EFFECT OF XPM AND FWM ON THE PERFORMANCE OF M-ary WSK-DWDM TRANSMISSION SYSTEM

A thesis submitted in partial fulfilled of the requirements for the degree of

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in
Electrical and Electronic Engineering

By
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The thesis entitled **"EFFECT OF XPM & FWM ON THE PERFORMANCE OF M-ary WSK-DWDM TRANSMISSION SYSTEM"** submitted by A.K.M. Jahangir Alam Majumder, Roll no: 040306241P, Session: April 2003 has been accepted as satisfactory in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING.

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Declaration

This is to certify that this thesis titled "EFFECT OF XPM AND FWM ON THE PERFORMANCE OF M-ary WSK-DWDM TRANSMISSION SYSTEM" is the result of my study for partial fulfillment of M.Sc. Engg. Degree under the supervision of Dr, Satya Prasad Majumder, Professor, Department of Electrical and Electronic Engineering (EEE), Bangladesh University of Engineering and Technology (BUET), and it has not been submitted else where for any other degree or diploma.

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Abstract

Optical dense wavelength division multiplexing (DWDM) systems using low dispersion fibers and erbium-doped fiber amplifier (EDFA) are very attractive to meet up the growing demand for broadband information distribution networks. High data rates as well as long spans between amplifiers in a chain require high optical power per channel to satisfy the signal to noise ratio (SNR) requirements. For DWDM systems with long repeater-less spans, the simultaneous requirements of high launched power and low dispersion fibers lead to the generation of new waves by four-wave mixing (FWM) which limits the allowable power input to the fiber and these limits the transmission distance.

In this thesis work, performance analysis is carried out for a DWDM system with M-ary walength shift keying (M-WSK) modulation considering the effect of XPM & FWM in a SMF. A direct detection receiver model is developed which is based on Mach-Zehnder Interferometer (MZI) and Maximum Likelihood (ML) detection. Analysis is carried out to find the expression for the signal photo current, shot noise due to signal and FWM power and beat noise components resulting out of beating of signal and FWM during photo detection process. Analysis is extended to find the expression for the bit error rate (BER) of M-WSK direct detection receiver in presence of XPM & FWM. Further, forward error correction coding like convolution coding is applied to mitigate the effect of XPM & FWM.

Performance results are evaluated in terms of BER for different fiber length, input power and number of DWDM channels. Numerical results show that there is a significant reduction in the effect of FWM at higher order M-WSK system compared to binary. Significant amount of coding gain as well as increase in allowable input power are obtained due to rate-1/2 convolution coding compared to the system without coding.

The results of this thesis will find application in design of a DWDM system in presence of FWM.

Chapter 1

INTRODUCTION

1.1 Introduction to communication system

Communication is the process of transferring information or message like voice, video, text, data, picture, etc. from one distance to another.Communication is a technique/method by which two or more entities exchange their information. The function of communication system is to convey the signal from the information source over the transmission medium to the destination.

Basic operation of communication system:

Communication systems convert information into a format appropriate for the communication link. Analog communication systems convert (modulate) analog information signals into modulated signals, which are also analog. Digital communication systems convert information in the form of bits into digital signals.

Any communication system is composed of the following basic components, like source encoder, transmitter, channel, receiver, source decoder etc.

Source encoder:

Converts the source or input message into an analog signal or bits called the message signal.

Transmitter:

Converts the message signal into a modulated signal in a format suitable for transmission over the channel.

Channel:

Bridges the distance between the transmitter and receiver and introduces distortion and random noise. As signal propagates through the channel, it gets attenuated due to transmission loss and distortion due to various nonlinear effect and interference.

Receiver:

Receiver extracts the original message signal or bits from the channel output signal.

Source Decoder:

Converts the message signal or bits back into the format of the original message.

In general the information carrying capacity should be high so that it can meet the requirement of the user. The information carrying capacity is closely related to the bandwidth supported by the communication system. The greater the bandwidth, the higher is the information carrying capacity of the communication system. The system should be such that the information can be carried at an affordable cost and the quality of the message received at the destination is sufficiently free from noise and interference. In this respect optical fiber communication system has been developed.

1.2 Optical Communication

An optical communication system in which the carrier is an optical carrier from the optical frequency of the electromagnetic spectrum.

In optical communications the information source provides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of the light wave carrier. The optical source which provides the electrical-optical conversion may be either a semiconductor laser or light emitting diode (LED). The transmission medium consists of an optical fiber cable and the receiver consists of an optical detector which drives a further electrical stage and hence provides demodulation of the optical carrier. Photo diodes (p-n, p-i-n or avalanche) and, in some instances, phototransistors and photoconductors are utilized for the detection of the optical signal and the optical-electrical conversion. Thus there is a requirement for electrical interfacing at either end of the optical link and at present the signal processing is usually performed electrically.

Initially the input of digital optical link, digital signal from the information source is suitably encoded for optical transmission. The laser drive circuit directly modulates the intensity of the semiconductor laser with the encoded digital signal. Hence a digital optical signal is launched into the optical fiber cable. The avalanche photodiode (APD) detector is followed by a front-end amplifier and equalizer or filter to provide gain as well as linear signal processing and noise bandwidth reduction. Finally, the signal obtained is decoded to give the original digital information.

Optical transmitter

The heart of the transmitter is a light source. The major function of a light source is to convert an information signal from its electrical form into light. Today's fiber-optic communications systems use, as a light source, either Light-emitting diodes (LED s) or laser diodes (LDs). Both are miniature semiconductor devices that effectively convert electrical signals into light. They need power-supply connections and modulation circuitry. All these components are usually fabricated in one integrated package. This package is denoted as an optical transmitter.

The transmitter includes a light source, coupling optics, a signaling circuit and a power control circuit. All these components are packed into one module.

Data conversion unit

The transmitter's data conversion unit performs three major functions encoding, parallel-to-serial conversion and reshaping the electric format of the data. Encoding means representing data (binary numbers) in a physical format (pulses).This is necessary because data are transmitted in different line codes.

The need for encoding the incoming data and is to convert it into a simple yes-no format. This is the first function of the data-conversion unit and a specific encoder is used for this purpose. The sccond function of the data-conversion unit is parallel-to-serial conversion. Data enter in parallel but a laser diodc can bc driven only by serial pulses of modulation current. Thus a parallel-in serial-out converter (PISO), which is often called a multiplexer, is used to convert data into the serial format.

The third function of the data-conversion unit is reshaping the electric format of data. Either a comparator or the buffer can be used for this purpose. Let's consider a comparator with differential input (figure).This is a circuit that compares two input signals: data and complementary. If the data signal is higher than the complcmentary signal, the output becomes almost equal to V_{cc} that is, to the power-supply. On the other hand, if the complementary signal is higher, the output becomes almost zero. In other words, the comparator produces high-voltage or low-voltage signals in response to input logic 1 or logic 0, regardless of the level of the electric voltage of the input signals. A comparator can also be driven by a single-ended input. This circuit is used to make the output compatible with digital logic in the units that follow. In addition this circuit has high input impedance, which makes it a compatible load for the previous block, the multiplexer.

A buffer is a device that isolates the input from the output and amplifies the current while transferring the logic signal from the input to the output unchanged. Thus, a buffer can also serve to reshape the electric from of the input's logic signal. Which circuit needs to be employed-the comparator or the buffer-depends on the design of the specific transmitter.

Laser driver

Data prepared for light transmission pass into a laser driver. We need this circuit because a laser diode is a current-driven rather than a voltage-driven device. While the power supply is always a voltage source. Thus, the first function of a laser driver is to convert outside voltage into the current needed to drive the laser.

Driving current has to bias a laser diode to speed the modulation process. So another function of a laser driver is to provide a bias current. The real problem with bias current is that it has to be very stable with respect to threshold current-otherwise, an error in data transmission can occur. The main factor causing a change in thc relative value of threshold and bias currents is temperature.

1.2.1 Types of optical communication

Two types of optical communication:

(i) Free Space Optical Communication

(ii) Optica fiber communication

(i) Free Space Optical Communication (FSO)

Free Space Optics (FSO) is a telecommunication technology that uses light propagating in free space to transmit data between two points. The technology is useful where the physical connection of the transmit and receive locations is difficult, for example in cities where the laying of fibre optic cables is expensive. Free Space Optics is also used to communicate between space-craft, since outside of the atmosphere there is little to distort the signal. The optical links usually use infrared laser light, although low-data-rate communication ovcr short distances is possible using LEDs. IrDA is a very simple form of free-space optical communications. Distances up to the order of 10 km are possible, but the distance and data rate of connection is highly dependent on atmospheric conditions.

Applications

Typically scenarios for application are:

-LAN-to-LAN connections on campuses at Fast Ethernet or Gigabit Ethernet speeds.

-LAN-to-LAN connections in a city. example, Metropolitan area network.

-To cross a public road or other barriers which the sender and receiver do not own.

-Speedy service delivery of high bandwidth access to fiber networks.

-Converged Voice-Data-Connection.

- Two solar-powered satellites communicating optically in space via lasers.
- Temporary network installation (for events or other purposes).
- Reestablish high-speed connection quickly (disaster recovery).
- As an alternative or upgrade add-on to existing wireless technologies.
- As a safety add-on for important fiber connections (redundancy).
- For communications between spacecraft, including elements of a satellite constellation.
- The light beam can be very narrow, which makes FSO hard to intercept, improving security. In any case, it is comparatively easy to encrypt any data traveling across the FSO connection for additional security. FSO provides vastly improved EMI behavior using light instead of microwaves.

(ii) Fiber Optic Communication

Fiber-optic communication is a method of transmitting information from one place to another by sending light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information. First developed in the 1970s, fiber-optic communication systems have revolutionized the telecommunications industry and played a major role in the advent of the Information Age. Because of its advantages over electrical transmission, the use of optical fiber has largely replaced copper wire communications in core networks in the developed world.

The process of communicating using fiber-optics involves the following basic steps: Creating the optical signal using a transmitter, relaying the signal along the fiber, ensuring that the signal does not become too distorted or weak, and receiving the optical signal and converting it into an electrical signal.

Applications

A mobile fiber optic splice lab being used to access and splice underground cables.

Optical fiber is used by many telecommunications companies to transmit telephone signals, Internet communication, and cable television signals. Due to much lower attenuation and interference, optical fiber has large advantages over existing copper wire in long-distance and high-demand applications. However, infrastructure development within cities was relatively difficult and time-consuming, and fiber-optic systems were complex and expensive to install and operate. Due to these difficulties, fiber-optic communication systems have primarily been installed in long-distance applications, where they can be used to their full transmission capacity, offsetting the increased cost.

Since 1990, when optical-amplification systems became commercially available, the telecommunications industry has laid a vast network of intercity and transoceanic fiber communication lines. By 2002, an intercontinental network of 250,000 km of submarine communications cable with a capacity of 2.56 Tb/s was completed, and although specific network capacities are privileged information, telecommunications investment reports indicate that network capacity has increased dramatically since 2002.

1.2.2: Types of optical fibers

The two classes of fiber used in telecommunications are multimode fiber (MMF) and single-mode fiber (SMF).

Multimode Fiber

- MMF is a fiber that supports multiple "lanes" of light.
- Multiple electromagnetic transmission modes are carried on MMF.
- Each lane is a different speed so that a pulse of light gets distorted sooner than in SMF.

Single-Mode Fiber

- One "lane" of light with minimum distortion

There are many types of MMF and SMF. For telecommunications transmission, the Characteristics of the two main varieties of SMF.

The three main groups include

• Non–dispersion-shifted fiber (NDSF), standard single-mode fiber (SMF or SSMF); the dispersion zero point is near 1310 nm λ

• Dispersion-shifted fiber (DS) has a zero point around 1550 nm λ

• Non–zero dispersion-shifted fiber (NZ-DSF) has a zero point around other λs.

