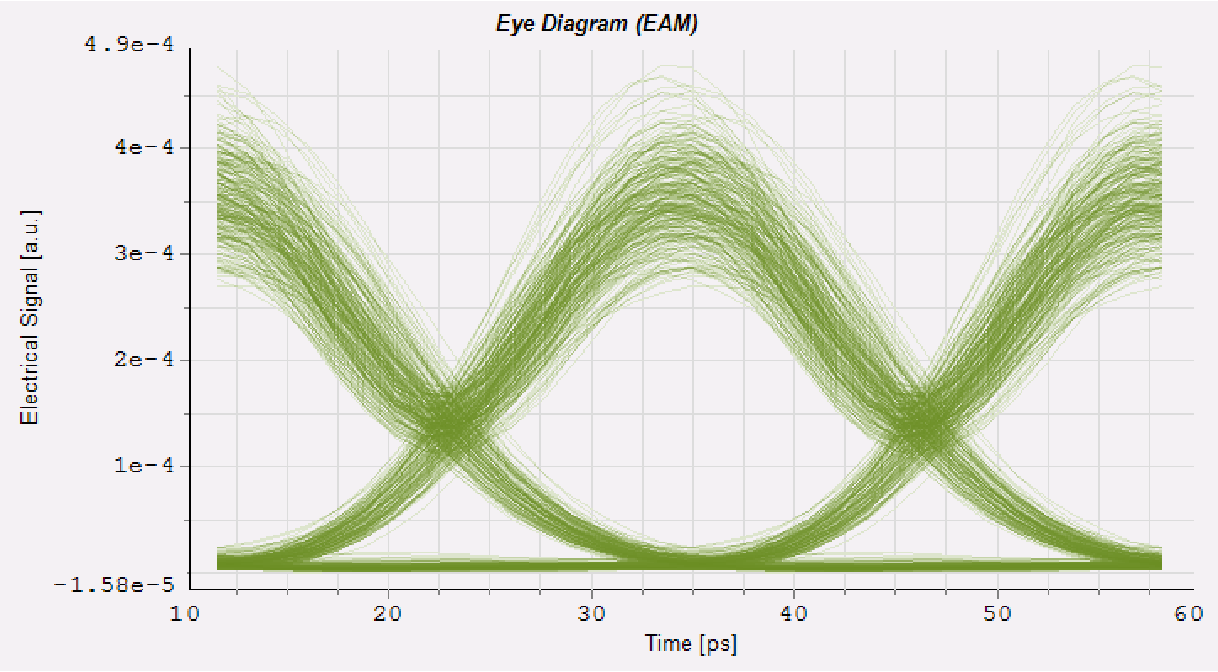


Fig. 4.3(b) Received eye diagram (using EAM)

Fig. 4.4 and 4.5 shows the plot of BER and Q factor respectively, both plotted against the transmission distance. The measurements of Q-factor and BER have been done for various channel spacing. We can see that MZM has lower BER as compared to EAM at every point of transmission.