The detailed list of fibers includes

• SMF or SSMF
- Corning SMF-28
- Lucent SMF
• DSF
- Corning SMF/DS
- Lucent DSF
• NZ-DSF
- Lucent True Wave® Classic
- Lucent True Wave Plus
- Lucent True Wave RS (Reduced Slope)
- Corning LS
- Corning LEAF® (Large Effective Area Fiber)
- Alcatel TeraLight

1.2.3: Optical Sources

In most optical communication systems, semiconductor light sources are used to convert electrical signals into light. Optical sources for wireless transmission must be compatible to overcome the atmospheric effects and they should be such that one can easily modulate the light directly at high data rates. Generally either LASERs or LEDs are used in optical communication systems.

Light Emitting Diode (LED)

Light emitting diodes (LEDs) used in optical communication system are the same as visual display LEDs except that they operate in the infra-red region and with many times higher intensity of emission. When the p-n junction is forward biased, photon emission takes place due to recombination of electron-hole pair. The wavelength of emission will depend on the energy gap.

Laser

Laser stands for "light amplification by stimulating emission of radiation". Compared to LED, a laser has wider bandwidth, higher power output, higher modulation efficiency, narrower spectral linewidth and narrower emission pattern. Laser sources are much brighter than LEDs.

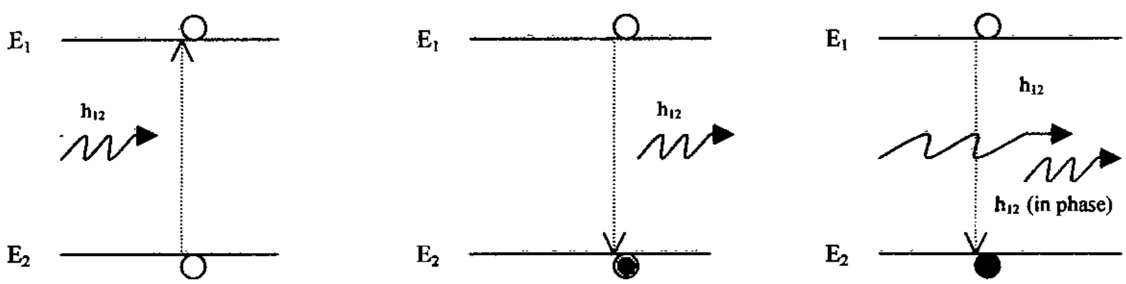


Figure 1.1: The three keys transition process involved in laser action

Figure 1.1: The three keys transition process involved in laser action. The open circle represents the initial state of the electron and the heavy dot represents the final state. Incident photons are shown on the left of each diagram and emitted photons are shown on the right.

Laser action is the result of three key processes. These are photon absorption, spontaneous emission and stimulated emission. These three processes are represented by the simple two energy-level diagrams in Fig. 1.1, where E_1 is the ground-state energy and E_2 is the excited state energy. According to Planck's law, a transition between these two states involves the absorption or emission of a photon energy $h\upsilon_{12}=E_2-E_1$. Normally the system is in the ground state. When a photon of energy $h\upsilon_{12}$ impinges on the system, an electron in state E_1 can absorb the photon energy and be excited to state E_2 and is called absorption. Since this is an unstable state, the electron will shortly return to the ground state, thereby emitting a photon of energy $h\upsilon_{12}$. This occurs without any external stimulation and is called spontaneous emission. The emissions are isotropic and of random phase and, thus, appear as a narrowband Gaussian output. When a photon of energy $h\upsilon_{12}$ impinges on the system while the electron is in excited state, the electron is immediately stimulated to drop to the ground state and give off a photon of energy $h\upsilon_{12}$. This emitted photon is in phase with the incident photon and the resultant emission is known as stimulated emission.

In thermal equilibrium, the density of excited electrons is very small. Most photons incident on the system will, therefore, be absorbed, so that stimulated emission is essentially negligible. Stimulated emission will exceed absorption only if the population of the excited states is greater than that of ground state. This condition is called population inversion. Since this is not an equilibrium condition, population inversion is achieved by various "pumping" techniques. In a semiconductor laser, population inversion is accomplished by injecting electrons into the material at the device contacts to fill the lower energy states of the conduction band. In solid-state lasers like the ruby laser or Neodymium laser, light from a powerful source is absorbed in the active medium and increases the population of a number of higher energy levels. In gas lasers a similar met stable level is preferentially populated with the help of electronic excitation.

1.2.4 Optical Detectors

The key component of an optical receiver is its photo detector. The major function of a photo detector is to convert an optical information signal back into an electrical signal(photocurrent).The photo detector in today's fiber-optic communication systems is a semiconductor photodiode(PD).This miniature device is usually fabricated together with its electrical circuitry to form an integrated package that provides power-supply connections and signal amplification.

An optical detector is a photon (light) to electron converter. Avalanche photo-diode (APD) and positive intrinsic negative (PIN) diode are the most commonly used detectors. The most important thing of the optical communication system is that the spectral response of both the source and the detector must be same, otherwise efficiency will suffer.

PIN diode

PIN is the simplest optical detector. It is composed of an n^+ substrate, a lightly doped intrinsic region and a thin p zone. Operated with a reverse bias, mobile carriers leave the p-n junction producing a zone of moderate electric field on both sides of the junction into the intrinsic region. As it only lightly doped, this field extends deeply. Incident light power is mainly absorbed in the intrinsic region, causing electron hole pairs to be generated. These carriers are separated by the influence of the electric field in the intrinsic region and represent a reverse diode current that can be amplified.

Avalanche Photo Diode (APD)

It is the second popular type of photo detector and has the advantage of internally multiplying the primary detected photocurrent by avalanche process, thus increasing the signal detection sensitivity. But some noises are also generated here.

The frequency response of both PIN and APD are similar, making them both suitable up to 1 GHz. The main advantage of APD over PIN diode is greater gain bandwidth product due to the inbuilt gain. Silica is the material used at short wavelength (< 1 nm), GE, InGaAsP and AlGaAsP becoming popular at the longer wavelength around 1.3 μm.

1.3 Review of Previous Works

Optical dense wavelength division multiplexing (DWDM) systems using low dispersion fibers and erbium-doped fiber amplifier (EDFA) are very attractive to meet up the growing demand for broadband information distribution networks. A large number of wavelength channels, operating at 10 Gb/s, can be multiplexed at several gigahertz intervals if fiber low dispersion region around 1.55μm (~ 12.5 THz bandwidth) is fully utilized [1-3]. High data rates as well as long spans between amplifiers in a chain require high optical power per channel to satisfy the signal to noise ratio (SNR) requirements. For DWDM systems with long repeater-less spans, the simultaneous requirements of high launched power and low dispersion fibers lead to the generation of new waves by four-wave mixing (FWM) [4-5]. The XPM & FWM is the dominant nonlinear effect that severely degrades the performance of a multi channel transmission system. Several methods have been proposed to mitigate the effect of FWM crosstalk, namely, arrangement of transmission fiber dispersion, unequal channel spacing (US) scheme, repeated unequal channel spacing (RUS) scheme, wavelength Shift Keying (WSK)[6-8]. The improvement of WSK-WDM system relative to conventional on-off wavelength division multiplexing (WDM) system has been studied [8]. The works on WSK-WDM considered only binary WSK although M-ary WSK (M>2) schemes have higher spectral efficiency than binary WSK system. In the above research works, the impact of four wave mixing (FWM) and cross phase modulation (XPM) on M-ary WSK-WDM uncoded system performance has not been considered while mitigating the effect of FWM. It is, therefore, very much important to include the effect of FWM as the performance of a M-ary WSK-WDM system is highly dependant on the interplay between the cross-phase modulation (XPM) and four-wave mixing (FWM) in a normal dispersive fiber as well as in a dispersion shifted fiber (DSF) [9-11].

1.4: Objectives of this thesis

The main objective of the this research is to analyze an optical M-ary WSK-DWDM system considering the combined influence of cross phase modulation (XPM) and four-wave mixing (FWM) in dispersive and non-dispersive fiber medium. To carry out analysis to find the signal distortion as well as the crosstalk due to XPM & FWM considering a direct detection M-ary WSK receiver. To extend the analysis to find signal to crosstalk ratio and Bit Error Rate (BER) and to evaluate the BER performance results numerically considering SMF and DSF at bit rate at and above 10 Gb/s for determining the effect of crosstalk due to influence of XPM & FWM limitations on channel separation imposed by XPM & FWM, and induced crosstalk. Finally, to evaluate optimum system design parameters such as maximum number of wavelength channels per fiber, optimum channel separation, maximum bit rate, transmission rate for a specific BER of 10^{-9}.

1.5 Contribution of this Work

A new receiver architecture will be proposed for detection and demodulation of an optical M-ary WSK signals. The receiver will be a direct detection maximum likelihood (ML) estimator type based on Mach Zehnder Interferometer (MZI). Considering the above receiver architecture, analysis will be carried out to find the expression for the output currents, receiver noise components and crosstalk arising out of the XPM & FWM as well as beating of signal current and crosstalk current in the photo detector. Analysis will be carried out to find the expression for BER for multi-channel DWDM transmission system, considering influence of XPM & FWM in terms of fiber parameters, channel separation, bit rate, fiber length etc. Performance results will then be evaluated by numerical computations. From the BER performance results, power penalty suffered by the system due to combined influence of XPM and FWM will be determined. Further, optimum system design parameters such as allowable number of DWDM channel per fiber, allowable fiber dispersion, optimum channel separation etc. will be determined for different M-ary WSK-DWDM system(such as M=4,8,16 etc.), at a specific value of system BER (say 10^{-9}).

1.6 Organization of the Thesis

Chapter 1 gives a brief overview of a communication system and description of different optical communication link. The background and objective of the thesis are also presented in chapter 1.

Chapter 2 gives a comparative description of WDM with different multiplexing/multiple access technologies. The concept of OTDMA, OCDMA, SCM-OC and different nonlinear effect (SPM, XPM, and FWM) are also described in this chapter.

In chapter 3 the performance analysis of binary WSK-DWDM and M-ary WSK-DWDM systems are carried out considering the effect of XPM & FWM. In this chapter we present the block diagrams of the systems under consideration. Analysis is carried out for the BER performance of the system with XPM & FWM and extended to a system with convolution coding. The analysis is extended to M-ary WSK-DWDM system for uncoded and coded system with XPM & FWM effect.

In chapter 4 we perform numerical computations to evaluate the performance results of the systems described in chapter 3. Different BER plots are shown and results are presented and compared.

Chapter 5 concludes the thesis by discussing the contribution of this worked and some of the expected problems and scope for further research.

Chapter 2

MULTIPLEXING SCHEMES AND NONLINEARITIES IN OPTICAL COMMUNICATION

2.1 Introduction

This chapter highlights different multiplexing techniques and technical details of WSK-DWDM technology. The overview of diversity, OTDM, OCDMA and SCM-OC technology are presented in this chapter. With the increase of data rates on optical fiber, transmission length, number of channels and optical power levels, non linear effects of fiber becomes dominant. The overview of different fiber nonlinearities are also presented in this chapter.

2.2 Multichannel Communication systems

The huge potential bandwidth of optical fiber can be afficiently utilized by multiplexing a number of channels and transmitting them through the fiber simultaneously. The transmission bandwidth of fiber is divided into a number of nonoverlapping frequency (or wavelength) bands and each of these bands is associated to support a single communication channel. Two principle kinds of multichannel systems are common in practical applications, namely, frequency division multiplexing (FDM) and wave length division multiplexing (WDM). The two schemes differ from each other in respect of transmitter/receiver configuration.

2.2.1 Wavelength Division Multiplexing (WDM)

WDM is a technique which allows the simultaneous transmission of multiple signals down a single optical fiber. Current deployment trends involve transmitting 64+ individual signals down a single fiber.

In fiber-optic communications, wavelength-division multiplexing (WDM) is a technology which multiplexes multiple optical carrier signals on a single optical fiber by using different wavelengths (colors) of laser light to carry different signals. This allows for a multiplication in capacity, in addition to making it possible to perform bidirectional communications over one strand off fiber.

The term wavelength-division multiplexing is commonly applied to an optical carrier (which is typically described by its wavelength), whereas frequency-division multiplexing typically applies to a radio carrier (which is more often described by frequency). However, since wavelength and frequency are inversely proportional, and since radio and light are both forms of electromagnetic radiation, the two terms are closely analogous.

A WDM system uses a multiplexer at the transmitter to join the signals together and a demultiplexer at the receiver to split them apart. With the .right type of fiber it is possible to have a device that does both simultaneously, and can function as an optical add-drop multiplexer.

It is expected that WDM will be one of the methods of choice for future ultra-high bandwidth multichannel systems. Of course, this could be changed as the technology evolves. As explained before, WDM enables the utilization of a significant portion of the available fiber bandwidth by allowing many independent signals to be transmitted simultaneously on one fiber, with each signal located at a different wavelength. Routing and detection of these signals can be accomplished independently, with the wavelength determining the communication path by acting as the signature address of the origin, destination or routing. Components are therefore required that are wavelength selective, allowing for the transmission, recovery, or routing of specific wavelengths.

The WDM system can be:

(i)Unidirectional and

(ii) Bidirectional.

<u>Unidirectional WDM Link:</u>

Unidirectional WDM, shown in figure 2.1 device is used to combine different signal carrier wavelengths onto a single fiber at one end and separate them onto their corresponding detectors at the other end. Here MUX combine all of the signals and create a composite signal. This signal passes through the optical fiber. And DMUX separate them. Then at the receiver we get all the signals individually.

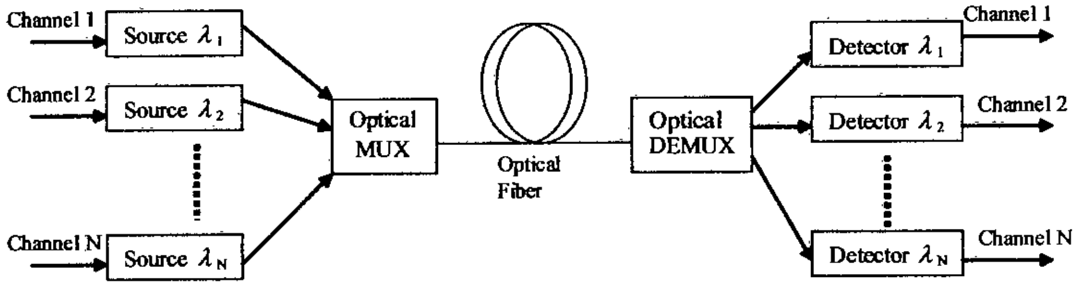


Fig 2.1: Block diagram of a simple unidirectional WDM system

Bi-directional WDM Link:

In Bidirectional WDM two or more waves are transmitted simultaneously over the same fiber which is shown in figure 2.2. It involves sending information in one direction at a wavelength λ_1 and simultaneously transmitting data in the opposite direction at a wavelength λ_2. That means information can be transmitted in both direction simultaneously. There causes no interfere because uplink and downlink wavelength is different.

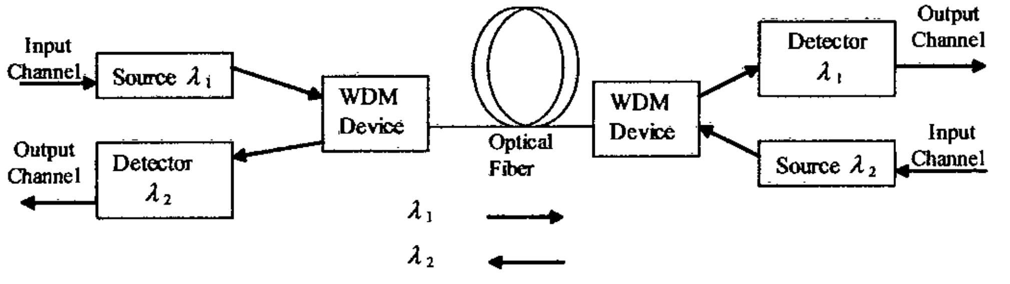


Fig 2.2: Block diagram of a simple bi-directional WDM system

WDM systems are classified into two market segments. They are:

(a) Coarse WDM (CWDM)

(b) Dense WDM (DWDM)

CWDM and DWDM technology are based on the same concept of using multiple wavelengths of light on a single fiber, but the two technologies differ in the spacing of the wavelengths, number of channels, and the ability to amplify signals in the optical space.

Coarse WDM (CWDM)

Systems with fewer than eight active wavelengths per fiber are generally considered as Coarse WDM (CWDM) systems. Originally, the term "Coarse Wavelength Division Multiplexing was fairly generic, and meant a number of different things. In general, these things shared the fact that the choice of channel spacing and frequency stability was such that Erbium Doped Fiber Amplifiers (EDFA s) could not be utilized. Prior to the relatively recent ITU standardization of the term, one common meaning for Coarse WDM meant two (or possibly more) signals multiplexed onto a single fiber, where one signal was in the 1550-nm band, and the other in the 1310-nm band.

Recently the ITU has standardized a 20 nanometer channel spacing grid for use with CWDM, using the wavelengths between 1310 nm and 1610 nm. CWDM wavelengths below 1470 nm are considered ', unusable" on older G.652 spec fiber, due to the increased attenuation in the 1310-1470 nm bands. Newer fiber which conform to the G.652.C and G.652.D standards, such as Corning SMF-28e and Samsung Wide pass nearly eliminate the "water peak" attenuation peak and allow for full operation of all twenty ITU CWDM channels in metropolitan networks.

Dense WDM (DWDM)

Systems with more than eight active wavelengths per fiber are generally considered as Dense WDM (DWDM) systems. Dense Wavelength Division Multiplexing or DWDM for short, refers originally to optical signals multiplexed within the 1550nm band so as to leverage the capabilities (and cost) of erbium doped fiber amplifiers (EDFAs), which are effective for wavelengths between approximately 1530 nm and 1560 nm. EDFAs were originally developed to replace SONET optical-electrical-optical (OEO) regenerators, which they have made practically obsolete. EDFAs can amplify any optical signal in their operating range, regardless of the modulated bit rate. In terms of multi wavelength signals, so long as the EDFA has enough pump energy available to it, it can amplify as many optical signals as can be multiplexed into its amplification band (though signal densities are limited by choice of modulation format). EDFAs therefore allow a single-channel optical link to be upgraded in bit rate by replacing only equipment at the ends of the link, while retaining the existing EDFA or series of EDFAs along a long haul route. Furthermore, single-wavelength links using EDFAs can similarly be upgraded to WDM links at reasonable cost. The EDFAs cost is thus leveraged across as many channels as can be multiplexed into the 1550-nm band. Figure2.2.5. shows a simple DWDM communication system.

DWDM channel spacing governs system performance; 50 GHz and 100 GHz outline the standards of ITU channel spacing. Currently, 100 GHz is the most commonly used and reliable channel spacing. This spacing allows for several channel schemes without imposing limitations on available fiber amplifiers. However, channel spacing depends on the system's components.

DWDM systems are significantly more expensive than CWDM because the laser transmitters need to be significantly more stable than those needed for CWDM. Precision temperature control of laser transmitter is required in DWDM systems to prevent "drift' off a very narrow centre wavelength. In addition, DWDM tends to be used at a higher level in the communications hierarchy, for example on the Internet backbone and is therefore associated with higher modulation rates, thus creating a smaller market for DWDM devices with very high performance levels, and corresponding high prices. In other words, they are needed only in small numbers and it is therefore not possible to amortize their development cost amongst a large number of transmitters. Recent innovations in DWDM transport systems include pluggable and software-tunable transceiver modules capable of operating on 40 or 80 channels. This dramatically reduces the need for discrete spare pluggable modules, when a handful of pluggable devices can handle the full range of wavelengths.

2.2.2 Frequency Division Multiplexing (FDM)

In FDM the optical channel bandwidth is divided into a number of non overlapping frequency bands and each signal is assigned one of these bands of frequencies. The individual signal can be extracted from the combined signal by appropriate electrical filtering or optical filtering at the receiver terminal. Hence FDM is usually done electrically at the transmit terminal prior to intensity modulation of a single optical source.

In both cases point-to-point and broadcast communication are possible. But FDM is costly. WDM has simpler and cheaper receiver circuit than FDM.

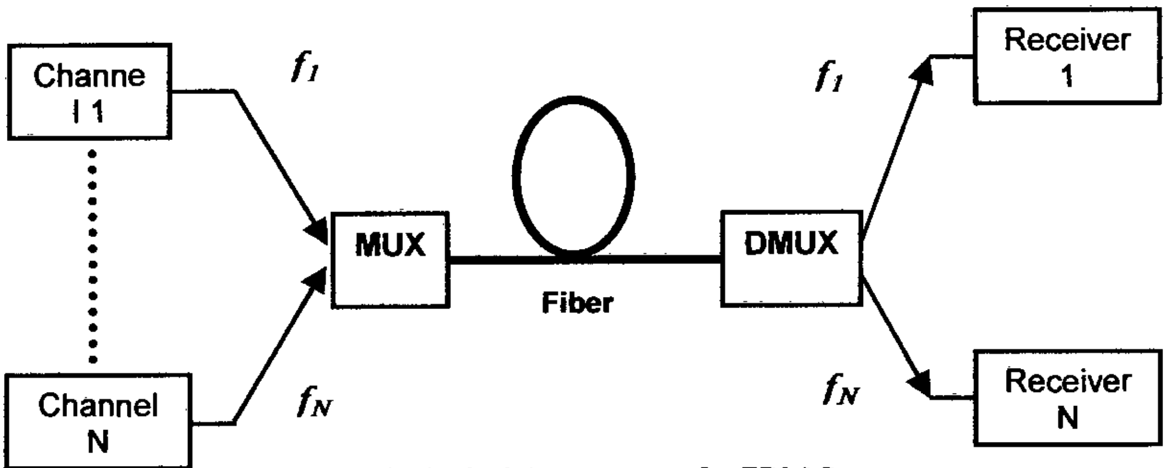


Fig 2.3: Typical Arrangement for FDM System

2.2.3 Optical Time-division multiplexing (O-TDM)

Time division multiplexing (TDM), is a type of digital or (rarely) analog multiplexing in which two or more signals or bit streams are transferred apparently simultaneously as sub-channels in one communication channel, but physically are taking turns on the channel. The time domain is divided into several recurrent time slots of fixed length, one for each sub-channel. A sample, byte or data block of sub-channel I is transmitted during time slot I, sub-channel 2 during timeslot 2, etc. One TDM frame consists of one time slot per sub-channel. After the last sub-channel it starts all over again with a new frame, starting with the second sample, byte or data block from sub-channel I, etc.

An alternative strategy for increasing the bit rate of digital optical fiber systems beyond the bandwidth capabilities of the drive electronics is known as optical time division multiplexing (OTDM). A block schematic of an OTDM system which has demonstrated 16Gbps transmission over 8 km is shown in Figure 2.3. The principle of this technique is to extend time division multiplexing by optically combining a number of lower speed electronic base band digital channels. In the case illustrated in Figure, the optical multiplexing and de multiplexing ratio is 1.4, with a base band channel rate of 4Gbps.