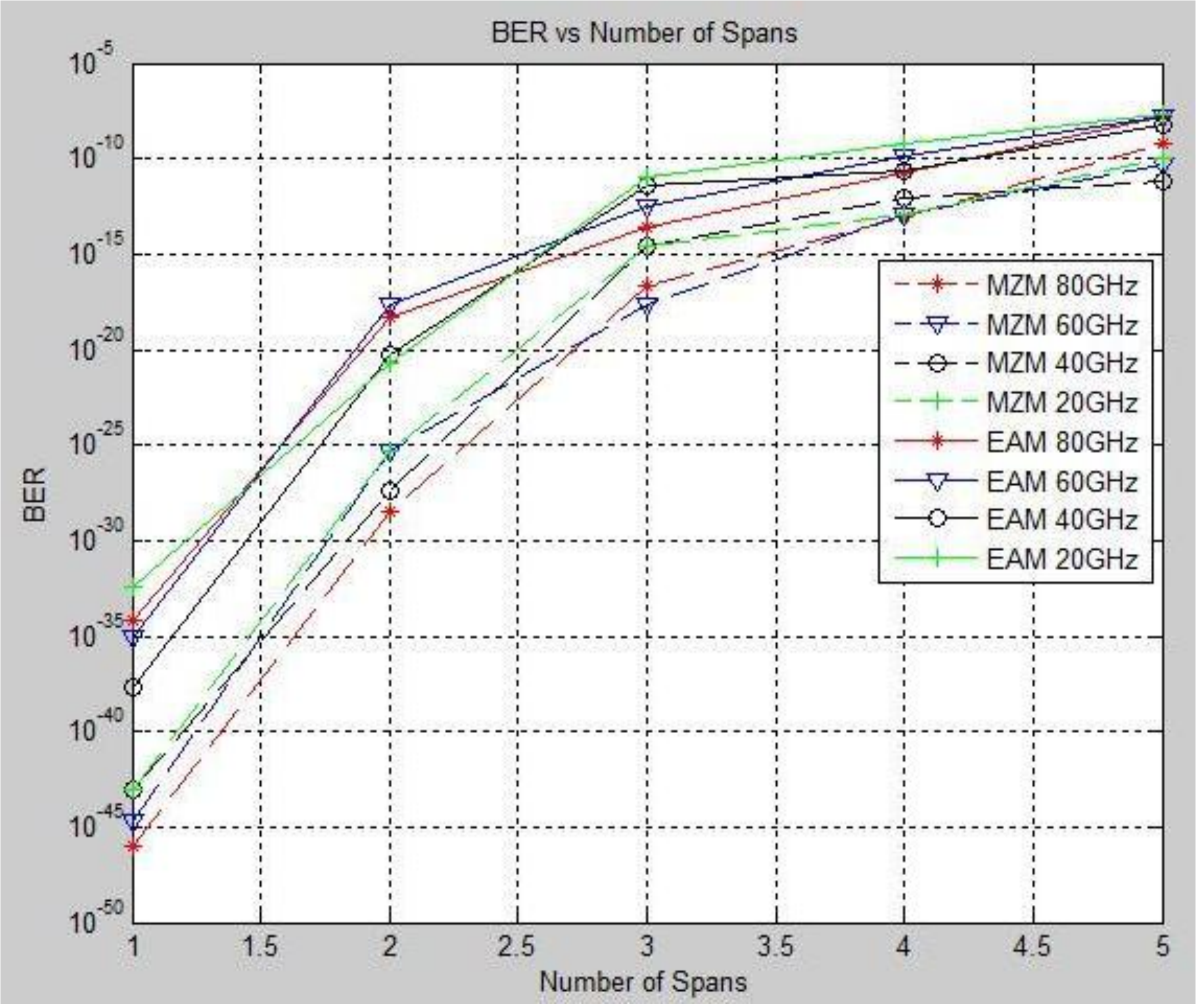


Fig 4.4. BER versus number of spans

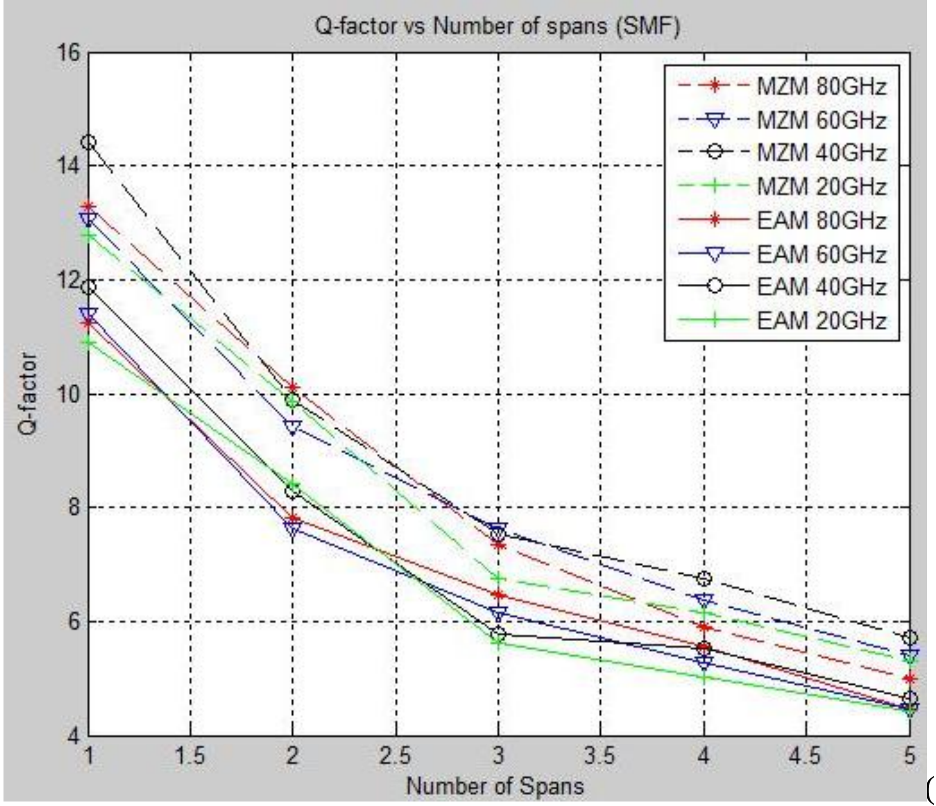
After the 1st span, the lowest BER is exhibited by MZM at 80GHz channel spacing and remains lowest even after traversing 180km of distance. After 3rd span, MZM at 60GHz spacing shows a BER of the power of $10^{-18}$ and after 4th span, the three of them show almost same BER i.e. $10^{-14}$. After travelling a total of 450km of distance, MZM shows best performance with a lowest BER of $10^{-12}$. At all the points the BER using MZM is lower than that exhibited by EAM.

The Q factor (shown in fig. 4.5(a),(b),(c)) of system was analyzed for three different fibers whose parameters have been listed in table 1.