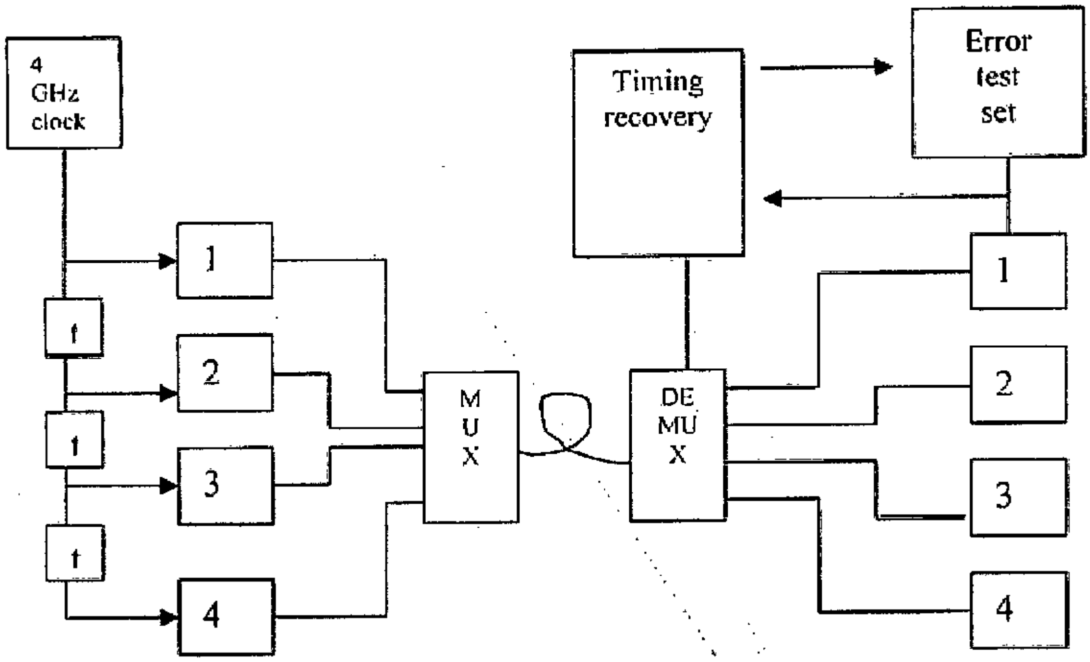


Fig 2.4: Four channel optical time division multiplexing (OTDM) fiber system.

2.2.4 Optical-CDMA (O-CDMA)

Instead of each channel occupying a given wavelength, frequency or time slot, each channel transmits its bits as a coded channel-specific sequence of pulses. This coded transmission typically is accomplished by transmitting a unique time-dependent series of short pulses. These short pulses are placed within chip times within the larger bit time. All channels, each with a different code, can be transmitted on the same fiber and asynchronously demultiplexed. One effect of coding is that the frequency bandwidth of each channel is broadbanded, or spread. If ultra-short (<100 fs) optical pulses can be successfully generated and modulated, then a significant fraction of the fiber bandwidth can be used. Unfortunately, it is difficult for the entire system to operate at these speeds without incurring enormous cost and complexity.

Code division multiple access (CDMA), is a form of multiplexing (not a modulation scheme) and a method of multiple access that does not divide up the channel by time (as in TDMA), or frequency (as in FDMA), but instead encodes data with a special code associated with each channel and uses the constructive interference properties of the special codes to perform the multiplexing. CDMA also refers to digital cellular telephony systems that make use of this multiple access scheme such as those pioneered by Qualcomm, and W-CDMA by the International Telecommunication Union or ITU. CDMA has since been used in many communications systems, including the Global Positioning System (GPS) and in the OmniTRACS satellite system for transportation logistics.

Recently, CDMA has been also investigated to be employed in optical communication networks, especially in local access network (LAN). Current optical CDMA (O-CDMA), shown in figure 1.28, techniques fall into two categories, coherent and incoherent O-CDMA. In incoherent O-CDMA unipolar codes (0, 1) are used to modulate the power of optical signals. In coherent O-CDMA bipolar (-1, 1) or multilevel codes are used to modulate the field of optical signals.

OCDMA is similar to PN-CDMA except that it employs a set of orthogonal sequences. such as Walsh-Hadamard (WH) sequences, for spectral spreading. The WH sequence length is equal to the spreading factor N, which in turn is equal to the number of chips per transmitted symbol. That is, unlike PN-CDMA, in which the spreading sequences look random, spreading sequences in OCDMA are fully deterministic and repeat from one symbol to the next. Provided the user signals are well synchronized in terms of symbol timing, orthogonality of the spreading sequences guarantees that there is no mutual interference between users. But the maximum number of orthogonal sequences of length N being exactly N, this is also the maximum number of users that can be accommodated (assuming again that all users require a fixed bit rate equal to the chip rate divided by N). This implies that in terms of the number of users which can be accommodated on a given channel. OCDMA is equivalent to TDMA and FDMA. In optical CDMA system transmission, N users share the same channel medium.

2.2.5 Sub carrier multiplexing (SCM)

Optical sub carrier multiplexing (SCM) is a scheme where multiple signals are multiplexed in the RF domain and transmitted by a single wavelength. The most significant advantage of SCM in optical communications is its ability to place different optical carriers together closely. This is because microwave and RF devices are much more mature than optical devices: the stability of a microwave oscillator is much better than an optical oscillator (laser diode) and the frequency selectivity of a microwave filter is much better than an optical filter. Therefore, the efficiency of bandwidth utilization of SCM is expected to be much better than conventional optical WDM.

SCM technology essentially uses a two step modulation. First, several low bandwidth RF channels carrying analog or digital signal are combined together and they are very close to each other in the frequency domain. Then this composite signal is further modulated onto a higher frequency microwave carrier or optical carrier and can be transmitted through different media. Because of its simple and low-cost implementation, high-speed optical data transmission using SCM technology attracted the attention of many researchers.

When the bandwidth of the information becomes higher, such as more than several GHz, and the transmission distance is very long, such as more than hundreds of kilometers, the DSB scheme will not work if it still use only a simple photon detector to detect. This is because the dispersion of the fiber will give quite different delay to + *if* and – *if* due to the large frequency difference between them. If the relative delay between + *if* and – *if* is comparable to the duration of a baseband bit. then after photon detector, the two side bands will interfere with each other destructively. Two methods can be used to solve this problem, one way is to use narrow band optical filter to filter out each sub carrier channel and then detect them separately. This is the method used in previous study of high-speed data transmission utilizing SCM techniques. In those studies, DSB is used as the optical modulation method and ASK is used as the RF modulation format. The demodulation of sub carrier is to filter out each sub carrier optically in order to avoid the fiber dispersion effect on the double side band modulation format. ASK RF modulation is used because it makes direct detection possible. The optical spectrums of these systems are very similar to the spectrum showing in Figure a. Another way is to use optical single side band modulation. The spectrum of optical single side band (OSSB) SCM the lower side band in the DSB spectrum is removed by ways such as optical filter or special modulating methods. The carrier itself could be removed or kept depending on the preferred demodulating method. The occupied spectrum is only half that of the optical DSB signal.

2.3 Fiber Nonlinearities

The response of any dielectric material to the light becomes nonlinear for intense electromagnetic fields. Fundamentally, the origin of nonlinear response is related to anharmonic motion of bound electrons under influence of an applied field. As a result, an intense light beam propagating through a fiber will induced a nonlinear polarization, which gives rise to nonlinear effect.

2.3.1 Self-Phase Modulation (SPM)

Self phase modulation (SPM) is due to the power dependence of the refractive index of the fiber core. SPM refers the self-induced phase shift experienced by an optical field during its propagation through the optical fiber; change of phase shift of an optical field is given by [18]

$$\phi=(n+n_2|E|^2)k_0 L=\phi_L+\phi_{NL} \tag{2.1}$$

Where, $k_0=\frac{2\pi}{\lambda}$ *and* L is the fiber length. ϕ_L is the linear part and ϕ_{NL} is the nonlinear part that depends on intensity.

SPM interact with the chromatic dispersion in the fiber to change the rate at which the pulse broadens as it travels down the fiber. Whereas increasing the dispersion will reduce the impact of FWM, it will increase the impact of SPM. As an optical pulse travels down the fiber, the leading edge of the pulse causes the refractive index of the fiber to rise causing a blue shift.

2.3.2 Cross Phase Modulation (XPM)

Cross phase modulation (XPM) is very similar to SPM except that it involves two pulses of light, whereas SPM needs only one pulse. In multi-channel WDM systems, all the other interfering channels also modulate the refractive index of the channel under consideration, and therefore its phase. This effect is called Cross Phase Modulation (XPM).

XPM refers the nonlinear phase shift of an optical field induced by co-propagating channels at different wavelengths; the nonlinear phase shift be given as [18]

$$\phi_{NL} = n_2\, k_0\, L\,(|E_1|^2 + 2|E_2|^2) \qquad (2.2)$$

Where, E_1 and E_2 are the electric fields of two optical waves propagating through the same fiber with two different frequencies.

In XPM, two pulses travel down the fiber, each changing the refractive index as the optical power varies. If these two pulses happen to overlap, they will introduce distortion into the other pulses through XPM. Unlike, SPM, fiber dispersion has little impact on XPM. Increasing the fiber effective area will improve XPM and all other fiber nonlinearities.

2.3.3 Four wave mixing (FWM):

Four-wave mixing (FWM) is a nonlinear process in optical fibers in which generally three signal frequencies combine and produce several mixing products. It originates from the weak dependence of the fiber refractive index on the intensity of the optical wave propagating along the fiber through the third order non linear susceptibility .If three signal waves with frequencies f_i , f_j, f_k are incident at the fiber input , new waves are generated whose frequencies are

$$f_{ijk}=f_i+f_j-f_k \quad (i, j, k = 1, 2, 3) \qquad (2.3)$$

Here we exclude f_{ijk} with i=k or j=k where interruptions from other channels to signal do not happen. As a result, we will examine FWM lights with the frequency of f_{321}, f_{312}, f_{213}, f_{332}, f_{331}, f_{223}, f_{221}, f_{113}, and f_{112} which are shown in Fig. 2.5. Note that the number of the FWM lights is enhanced drastically with an increase in the number of channels.

This is called "four wave mixing" since three waves interfere to provide a fourth wave. Again it is sometimes called "four photon mixing".

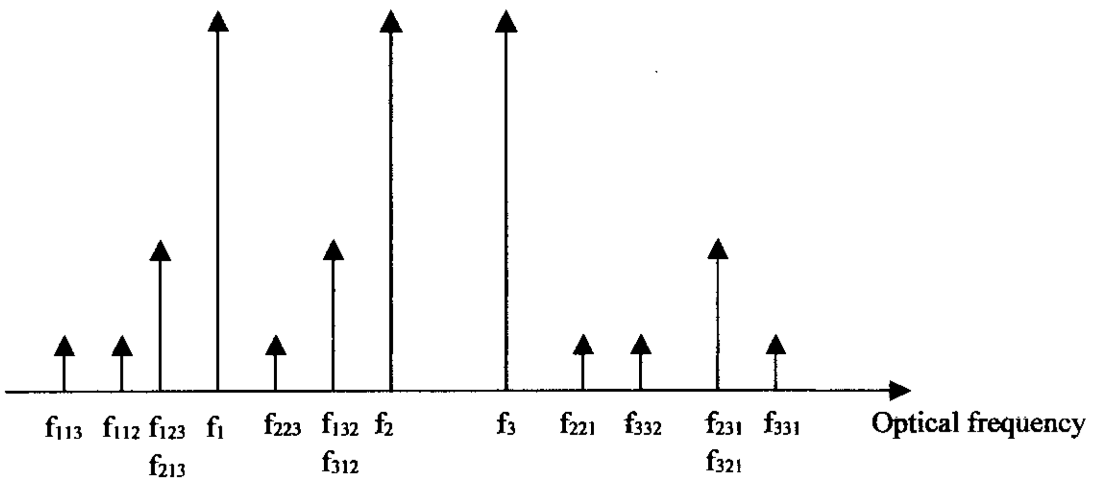


Fig 2.5: Generated waves through fiber four wave mixing

Let four channels consist frequencies f_a, f_b, f_c and f_d. The detailed explanation of FWM lights produced is as follows:

TABLE 2.1: The FWM frequency combinations

Row No.	***I=a, j=b, k=c***	***i=b, j=c, k=d***	***i=c, j=d, k=a***	***i=a, j=b, k=d***
1	$f_{abc}=f_a+f-f_c$	$f_{bcd}=f_b+f_c-f_d$	$f_{cda}=f_c+f_d-f_a$	$f_{abd}=f_a+f_b-f_d$
2	$f_{bca}=f_b+f_c-f_a$	$f_{cdb}=f_c+f_d-f_b$	$f_{dac}=f_d+f_a-f_c$	$f_{bda}=f_b+f_d-f_a$
3	$f_{acb}=f_a+f_c-f_b$	$f_{bdc}=f_b+f_d-f_c$	$f_{cad}=f_c+f_a-f_d$	$f_{adb}=f_a+f_d-f_b$
4	$f_{aab}=f_a+f_a-f_b$	$f_{bbc}=f_b+f_b-f_c$	$f_{cca}=f_c+f_c-f_a$	$f_{aab}=f_a+f_a-f_b$

5	$f_{aac}=f_a+f_a-f_c$	$f_{bbd}=f_b+f_b-f_d$	$f_{ccd}=f_c+f_c-f_d$	$f_{aad}=f_a+f_a-f_d$
6	$f_{bbc}=f_b+f_b-f_c$	$f_{ccb}=f_c+f_c-f_b$	$f_{dda}=f_d+f_d-f_a$	$f_{bbd}=f_b+f_b-f_d$
7	$f_{bba}=f_b+f_b-f_a$	$f_{ccd}=f_c+f_c-f_d$	$f_{ddc}=f_d+f_d-f_c$	$f_{bba}=f_b+f_b-f_a$
8	$f_{cca}=f_c+f_c-f_a$	$f_{ddb}=f_d+f_d-f_b$	$f_{aac}=f_a+f_a-f_c$	$f_{dda}=f_d+f_d-f_a$
9	$f_{ccb}=f_c+f_c-f_b$	$f_{ddc}=f_d+f_d-f_c$	$f_{aad}=f_a+f_a-f_d$	$f_{ddb}=f_d+f_d-f_b$

From the above table we can easily see that for each element in the last 6 rows there is an extra repetition. There are 24 elements in the last 6 rows. If we eliminate each extra repetition we will have 24-12=12 elements. From the upper 3 rows we get 3x4=12 individual combinations. So we get a total of 12+12=24 elements. So if we calculate using the previous equation ${}^4C_3 \times 9 = 36$ we will get erroneous results. To eliminate this problem of calculating the total lights produced by FWM we developed an equation which gives the desired no of FWM lights without any error. The equation is as follows:

Number of FWM lights = ${}^nC_3 \times 9 - n\,[(n-2)^2 - 1]$

Where, n is the number of channels.

If we take the number of channels as n=4. If we put this value in equation no 1 we get the total no of FWM lights produced as 24 which verifies the validity of our equation. The equation has been also verified for various numbers of channels by a programme coded in C++.

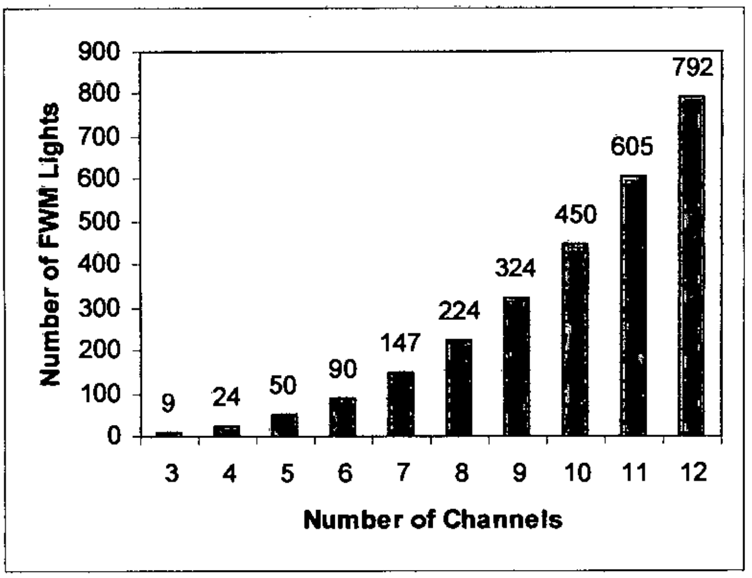


Fig 2.6: No. of FWM Lights with increasing No. of Channels.

Now if there are three channels of frequencies f_a, f_b and f_c, then the frequency components generated by FWM process are,

$$f_F = f_i + f_j - f_k, \qquad i,j,k = a,b,c \text{ and } i,j \neq k \tag{2.4}$$

The power of FWM signal for general case of WSK-WDM system can be found as [20]-

$$P_{FWM} = \frac{1024\ \Pi^2}{n^4 \lambda^2 c^2}\left[\frac{D\chi_{1111} L_{eff}}{A_{eff}}\right]^2 P_i P_j P_k e^{-\alpha L}\eta . \tag{2.5}$$

where, A_{eff} is the effective mode area, P_i, P_j and P_k are the input powers of channels i, j and k, n is the refractive index, λ is the wavelength, D is the degeneracy factor and L_{eff} is the effective length of each fiber so that $NL_0 = L$ is the length of each section, M is the number of span, N is the number of fiber in a span.

<u>Necessity of channel coding:</u>

<u>Digital data transmission suffers from channel influence for the following aspect:</u>

- Severe (multipath) fading in terrestrial mobile radio communications
- Very low signal-to-noise ratio for satellite communications due to high path loss and limited transmit power in the downlink
- Compressed data (e.g. audio and video signals) is very sensitive to transmission errors.
- To improve transmission performance, channel coding is added.
- To optimize the use of the correction capacity of a particular code, soft decision is always a good solution.
- Channel coding protects data against transmission errors to ensure adequate transmission quality (bit or frame error rate).
- Channel coding is power efficient: Compared to the uncoded case, the same errors rates are achieved with much less transmit power at the expense of a bandwidth expansion.

2.4 Convolution Coding:

In telecommunication, a convolutional code is a type of error-correcting code in which (a) each m-bit information symbol (each m-bit string) to be encoded is transformed into an n-bit symbol, where m/n is the code rate ($n \geq m$) and (b) the transformation is a function of the last k information symbols, where k is the constraint length of the code. Convolutional codes are often used to improve the performance of digital radio, mobile phones, satellite links, and Bluetooth implementation.

A free distance d is a minimal Hamming distance between different encoded sequences. A correcting capability t of a convolutional code is a number of errors that can be corrected by the code. Since a convolutional code doesn't use blocks, processing instead a continuous bitstream, the value of t applies to a quantity of errors located relatively near to each other. That is, multiple groups of t errors can usually be fixed when they are relatively far. Free distance can be interpreted as a minimal length of an erroneous "burst" at the output of a convolutional decoder. Several algorithms exist for decoding convolutional codes. For relatively small values of k, the Viterbi algorithm is universally used as it provides maximum likelihood performance and is highly parallelizable. [21]

W(d) is obtained from the code weights in Table 2.2 as [12]. Substituting the unconditional BER (Pe) from Eq. (2.6) in Eq. (2.7b), we can calculate the coded BER from Eq. (2.6).

Table 2.2: Weigh Spectrum of convolutional encoders

Hamming Weight d	**W(d) for R=1/2**	**W(d) for R=1/3**
10	3.6×10^{01}	-
11	0	-
12	2.11×10^{02}	-
13	0	-
14	1.404×10^{03}	-
15	0	1.1
16	1.633×10^{04}	1.6
17	0	1.9
18	7.7433×10^{04}	2.8
19	0	5.5

20	5.0269×10^{05}	9.6
21	0	1.69×10^{02}
22	3.322763×10^{06}	3.38×10^{02}
23	0	6.36×10^{02}
24	2.129291×10^{07}	1.276×10^{03}
25	0	2.172×10^{03}
26	1.3436491×10^{08}	-

Chapter 3

PERFORMANCE ANALYSIS

3.1 Introduction

The performance of a multichannel WSK-DWDM transmission system in presence of XPM & FWM has been evaluated in this chapter for binary and M-ary system. The system performance depends on various system parameters such as transmission power per channel, number of channel, fiber length; different channel spacing will be examined. Finally, the performance of WSK-DWDM system is compared for binary and M-ary coded and uncoded system with different parameters.

3.2: System Model:

The model of the WSK-DWDM system considered for analysis is shown in Fig 3.1.

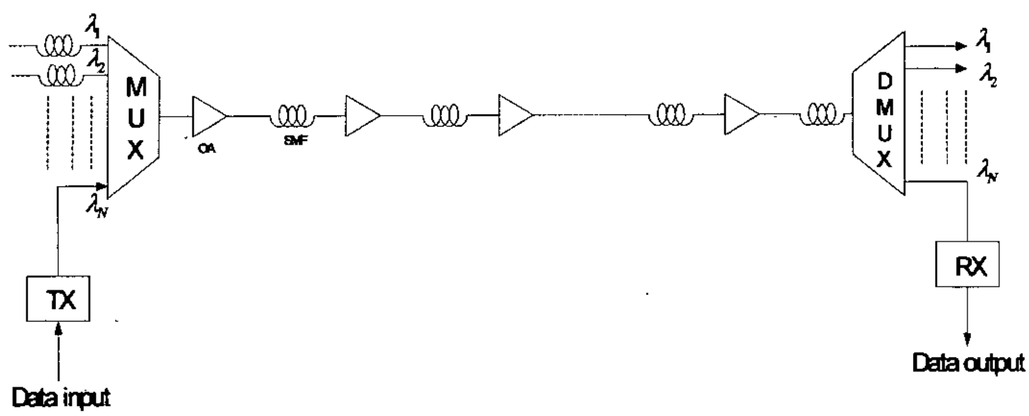


Fig: 3.1: Block diagram basic WSK-DWDM transmission system.

The system is used to combine different signal carrier wavelengths onto a single fiber at one end and separate them onto their corresponding detectors at the other end.

Here MUX combine all of the signals and create a composite signal. This signal passes through the optical fiber and optical amplifier.

Optical amplifier amplifies an optical signal directly, without the need to first convert it to an electrical signal. An optical amplifier may be thought of as a laser without an optical cavity, or one in which feedback from the cavity is suppressed. Stimulated emission in the amplifier's gain medium causes amplification of incoming light.

DMUX separate them. Then at the receiver we get all the signals individually.

3.3: Performance Analysis of a binary WSK-DWDM uncoded system

3.3.1: Receiver Model:

The Receiver Model of direct detection WSK-DWDM system is shown in fig 3.2.