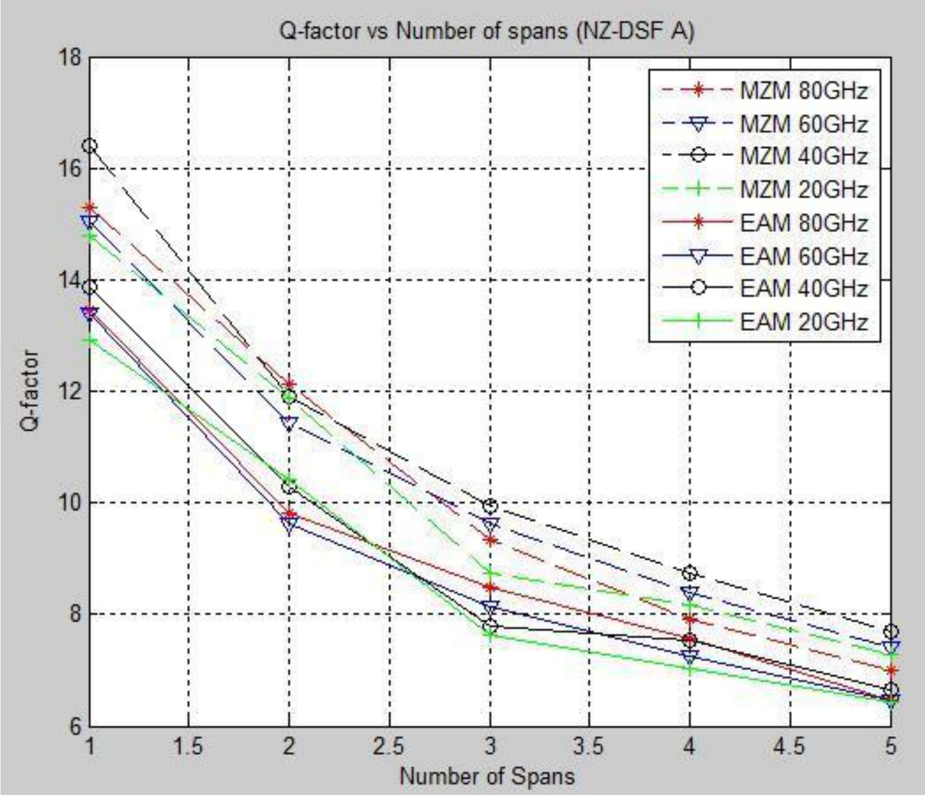
Table 4.1. Types of fibers

| | D (ps/nm/km) | S (ps/$nm^2$/km) | $A_{eff}$ ($\mu m^2$) | $n_2$ | A (dB/km) |
|---|---|---|---|---|---|
| SMF | 17 | 0.06 | 85 | 2.9 | 0.25 |
| DCF for SMF | -80 | -0.216 | 14.3 | 4.3 | 0.45 |
| NZ-DSF A | 8 | 0.06 | 65 | 2.6 | 0.25 |
| NZ-DSF B | 4 | 0.06 | 55 | 2.6 | 0.25 |
| DCF for NZ-DSF | -88 | -0.62 | 19.3 | 4.3 | 0.55 |

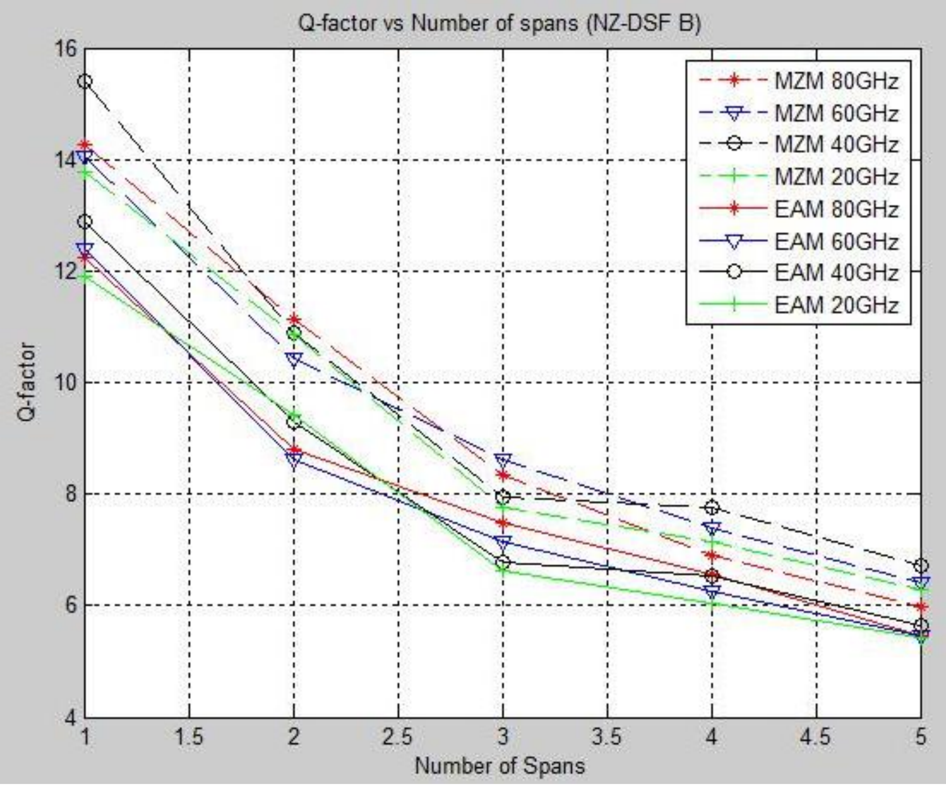
The results given below show that the NZ-DSF A gives the best Q-factor at every point of transmission. After passing through the 90km long fiber, this fiber shows a Q-factor of around 16 at 40GHz spacing. After the 2nd span, 80GHz spaced system shows a Q-factor of 11.12 closely followed by 20GHz and 40GHz spaced channels. After traversing a distance of 120km, the Q-factor of 40GHz spaced channel shows the best performance as can be seen in fig. 4.5(b).


Q-factor vs Number of spans (SMF)
Q-factor
Number of Spans
16
14
12
10
8
6
4
1
1.5
2
2.5
3
3.5
4
4.5
5
MZM 80GHz
MZM 60GHz
MZM 40GHz
MZM 20GHz
EAM 80GHz
EAM 60GHz
EAM 40GHz
EAM 20GHz

(a)


Q-factor vs Number of spans (NZ-DSF A)
Q-factor
Number of Spans
18
16
14
12
10
8
6
1
1.5
2
2.5
3
3.5
4
4.5
5
MZM 80GHz
MZM 60GHz
MZM 40GHz
MZM 20GHz
EAM 80GHz
EAM 60GHz
EAM 40GHz
EAM 20GHz

(b)



(c)

Fig 4.5. Q-factor versus number of spans (a) SMF (b) NZ-DSF A (c) NZ-DSF B

## 4.4 Conclusion

The overall performance comparison of MZM and EAM modulators in IM-DPSK modulation format using various channel spacing, i.e., 80GHz, 60GHz, 40GHz, 20GHz has been presented in this chapter. For the evaluation of Q-factor and BER a number of factors have been considered e.g. neighboring channel crosstalk, pass-band effects in optical filters, tolerances to optical noise and fiber nonlinear effects. MZM provides approximately 2dB lower BER after traversing a distance of 5*90km. The Q-factor of the two systems has been evaluated for three types of fibers namely, SMF, NZ-DSF A, NZ-DSF B and the best performance was given by NZ-DSF A fiber. The Q-factor remains high for the system using MZM at all the transmission points as compared to that exhibited by the one using EAM. The above results prove MZM to be a better choice for intensity modulation in IM-DPSK technique.