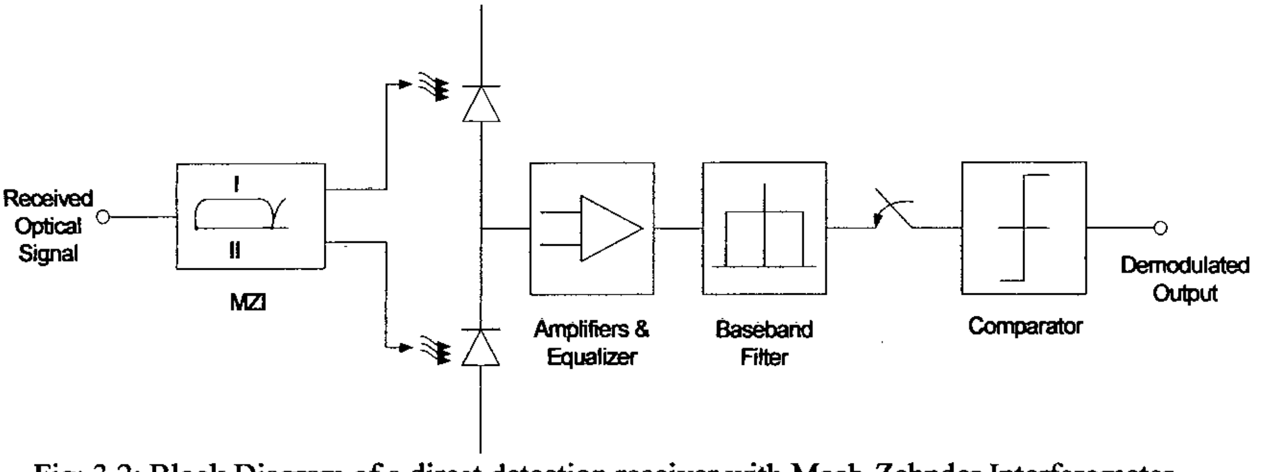


Fig: 3.2: Block Diagram of a direct detection receiver with Mach-Zehnder Interferometer (MZI).

In the transmitter, the data of 10 Gbps is used to directly modulate a laser to generate the WSK signal which is transmitted through a single-mode fiber. At the receiving end, the received optical signal is detected by a Mach-Zehnder interferometer based direct detection receiver.

In the WSK direct detection receiver with MZI, the MZI act as an optical filter and differentially detect the 'mark' and 'space' of received WSK signal which are then directly fed to a pair of photo detectors. The difference of the two photo currents are applied to the amplifier which is followed by an equalizer. The equalizer is required to equalize the pulse shape distortion caused by the photo detector capacitance and due to the input resistance and capacitance of the amplifier. After passing through the baseband filter, the signal is detected at the decision circuit by comparing it with a threshold of zero value.

One other type of discriminator is the Fabry-Perot etalon interferometer; a small comparison in connection to direct detection would reveal some relevant aspects.

I. Mach-Zehnder Interferometer and Fabry-Perot etalon Interferometer both can act as tunable filter (for multichannel application) and optical discriminator.
II. The OFDs (MZI/FPI) are built with passive components which are less costly compared to heterodyne system.
III. MZI provides easy tunability in multichannel system compared to heterodyne system which requires LDs with wide tuning range and narrow LW.
IV. Receiver design is simple and less costly due to the absence of the sophisticated wideband IF circuits.

Operation of MZI:

It is a common property of the interference filter to transmit a narrow band of wave length and blocking of all wavelengths outside the band. In our receiver, MZI is employed which is integrated with a silica wave guide. It is a very promising device in wavelength division multiplexing (WDM) and frequency division multiplexing (FDM) systems. Because of their high frequency selectivity without mechanical actuator (which is essential for an FPI). MZI's can be series cascaded to achieve increase transmission capacity [22].

MZI has two input ports, two output ports, 3 dB couplers and two waveguide arms with length difference ΔL. A thin film heater is placed in one of the arms to act as a phase shifter, because light path length of heated wave guide arm changes due to the change of refractive index. The phase shifter is used for precise frequency tuning. Frequency spacing of the peak to bottom transmittance of the OFD is set equal to the peak frequency deviation 2Δf of the FSK signal. Consequently, the 'mark' and the 'space' appear at the two output ports of the OFD. These outputs are differentially detected by the photo detectors with balanced configuration.

MZI Characteristics:

If E(t) represents the signal input to the MZI, then the signals received at the output ports can be expressed as [22]

$$|E_2(t)| = |E(t)|\sin\left[\frac{k(l_2 - l_1)}{2}\right] \tag{3.1}$$

$$|E_1(t)| = |E(t)|\cos\left[\frac{k(l_2 - l_1)}{2}\right] \tag{3.2}$$

where l_1 and l_2 are the length of two arms of MZI and k is the wave number which can be expressed as

$$k = \frac{w}{v} = \frac{2\pi}{\lambda} = \frac{2\pi f \eta_{eff}}{c} \tag{3.3}$$

η_{eff} , f and c are the effective refractive index of the wave guide, frequency of optical input signal and velocity of light in vacuum, respectively.

The transmittance of arm II of MZI is given by

$$T_{II}(f) = \frac{|E_2(t)|^2}{|E(t)|^2} = \sin^2\left[\frac{k(l_2 - l_1)}{2}\right] = \sin^2\theta \tag{3.4}$$

and that of arm I of MZI is

$$T_I(f) = \frac{|E_1(t)|^2}{|E(t)|^2} = \cos^2\left[\frac{k(l_2 - l_1)}{2}\right] = \cos^2\theta \tag{3.5}$$

where, θ is the phase factor related to the arm path difference $\Delta L = l_2 - l_1$ and can be express as

$$\theta = \frac{k\Delta L}{2} = \frac{\pi f \eta_{eff} \Delta L}{c} \tag{3.6}$$

Normally ΔL is chosen as

$$\Delta L = \frac{c}{4\eta_{eff} \Delta f} \tag{3.7}$$

Therefore,

$$\theta = \frac{\pi f}{4\Delta f} \tag{3.8}$$

Then we get

$$T_{II}(f) = \sin^2\left(\frac{\pi f}{4\Delta f}\right) \tag{3.9}$$

and

$$T_{I}(f) = \cos^2\left(\frac{\pi f}{4\Delta f}\right) \tag{3.10}$$

The output of the MZI are, Δf is so chosen that $\Delta f = \frac{f_c}{2n+1}$, f_c is the carrier frequency of the FSK signal and n is an integer. The 'mark' and 'space' of FSK signals are represented by f_1 and f_2 respectively where $f_1 = f_c + \Delta f$ and $f_2 = f_c - \Delta f$.

Therefore, when 'mark' (f_1) is transmitted

$T_I = 1$ and $T_{II} = 0$

Similarly, for transmission of 'space'

$T_I = 0$ and $T_{II} = 1$

Thus, two different signals f_1 and f_2 can be extracted from two output ports of MZI.

The MZI is used in our analysis in receiver model based on single channel operation. The complete potential of an MZI can be extracted when a multiplexer / demultiplexer or a frequency selector switch for a multi channel WDM/ FDM system is fabricated utilizing the periodicity of the transmittance versus frequency characteristic of a MZI.

The optical field at the output of two branches of MZI can now be expressed as:

And $E_2(t) = \frac{1}{2}[E(t-\tau_b) - E(t-\tau_a)]$ (3.11)

$$E_1(t) = \frac{-j}{2}[E(t-\tau_a) - E(t-\tau_b)] \quad (3.12)$$

$$\tau_a = \frac{\eta_1^l}{c}$$

where

$$\tau_b = \frac{\eta_2^l}{c}$$

let us define the time delay due to path difference in MZI as

$$\tau = \tau_b - \tau_a = \frac{\eta(l_2 - l_1)}{c} \quad (3.13)$$

Without any loss of generality we can take τ_a=0, then $\tau_a = \tau$. The output current of upper photo detector is given by [...]

$$i_2(t) = R_d |E_2(t)|^2$$
$$= \frac{R_d P_s}{2}\left[1 - \cos\{2\pi f_c \tau + 2\pi\Delta f \int_{t-\tau}^{t} \sum_k a_k g(t_1 - kT)dt_1 + \Delta\phi_n(t,\tau)\}\right] \quad (3.14)$$

Where, R_d is the responsivity of the photo detector.

Similarly, the output current at the lower photo detector can be expressed as:

$$i_1(t) = R_d |E_1(t)|^2$$
$$= \frac{R_d P_s}{2}\left[1 - \cos\{2\pi f_c \tau + 2\pi\Delta f \int_{t-\tau}^{t} \sum_k a_k g(t_1 - kT)dt_1 + \Delta\phi_n(t,\tau)\}\right] \quad (3.15)$$

the output of the balanced photo detectors is then found as

$i_0 = i_1 - i_2$

$$= R_d P_s \cos[\omega_c \tau + \Delta\phi_s(t,\tau) + \Delta\phi_n(t,\tau) + \phi_0] \quad (3.16)$$

3.3.2: Expression of Bit Error Rate (BER) with FWM.

In any communication system the BER is the most important factor. A standard BER in communication system some times is maintained. For video, speech, data and for every information the separate BER is maintained. BER is related to the input signal power and also SNR. As the input signal power increases the BER decreases.

$$BER = \frac{Number\ of\ bits\ received\ with\ error}{Total\ number\ of\ bits}$$

The required SNR to maintain particular bit error rates may be obtained using procedure adopted for error performance of electrical digital systems where the noise distribution is considered to be white Gaussian. This Gaussian approximation is sufficiently accurate for design purposes and is far easier to evaluate than the more exact probability distribution within the receiver.

Two types of noises, such as, thermal noise and shot noise are considered and also assumed that all these noises have Gaussian distribution. It is assumed that lights from all optical sources have an identical state of polarization, which corresponds to considering the worst case situation for system degradation. We also consider the four wave mixing (FWM) in the BER performance analysis.

Thermal Noise

Thermal noise is the spontaneous fluctuation due to thermal interaction between, say, the tree electrons and the vibrating ions in a conducting medium, and it is especially prevalent in resistors at room temperature. The thermal noise current in mean square value is given below.

$$P_{th} = Thermal\ noise = \frac{4kTB}{R_L} \tag{3.17}$$

Where,

K= Boltzmann's constant

T= the absolute temperature

B= the post detection bandwidth of the system

Shot Noise:

Shot noise occurs due to radiation. In fiber optic communication system, due to background radiation, some electron or charge penetrate rapidly and generate noise. The noise in mean square value is given below.

$$P_{shot} = shot\ Noise = 2eI_sB \quad (3.18)$$

Where,

e= The charge on an electron

I_s= The current

B= The post detection bandwidth of the system

Calculation of FWM

We have already mentioned that FWM is third-order nonlinear parametric process in silica (glass), which is analogous to third-order intermodulation of radio system [19], that is multichannel system, three optical frequencies mix through the third-order electric susceptibility in optical fiber to generate a fourth signal with frequency $f_{ijk}=f_i+f_j-f_k$, where f_i, f_j, and f_k are the frequencies of three of the channels.

Thus three copropagating waves gives rise to nine new optical waves by FWM in WDM system, this happens for every possible choice of three channels. In conventional WDM system, the channels are typically equally spaced and this choice causes huge number of FWM products in the bandwidth of the system that may fall at the channel frequencies. The total number of FWM products can be calculated from the following equation

$$Total\ no.of\ FWM\ Products = \frac{1}{2}(N^3 - N^2), \qquad where, N\ is\ the\ no.of\ channel.$$

If we assume that the input signals are not depleted by the generation of mixing products, the power of the new optical signal generated at frequency f_{ijk} exiting the fiber is given by [20].

$$P_{FWM} = \frac{1024\pi^2}{n^4\lambda^2c^2}\left[\frac{D\chi_{1111}L_{eff}}{A_{eff}}\right]^2 P_iP_jP_ke^{-\alpha L}\eta\ . \tag{3.19}$$

where n is refractive index, λ is the wavelength of light, P_i, P_j *and* P_k are the input powers of three waves, D is the degeneracy factor. χ_{1111} is nonlinear susceptibility and $\chi_{1111} = 4\times10^{-15}\ esu$ and η is the mixing efficiency, A_{eff} is the effective area of the fiber and L_{eff} is the effective length of fiber, given by

$$L_{eff} = \frac{1}{\alpha}(1-e^{-\alpha L}) \tag{3.20}$$

where α as fiber attenuation loss. The third-order nonlinear susceptibility can be expressed in terms of nonlinear index of refraction n_2 , in case of a single polarization, as

$$\chi_{1111}[esu] = \frac{cn^2}{480\pi^2}n_2[m^2/W] \tag{3.21}$$

The mixing efficiency η is given by [20]

$$\eta = \frac{\alpha^2}{\alpha^2+\Delta\beta^2}\left(1+\frac{4e^{-\alpha L}\sin^2(\Delta\beta L/2)}{(1-e^{-\alpha L})^2}\right) \tag{3.22}$$

where $\Delta\beta$ is the propagation constant difference can be written as

$$\Delta\beta = \beta_{ijk}+\beta_k-\beta_j-\beta_i \tag{3.23}$$

Here β indicates the propagation constant. Efficiency η takes the maximum value of 1 for $\Delta\beta$ = 0. In this situation the phase matching condition is satisfied.

Cross-Phase Modulation:

A multi-channel system, the nonlinear phase shift of the signal at the center wavelength λ_i is described by [23],

$$\phi_{NL} = \frac{2\pi}{\lambda_i} n_2 z \,[I_i(t) + 2\sum_{i \neq j}^{M} I_j(t)] \qquad (3.24)$$

where M is the number of co-propagating channels in the fiber. The first term is responsible for self-phase modulation (SPM) and the second term is for XPM. Equation (1) might lead to a speculation that the effect of XPM could be at least twice as significant as that of SPM. To investigate the effect of XPM alone, SPM and XPM part from Equation (1) must be separated. A pump-probe approach helps isolate the effect of XPM [23]. The total XPM induced IM of probe channel at fiber output is the sum of the XPM induced IM at infinitesimal section z along the fiber with length L is given by [23]:

$$P_{XPM} = 2\gamma_1 P_1(0) P_2(\omega) e^{-aL} e^{-\frac{j\omega L}{V_{g1}}}$$

$$\left\{ \frac{1}{a^2 + (b+q)^2} \left[a.\sin(bL) - (b+q).\cos(bL) + \right.\right.$$

$$\left.[a.\sin(qL) + (b+q).\cos(qL)]\exp(-\alpha L)\right]$$

$$\frac{1}{a^2 + (b-q)^2} \left[a.\sin(bL) - (b-q).\cos(bL) + \right.$$

$$\left.\left.[-a.\sin(qL) + (b-q)\cos(qL)]\exp(-\alpha L)\right]\right\} \qquad (3.25)$$

Here $a = \alpha - j\omega d_{12}$, $b = \omega^2 D\lambda_1^2/(4\pi c)$ and $q = \omega^2 D\lambda_2^2/(4\pi c)$. α is the attenuation constant, ω is the angular frequency, D is the dispersion of the fiber, λ is the wave length, d_{12} is the walk-off length and c is the velocity of light. In a nonzero dispersion region $d_{12} \approx D_1.\Delta\lambda_{12}$ where $\Delta\lambda_{12} = \lambda_1 - \lambda_2$ is the wavelength separation between channel 1 and 2.

Bit Error Rate (BER):

The probability of error or bit error rate (BER) is given by-

$$BER(P_e) = 0.5\, erfc[SNR] \qquad (3.26)$$

where, signal-to-noise ration,

$$SNR(r) = \frac{I_s}{\sigma\sqrt{2}}$$

where, $I_s = R_d P_s(r)$

and, $\sigma = \sqrt{P_{th} + P_{shot} + P_{FWM}}$

Where,

$$P_{th} = Thermal\ noise = \frac{4kTB}{R_L}$$

and, $P_{shot} = shot\ Noise = 2eI_s B$

where,

$B = Bandwidth$

$e = electron\ \ charge$

$$P_{FWM} = \frac{1024\ \pi^2}{n^4 \lambda^2 c^2}\left[\frac{D\,\chi_{1111}\ L_{eff}}{A_{eff}}\right]^2 P_i P_j P_k e^{-\alpha L}\eta\ .$$

and,

$$P_{XPM} = 2\gamma_1 P_1(0) P_2(\omega) e^{-\alpha L} e^{-\frac{j\omega L}{V_{g1}}}$$

$$\left\{\frac{1}{a^2+(b+q)^2}[a.\sin(bL)-(b+q).\cos(bL)+\right.$$

$$[a.\sin(qL)+(b+q).\cos(qL)]\exp(-\alpha L)]$$

$$\frac{1}{a^2+(b-q)^2}[a.\sin(bL)-(b-q).\cos(bL)+$$

$$\left.[-a.\sin(qL)+(b-q)\cos(qL)]\exp(-\alpha L)]\right\}.$$

3.4: Performance Analysis of an M-ary WSK-WDM uncoded system

3.4.1: Receiver Model

The Receiver Model of direct detection WSK-WDM system is shown in fig 3.3.

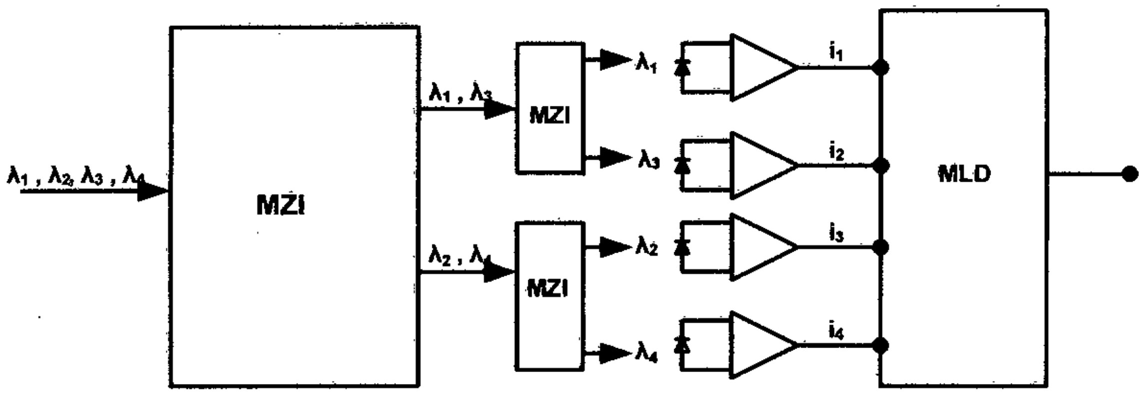


Fig 3.3: Block Diagram of a M-ary receiver with Mach-Zehnder Interferometer (MZI) and Maximum Likelihood Detector (MLD).

In the transmitter, the data of 10 Gbps is used to directly modulate a laser to generate the WSK signal which is transmitted through a single-mode fiber. At the receiving end, the received optical signal is detected by a Mach-Zehnder interferometer.

In the WSK direct detection receiver with MZI, the MZI act as an optical filter and differentially detect the 'mark' and 'space' of received WSK signal. The 1st MZI received the multiple channel signals then it differentially detects the odd and even signals. Those are then directly fed to a pair of MZIs. The 'Odd' signals go to one MZI and the even signals go to another MZI. After that the signals are separated gradually, which are then directly fed to a photo detector. All photo currents are applied to the amplifier which is followed by a Maximum Likelihood Detector (MLD). After passing through the MLD, the signal is detected at the decision circuit by comparing it with a threshold of zero valThen we can write,

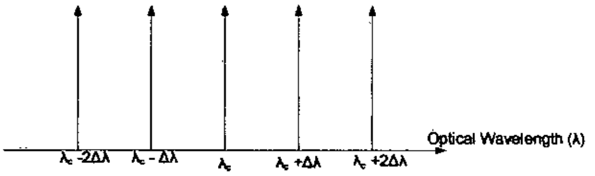
<u>Maximum Likelihood Detector</u>

A maximum likelihood detector receiving a data stream corresponding to ideal values which may include noise, and outputting information specifying a sequence of states of maximum likelihood selected from possible states corresponding to the data stream according to weighting value selections made by the processors, the ideal values being determined by the possible states, including: a pre-processor to obtain first weighting values; processors in a hierarchy, each processor in a select level of the hierarchy is programmed to use, respectively, a plurality of the weighting values to calculate subsequent weighting values indicating respective likelihoods that a section of the data stream values corresponds to each of a plurality of possible state sequences, for each possible initial state and each possible final state, to select further weighting value of highest likelihood corresponding to a state sequence from the initial state to the final state.

3.4.2: Bit Error rate (BER) M-ray WSK-WDM system:

In orthogonal MWSK, the M=2k district symbols are represented by M-WSK waveforms

$S_m(t) = ACos(\omega_m t + \phi_m)$, where, m = 1, 2, ..., M (3.27)



where

$$\omega_m = 2\pi f_m = \frac{2\pi C}{\lambda_m}$$

ϕ_m = initial phase

A = Signal amplitude

$T_s = KT_b$ = Signaling interval

T_b = bit duration

$E_s = \frac{A^2 T_s}{2}$ = Signal Energy

= Energy/symbol

To derive the average probability of symbol error, we assume that the signal (S, H) was sent and received signal

r(t)=S_1 (t)+ n(t)

Where,

n(t)=AWGN with zero mean.

Where,

$S_1 = E_s + n_1$

$S_m = n_m$,m=2,3........M

$n_m = \int_0^{T_s} n(t) S_m(t) dt$

The output of photo detector (PD):

$$i_m = R_d \left|S_m(t) + S_{fwm}(t)\right|^2 \tag{3.28}$$

$$= R_d \left|S_m(t)\right|^2 + R_d \left|S_{fwm}(t)\right|^2$$

$$= R_d \left|\left\{\sqrt{2P_s}\cos(\omega_m t + \phi)\right\}\right|^2 + R_d \left|P_{th}\right| + R_d \left|P_{sh}\right| + R_d \left|P_{fwm}\right| + R_d \left|P_{XPM}\right|, \; where, S_m(t) = \sqrt{2P_s}\cos(\omega_m t + \phi)$$

Considering only FWM & XPM,

$$= R_d \left|\left\{\sqrt{2P_s}\cos(\omega_m t + \phi)\right\}\right|^2 + R_d \left|\frac{1024\pi^2}{n^4\lambda^2c^2}\left[\frac{D\chi_{1111} L_{eff}}{A_{eff}}\right]^2 P_i P_j P_k e^{-\alpha L}\eta\right| + R_d \left|P_{XPM}\right|, where\, m = 2,3,4........$$

$$= R_d\, 2P_s \cos^2(\omega_m t + \phi) + R_d \left|\frac{1024\pi^2}{n^4\lambda^2c^2}\left[\frac{D\chi_{1111} L_{eff}}{A_{eff}}\right]^2 P_i P_j P_k e^{-\alpha L}\eta\right| + R_d \left|P_{XPM}\right|$$

$$= R_d P_s \left[1 + \cos 2(\omega_m t + \phi)\right] + R_d \left|\frac{1024\pi^2}{n^4\lambda^2c^2}\left[\frac{D\chi_{1111} L_{eff}}{A_{eff}}\right]^2 P_i P_j P_k e^{-\alpha L}\eta\right| + R_d \left|P_{XPM}\right|$$

$$= R_d P_s + R_d P_s \cos 2(\omega_m t + \phi) + R_d \left|\frac{1024\pi^2}{n^4\lambda^2c^2}\left[\frac{D\chi_{1111} L_{eff}}{A_{eff}}\right]^2 P_i P_j P_k e^{-\alpha L}\eta\right| + R_d \left|P_{XPM}\right| \tag{3.29}$$

Then we can write,

When m=1, then $i_1 = R_d P_s + n_1$

And, $i_m = n_m$, *where* $m = 2,3,4.......M$.