# CHAPTER-5

# USING MID-LINK SPECTRAL INVERSION TO REDUCE THE EFFECT OF NONLINEARITIES IN IM-DPSK TRANSMISSION SYSTEM

In this chapter, it is shown that in an IM-DPSK based transmission system the effects of non-linearities can be reduced by using a mid-link spectral inverter (MLSI). The BER has been measured at different channel spacing and by using different fibers in the channel. The results obtained by using the numerical simulations show that the use of mid-link spectral inverter (MLSI) gives over two decades better performance than the non-inverted signal. By using MLSI, the system becomes more tolerant to the effects of nonlinearities and is convenient to use since it reduces the need of OEO conversion.

## 5.1 Introduction

Recently a lot of interest has been shown in using advanced modulation techniques in order to reduce impairments in the system. One such technique is differential phase-shift-keying which has been very popular due to the various advantages it provides, like higher receiver sensitivity, robustness, and bandwidth efficiency [43, 44]. However, DPSK can be affected by nonlinear phase noise unlike the ON-OFF-keying (OOK) system. The amplified spontaneous emission noise from erbium doped fiber amplifiers causes changes in the optical intensity to be converted into phase fluctuations through the Kerr non linearity [38, 46]. This phase noise degrades the performance of DPSK transmission systems and is usually known as Gordon-Mollenauer noise.

The transmission length can be extended by using 2R regenerators. Unlike other techniques which depend on the amplitude of the transmitted signal, DPSK depends on the phase of the signal for information hence, its regeneration is non-trivial. It has already been shown in previous papers that using MLSI helps reducing the effects of nonlinearities [47]. It has been shown experimentally that intra-channel nonlinearities can be compensated by using mid link spectral inversion and allows to extend the transmission distance. Also, MLSI can restore the phase information from duo binary encoded signals [48].

Takeshi Hoshida *et al.* [22] compared three modulation techniques- NRZ, CS-RZ, IM-DPSK. The NRZ technique had a very simple transmitter and receiver design and was proved to be capable only for shorter distances i.e. less than 1000 km. the CS-RZ technique performed better than the NRZ counterpart but its transmission distance was limited by FWM. The Intensity modulated DPSK (IM-DPSK) seemed to be the better option for long haul transmission i.e. for a distance beyond 1000 km.

S.L. Jansen *et al.* [26] showed that inserting a mid-link spectral inversion reduces the effect of nonlinear phase noise for phase encoded modulation techniques like DPSK. This was proved by using an 800km standard single mode fiber in the channel. The results showed that when the transmitted OSNR was low, where the phase noise affects the signal strongly, the system showed a BER improvement of about 2dB. Therefore, by using this technology the impairments due to nonlinear phase noise are reduced which can be advantageous for long-haul transmission of data.

In [22], numerical simulations show that the quality of IM-DPSK signal suffers due to low tolerance to neighboring channel crosstalk, optical noise, fiber non-linear effects and pass-band effects in optical filters. In this paper, we use a mid-link spectral inversion in order to improve the quality of signal transmitted. The transmitted signal has been analyzed for various channel spacing to overcome the pass-band effects and neighboring channel cross talk. Three different fibers have been used in the channel namely, SMF, NZ-DSF A, NZ-DSF B and the results are given in the results section.

This chapter is divided into four sections. Section 5.2 describes the simulation model used to reduce the effect of non linearities using mid-link spectral inversion. Section 5.3 reports the results of the transmission performance for this system at different channel spacing, using different fibers and finally in section 5.4, conclusions are made.

## 5.2 Simulation Model

Fig. 1 shows the schematic of the transmitter of simulation model. A phase modulator is used to modulate the phase of the original carrier derived from a CW laser source. NRZ data stream encoded differentially is used to drive this modulator. For differential encoding we use an exclusive-OR gate and one bit delay feedback loop.

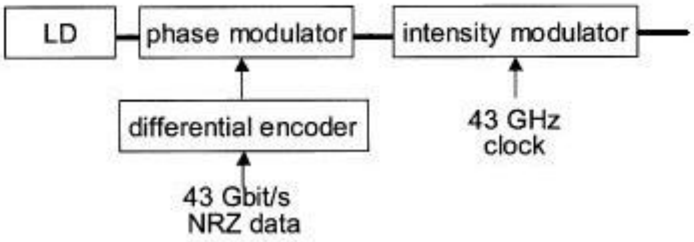


Fig 5.1. Transmitter

The modulated signal used here is a regular DPSK signal which is shown in Fig. 5.2. As shown in the figure, the phase of DPSK signal, at the transition point from 0 to 1, changes rapidly from 0 to π. This swift phase change, known as frequency chirping, is responsible for the appearance of intensity ripples due to CD. Chromatic dispersion in turn induces pattern-dependent SPM-GVD effect in the optical fiber used for transmission. This reduces the tolerance of nonlinear effects in a DPSK system.

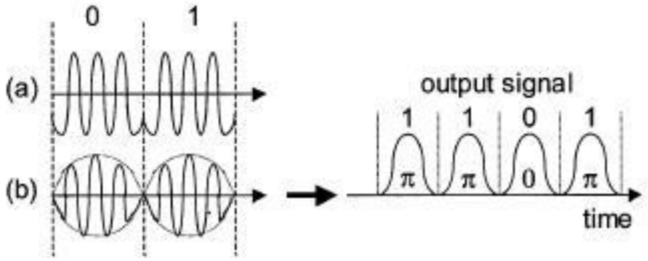


Fig 5.2. Data Signal

In IM-DPSK modulation technique, the intensity modulator is used to re-modulate the signal to be transmitted. This modulator is driven by clock signal which is synchronized with the data signal to curb the waveform degradation which is caused due to SPM-GVD effect. By using this technique, the optical intensity is attenuated at the bit transition points, which significantly reduces the effects of the frequency chirping.

In the middle of the transmission link, using FWM in a semiconductor optical amplifier spectral inversion is realized as shown in the figure 5.3. A pump signal from CW laser is combined with the data signal using a 3dB coupler and is then fed into SOA. In SOA, the incoming data signal is spectrally inverted by FWM product. The injection current of the SOA was set to 730mA. For pump signals, the input optical power into the SOA was 11dBm and the same for data signals was -1dBm. The optical power ratio between the converted and the input data signal, known as conversion efficiency, was -16dB on average. After conversion, the fiber Bragg grating (FBG) is used to remove the pump. The spectral components reflected from FBG are prevented from going back into the SOA by an isolator. Finally, a BPF is used to filter the converted data signal.

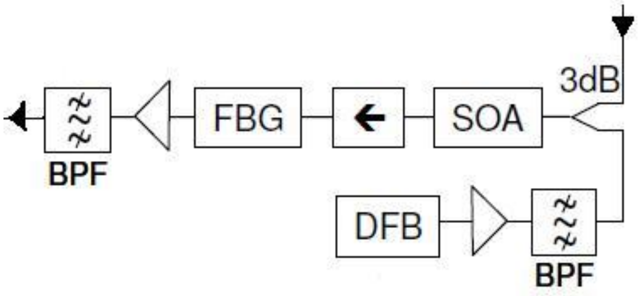


Fig 5.3. Spectral inverter

For the detection of IM-DPSK signal, a Mach–Zehnder interferometer based delayed detector based is required at the receiver side. For conventional direct detection, this detector converts the phase information into the intensity information. In the MZI, the incoming signal is divided into two parts and one of them is allowed to pass as it is and the other one is delayed by one bit period, and then interference is done such that the bit is 1 if there is no phase difference and is zero otherwise.

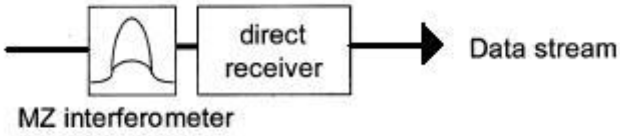


Fig 5.4. Receiver

### 5.3 Results and discussion

Eye diagram shows the width and height of the eye opening. When the received signal is clear, then width and height of the eye opening is large. The noise margin is represented by the height of the eye opening whereas time interval over which distortion-less received signal can be sampled is represented by the width of the eye opening. It is very much clear from fig. 5.5(a) and 5.5(b) that using mid link spectral inverter in IM-DPSK technique provides better results than the one without it.

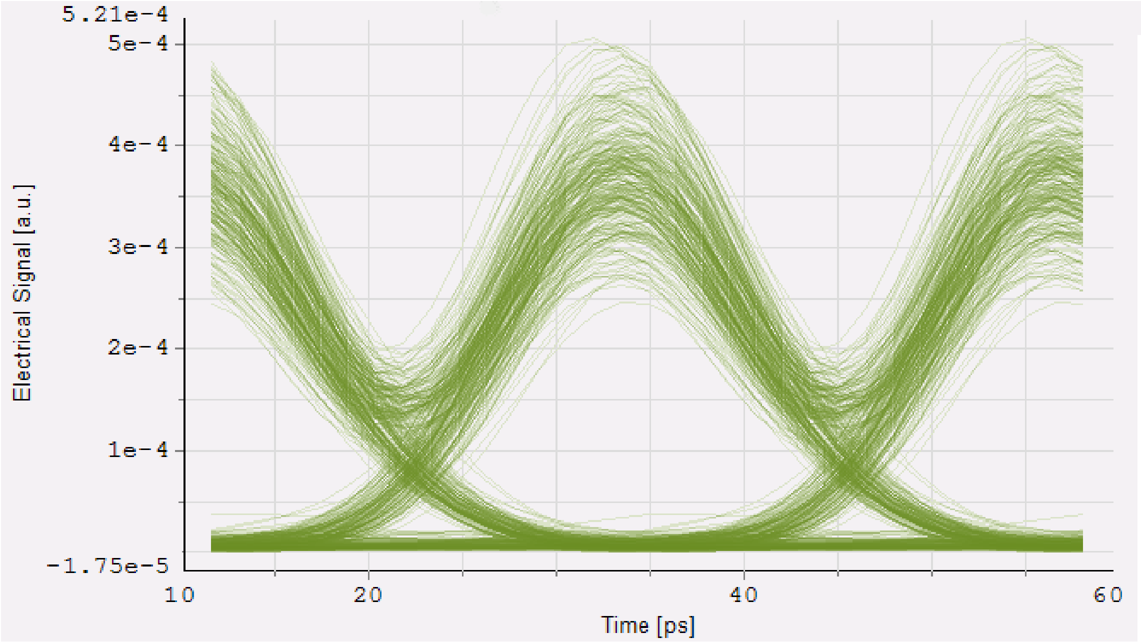


Fig. 5.5(a) Eye diagram without using MLSI

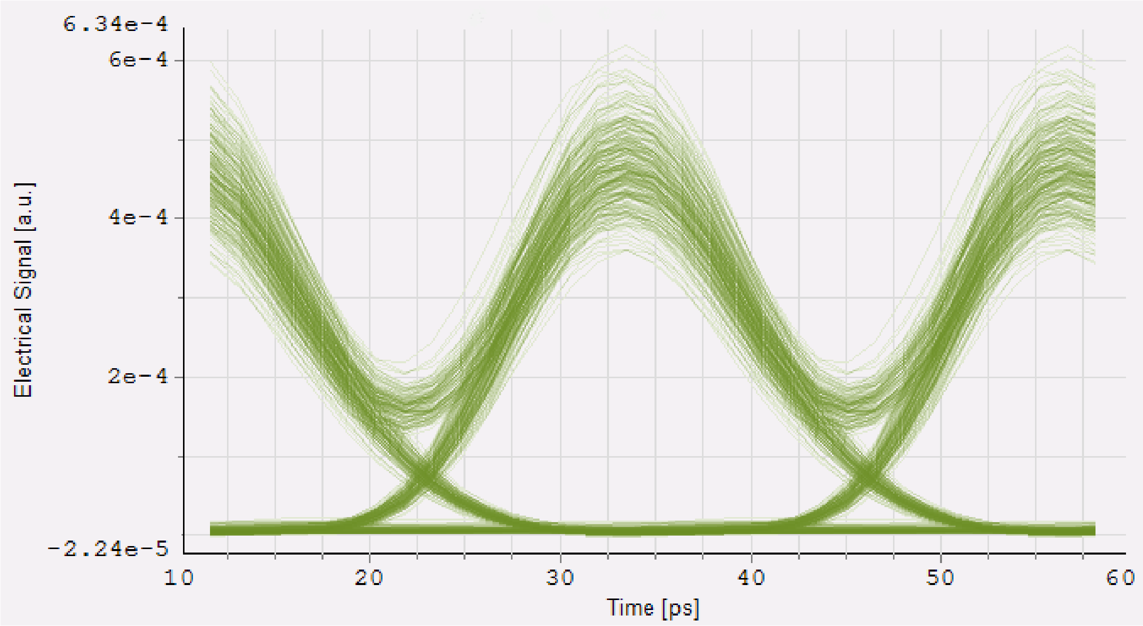


Fig 5.5(b) Eye diagram using MLSI

Fig. 5.6 shows the BER performance of the system, when MLSI is inserted in the middle of the link and compared to the case when it's not used. The measurements were carried out for three different fibers whose parameters have been given in table 5.1.

Table 5.1. Parameters of transmission fiber

| | D (ps/nm/km) | S (ps/$nm^2$/km) | $A_{eff}$ ($\mu m^2$) | $n_2$ | A (dB/km) |
|---|---|---|---|---|---|
| SMF | 17 | 0.06 | 85 | 2.9 | 0.25 |
| DCF for SMF | -80 | -0.216 | 14.3 | 4.3 | 0.45 |
| NZ-DSF A | 8 | 0.06 | 65 | 2.6 | 0.25 |
| NZ-DSF B | 4 | 0.06 | 55 | 2.6 | 0.25 |
| DCF for NZ-DSF | -88 | -0.62 | 19.3 | 4.3 | 0.55 |

From the figure 5.6 it can be observed that when the OSNR is low, the BER shows over 2dB improvement by using mid-link spectral inversion (MLSI) despite the fact that at these points the BER is very strongly affected by the Gordon-Mollenauer noise as compared to the higher OSNR values. When the transmitted OSNR is high, the BER is better without using the mid-link spectral inverter. This is due to the fact that at relatively high noise figure and the moderate conversion efficiency of the SOA, the maximum OSNR after the spectral inverter is 26dB. When the transmitted OSNR is high, the OSNR at the end of the spectral converter is lower as compared to when we do not use the converter. This is the reason for causing relatively more impairments in the remaining transmission link due to the higher nonlinear phase noise.

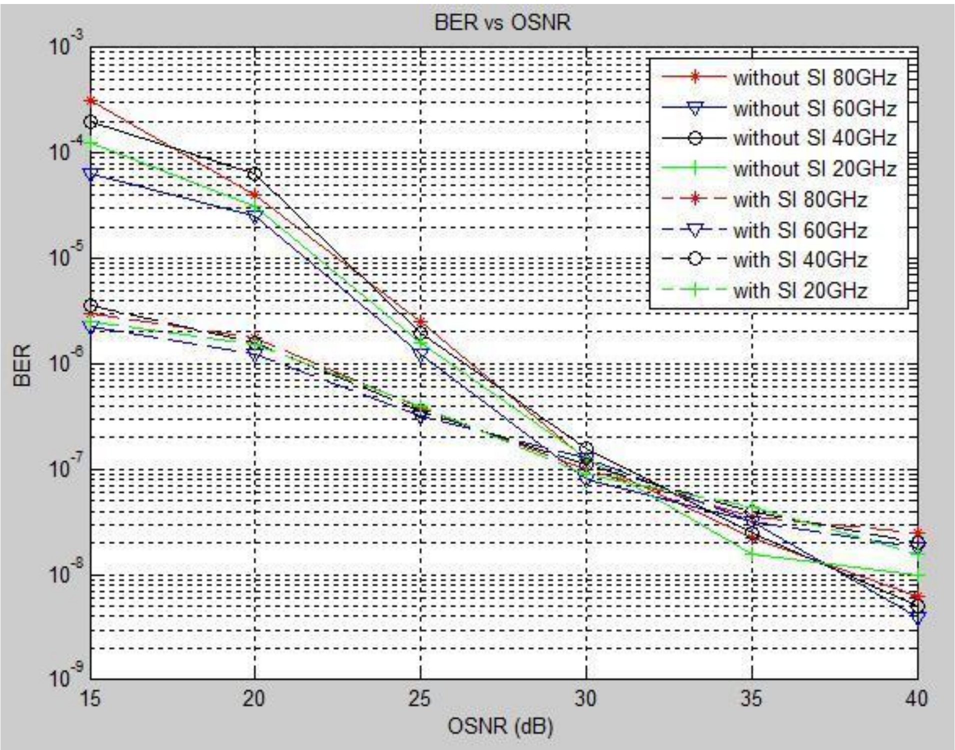


Fig. 5.6(a)

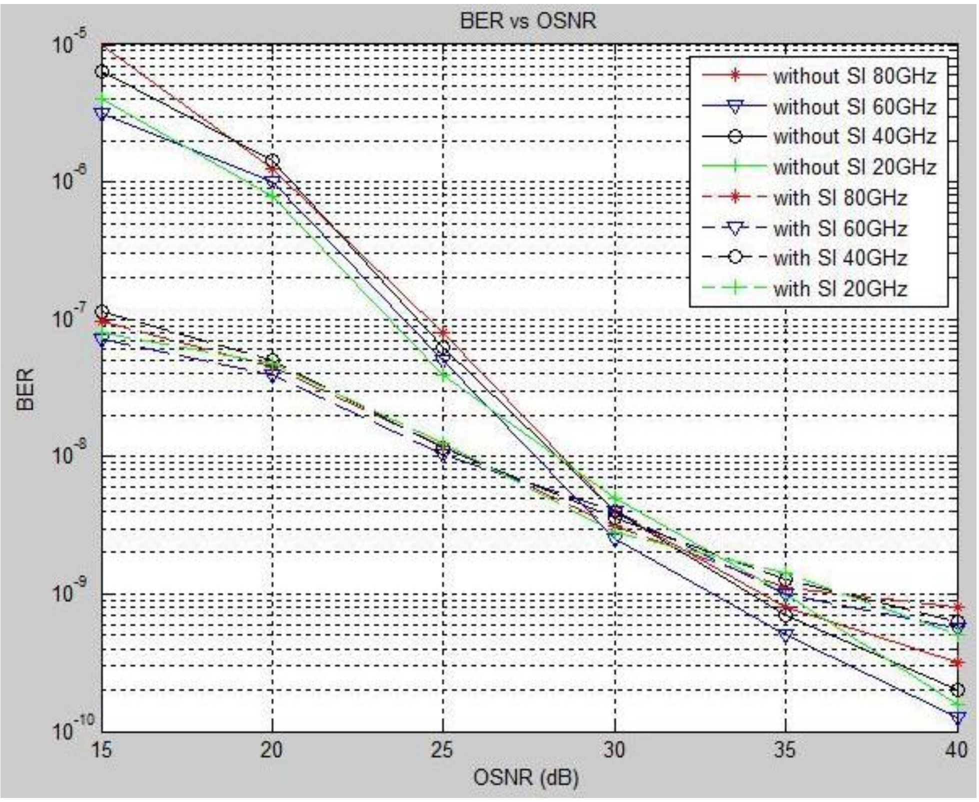


Fig. 5.6(b)

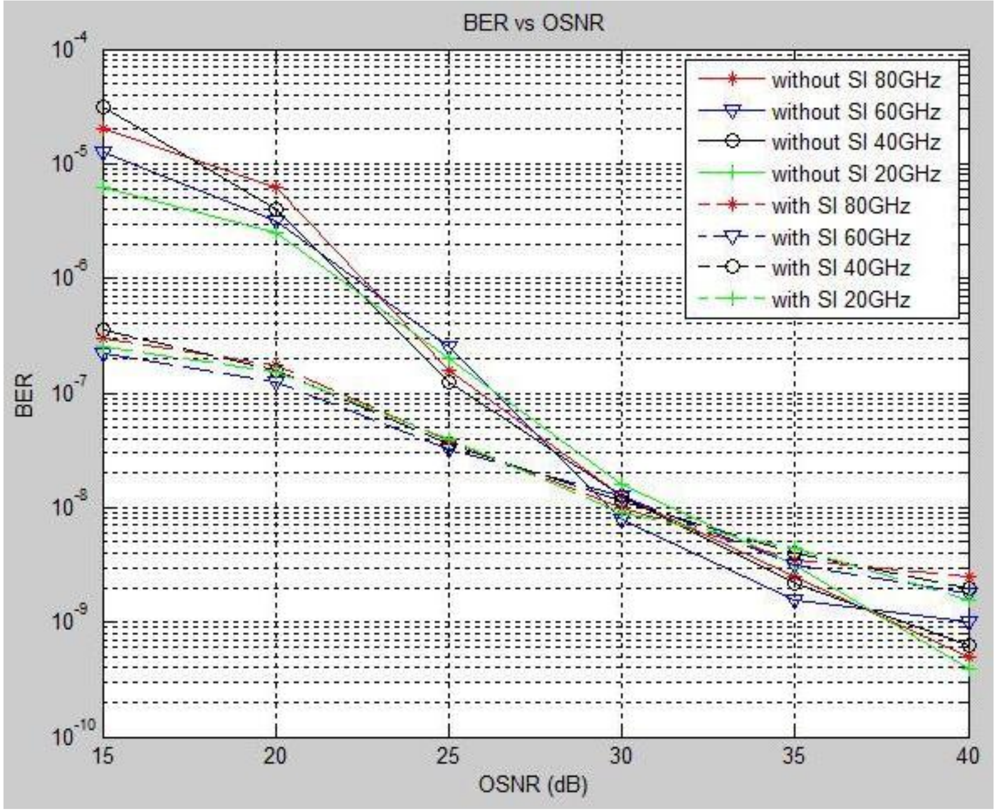


Fig. 5.6(c)

Fig 5.6. BER versus OSNR (a) SMF (b) NZ-DSF A (c) NZ-DSF B

### 5.6 Conclusion

In this chapter, it is shown that using MLSI in the middle of the transmission link reduces the effect of nonlinear phase noise in advanced phase shift keyed modulation techniques like DPSK,IM-DPSK. The BER measurements have been made at different channel spacings i.e. 80GHz, 60GHz, 40GHz, 20GHz. Three different fibers have been used in the channel, namely, SMF, NZ-DSF A, NZ-DSF B and the best performance was given by NZ-DSF A fiber. From the results we infer that when the OSNR is low, the BER shows over 2dB improvement by using mid-link spectral inversion (MLSI) despite the fact that at these points the BER is very strongly affected by the Gordon-Mollenauer noise as compared to higher OSNR. This technology reduces the degradation of signal due to nonlinearities in the fiber and can be advantageous since it reduces the need of OEO conversion.

# CHAPTER 6

# CONCLUSION, RECOMMENDATIONS AND FUTURE SCOPE

## 6.1 CONCLUSION

This chapter provides the summary of research work done in this dissertation. First the conclusions have been made from this study, then the recommendations have been given on the basis of the conclusions and then suggestions for future research are discussed. The major results obtained in this thesis are summarized below:

1. The overall performance comparison of NRZ and DPSK modulation techniques in long-haul transmission has been presented. For the evaluation of Q-factor and BER a number of factors have been considered e.g. neighboring channel crosstalk, pass-band effects in optical filters, tolerances to optical noise and fiber nonlinear effects. Further, results divulge that NRZ performed better for shorter system lengths and made it attractive due to the advantages it offers like low-cost configuration, simple design. DPSK technique, in which SPM-GVD penalty was smaller as compared to the previous studies, in addition it had approximately 3 dB higher optical noise tolerance. Above results proved it an optimum modulation technique and thus it is one of the key enabling technologies for spectrally efficient ultralong-haul 40 Gb/s DWDM transmission systems.

2. The comparison in the performance of MZM and EAM modulators in IM-DPSK modulation format using various channel spacing, i.e., 80GHz, 60GHz, 40GHz, and 20GHz has been presented. For the evaluation of Q-factor and BER a number of factors have been considered e.g. neighboring channel crosstalk, pass-band effects in optical filters, tolerances to optical noise and fiber nonlinear effects. MZM provides approximately 2dB lower BER after traversing a distance of 5*90km. The Q-factor of the two systems has been evaluated for three types of fibers namely, SMF, NZ-DSF A, NZ-DSF B and the best performance was given by NZ-DSF A fiber. The Q-factor remains high for the system using MZM at all the transmission points as compared to

that exhibited by the one using EAM. The above results prove MZM to be a better choice for intensity modulation in IM-DPSK technique.

3. It is shown that using MLSI in the middle of the transmission link reduces the effect of nonlinear phase noise in advanced phase shift keyed modulation techniques like DPSK, IM-DPSK. The BER measurements have been made at different channel spacing i.e. 80GHz, 60GHz, 40GHz, and 20GHz. Three different fibers have been used in the channel, namely, SMF, NZ-DSF A, NZ-DSF B and the best performance was given by NZ-DSF A fiber. From the results we infer that when the OSNR is low, the BER shows over 2dB improvement by using mid-link spectral inversion (MLSI) despite the fact that at these points the BER is very strongly affected by the Gordon-Mollenauer noise as compared to higher OSNR. This technology reduces the degradation of signal due to nonlinearities in the fiber and can be advantageous since it reduces the need of OEO conversion.

## 6.2 RECOMMENDATIONS

Based on the above conclusions, some recommendations have been made:

The DPSK technique, due to its many advantages, proves to be an optimum modulation technique and thus can be used for spectrally efficient ultra long-haul WDM transmission systems for bit-rate of 40Gbps with different channel spacing.

The Mach-Zehnder modulator proves to be a better choice for intensity modulation in IM-DPSK, and hence can be used for long haul transmission as it has higher tolerance to nonlinear effects as it is having its inherent advantage for 20 GHz channel spacing.

The mid-link spectral inversion can be used where higher nonlinear tolerance is required at low Optical signal to noise ratio. It also proves to be cost effective as it reduces the need of OEO conversion. Further, it can also reduce the complexity of the system.

## 6.3 FUTURE SCOPE

During the course of this dissertation, several avenues for continuation of this study became evident. The topics which were considered worthwhile are summarized below:

In this dissertation, the performances of NRZ and DPSK techniques have been analyzed. This analysis can be extended to other advanced modulation techniques and evaluated to see if they can tolerate nonlinear effects better than DPSK scheme.

The polarization effects have been neglected. Simulation studies can be done for same architectures while taking into account the polarization effects.

Only DCF has been used to compensate dispersion. Other compensation techniques can be used to improve results.

We have considered different channel spacing- 20GHz, 40GHz, 60GHz, and 80GHz. This channel spacing can be increased and the results can be observed.

In this design, transmission through single channel has been considered for different channel spacing. We can use multi channel transmission to reduce the BER and increase the Q-factor.

The different receiver filters can be compared on the basis of simulation results. It will be interesting to prove these results mathematically.

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# LIST OF PUBLICATIONS

[1] Navpreet Kaur Waraich, R.S. Kaler, "Investigation of impact of non-linear effects on various modulation techniques at different channel spacing" Communicated to Optik- International journal for light and electron.

[2] Navpreet Kaur Waraich, R.S. Kaler, "Investigation of different intensity modulators used in IM-DPSK technique" Communicated to Optik- International journal for light and electron.

[3] Navpreet Kaur Waraich, R.S. Kaler, "Using mid-link spectral inversion to reduce the effect of nonlinearities in IM-DPSK transmission system" Communicated to Optik- International journal for light and electron.