Where, n is AWGN with zero mean.

The signal to noise ratio (SNR):

$$SNR = \frac{R_d \, P_S}{\sigma_0} \tag{3.30}$$

Where,

$$\sigma_0 = \sqrt{P_{th} + P_{sh} + P_{FWM} + P_{s-fwm} + P_{XPM}}$$

and,

$$P_{th} = Thermal\ noise = \frac{4KTB}{R_L}$$

$$P_{sh} = Shot\ noise = 2 e I_S B$$

$$P_{FWM} = R_d^{\ 2} . \left[\frac{1024\Pi^2}{n^4 \lambda^2 c^2} \left[\frac{D\chi_{1111} L_{eff}}{A_{eff}} \right]^2 P_i P_j P_k e^{-\alpha L} \eta \right].$$

$$P_{s-fwm} = 2 (R_d \, P_{fwm})(R_d \, P_s)$$

$$= 2 R_d^{\ 2} P_{fwm} P_s .$$

$$P_{XPM} = 2\gamma_1 P_1(0) P_2(\omega) e^{-\alpha L} e^{-\frac{j\omega L}{V_{g1}}}$$

$$\left\{ \frac{1}{a^2 + (b+q)^2} [a.\sin(bL) - (b+q).\cos(bL) + \right.$$

$$[a.\sin(qL) + (b+q).\cos(qL)] \exp(-\alpha L)]$$

$$\frac{1}{a^2 + (b-q)^2} [a.\sin(bL) - (b-q).\cos(bL) +$$

$$\left. [-a.\sin(qL) + (b-q)\cos(qL)] \exp(-\alpha L)] \right\}$$

The probability density function of S_m, given that S_1 (t) was sent is

$$\mathrm{P}(S_m / S_1) = \frac{e^{\frac{[(S_m - \delta_{1m} E_s)^2}{E_s N_0}}}{\sqrt{\pi E_s N_0}} \tag{3.31}$$

$$\mathrm{P}(S_m / S_1) = \frac{e^{\{-[\frac{(S_m - \delta_{1m} E_s)^2}{E_s N_0}]\}}}{\sqrt{\pi \, E_s N_0}}$$

Thus the probability that the demodulator will make an impact decision is simply

$$P_{e1} = 1 - P_r(S_2 \langle S_1 \cap S_3 \langle S_1 \cap ...... \cap S_m \langle S_1 / S_1) \tag{3.32}$$

$$P_{e1} = 1 - \int_{-\infty}^{\infty}\int_{-\infty}^{S_1} .... \int_{-\infty}^{S_1} P(S_1, S_2 .... S_M / S_1) dS_1\, dS_2 ..... dS_M$$

Now

$$P(S_1, S_2, ... S_M / S_1) = \prod_{m=1}^{M} P(S_m / S_1)$$

$$P_{e1} = 1 - \int_{-\infty}^{\infty} \left[\int_{-\infty}^{S_1} P\left((S_m / S_1) dS_m \right) \right]^{M-1} P(S_1 / S_1) dS_1 \tag{3.33}$$

Now,

$$\int_{-\infty}^{S_1} P(S_M / S_1)\, dS_m = 1 - \int_{S_1}^{\infty} \frac{e^{-\frac{S_m^2}{E_S N_0}}}{\sqrt{\pi E_S N_0}} dS_m$$

$$Let, x = \sqrt{\frac{2}{E_S N_0}}\, S_m$$

$$\int_{-\infty}^{S_1} P(S_M / S_1)\, dS_m = 1 - \int_{\sqrt{\frac{2}{E_S N_0}} S_1}^{\infty} \frac{e^{-\frac{x^2}{2}}}{\sqrt{2\pi}} dx$$

$$= 1 - Q\left(\sqrt{\frac{2}{E_S N_0}}\, S_1\right)$$

By substitution we get,

$$P_{e1} = 1 - \int_{-\infty}^{\infty} \left[1 - Q\left(\sqrt{\frac{2}{E_S N_o}} . S_1 \right) \right]^{M-1} \frac{e^{-\frac{(S_1 - E_S)^2}{E_S N_o}}}{\sqrt{\pi E_S N_o}} dS_1$$

Now, *let*, $y = \sqrt{\frac{2}{E_S N_0}} (S_1 - E_s)$, then P_{e1} becomes,

$$P_{e1} = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \left[1 - Q\left(y + \sqrt{\frac{2E_S}{N_o}} \right) \right]^{M-1} e^{(\frac{-y^2}{2})} dy$$

Let, $y_1 = 1 - Q\left(y + \sqrt{\frac{2E_s}{N_0}}\right)^{M-1} = 1 - Q\left(y + \frac{R_d P_s}{\sigma_0}\right)^{M-1}$

where, $Q(y) = \frac{1}{\sqrt{2\pi}} \int_y^{\infty} e^{(\frac{-y^2}{2})} dy$ = Gaussian Integral Function = $0.5\, erfc(\frac{y}{\sqrt{2}})$.

$$y_2 = e^{-\frac{y^2}{2}}$$

so, $P_{e1} = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} [y_1 y_2] dy$

We can write, the probability of BER for WSK-WDM system,

$$P_{el} = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} [1 - Q(y + \frac{R_d P_S}{\sigma_O})]^{M-1}\ e^{(\frac{-y^2}{2})\,dy} \tag{3.34}$$

where, $\sigma_0 = \sqrt{P_{th} + P_{shot} + P_{fwm} + P_{s-fwm}}$.

and,
$$P_{s-fwm} = 2(R_d P_{fwm})(R_d P_s)$$
$$= 2 R_d^{\,2} P_{fwm} P_s .$$

$$P_{e1} = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \left[1 - Q(y + \sqrt{\frac{2E_s}{\sigma_0}})\right]^{M-1} e^{(\frac{-y^2}{2})\,dy}$$, Where, $\frac{R_d P_s}{\sigma_0} = \sqrt{\frac{2E_s}{\sigma_0}}$

$$P_{e1} = 1 - \frac{1}{\sqrt{2\pi}} \left[\int_{-\infty}^{\infty} e^{-\frac{y^2}{2}} dy - \int_{-\infty}^{\infty} e^{-\frac{y^2}{2}} Q(y + \sqrt{\frac{2E_s}{\sigma_0}}) dy \right]^{M-1}$$

$$P_{e1} = 1 - \frac{1}{\sqrt{2\pi}} \left[\sqrt{2\pi} - \int_{-\infty}^{\infty} e^{-\frac{y^2}{2}} Q(y + \sqrt{\frac{2E_s}{\sigma_0}}) dy \right]^{M-1}$$

for, M=2 (binary):

$$P_{e1} = 1 - \frac{1}{\sqrt{2\pi}}\left[\sqrt{2\pi} - \int_{\infty}^{\infty} e^{-\frac{y^2}{2}} Q(y + \sqrt{\frac{2E_s}{\sigma_0}})\,dy\right] \tag{3.35}$$

$$P_{e1} = 1 - 1 + \frac{1}{\sqrt{2\pi}}\left[\int_{\infty}^{\infty} e^{-\frac{y^2}{2}} Q(y + \sqrt{\frac{2E_s}{\sigma_0}})\,dy\right]$$

$$P_{e1} = \frac{1}{\sqrt{2\pi}}\left[\int_{\infty}^{\infty} e^{-\frac{y^2}{2}} Q(y + \sqrt{\frac{2E_s}{\sigma_0}})\,dy\right]$$

3.5 Performance Analysis with convolution coding.

3.5.1 System Model

The model of the WSK-DWDM system considered for analysis is shown in Fig 3.4.

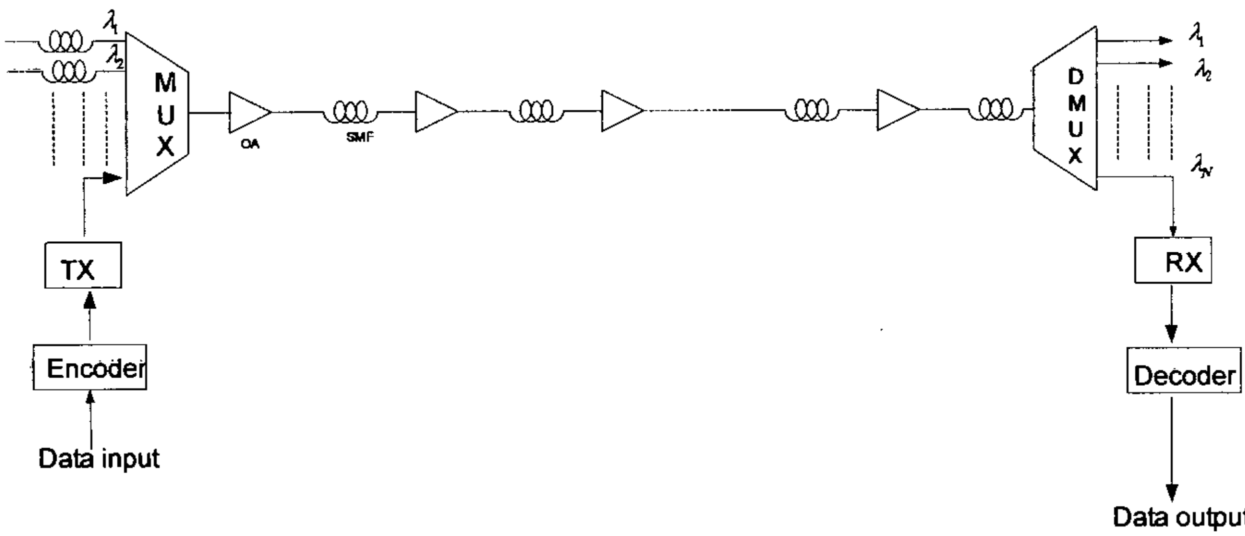


Fig: 3.4: Block diagram basic coded WSK-WDM transmission system

The system is used to combine different signal carrier wavelengths onto a single fiber at one end and separate them onto their corresponding detectors at the other end.

The Encoder encoded the data and at the receiving end the decoder decoded that data to received same signal. The convolution coding is used in this system.

Here MUX combine all of the signals and create a composite signal. This signal passes through the optical fiber and optical amplifier.

Optical amplifier amplifies an optical signal directly, without the need to first convert it to an electrical signal. An optical amplifier may be thought of as a laser without an optical cavity, or one in which feedback from the cavity is suppressed. Stimulated emission in the amplifier's gain medium causes amplification of incoming light.
And DMUX separate them. Then at the receiver we get all the signals individually.

3.5.2 BER Analysis for coded system

Three types of noise also consider in this analysis, thermal noise, shot noise and FWM and all other noise are assume to negligible. The allowable input power is determined for various transmission distances to achieve a BER of 10^{-9} for the bit rate of 10Gbps limiting each system to the same total bandwidth. It is indicating that for a given BER of 10^{-9}, WSK-WDM gives longer repeater spacing.

The probability of bit error rate (BER) for a coded (Convolution Coding) system is given by-- ----------

$$P_b \le \sum_{h=d_f}^{\infty} W_h P_e(h) . \qquad [3.36]$$

Where,

$$P_e(h) = \left[\sqrt{2P_e(1-P_e)}\right]^h$$

Where,

$$P = \Pr obability \;\; of \;\; BER \;\; rate \; for \, ucoded \;\; system.$$

$$= \frac{1}{2} erfc\left[\frac{R_d P_s}{\sigma_0 \sqrt{2}}\right]$$

Where,

$$\sigma_0 = \sqrt{P_{th} + P_{shot} + P_{fwm} + P_{s-fwm} + P_{XPM}}$$

By taking values for various values of k which is a constant length, like if take k=6 then we are considering the haming weight from 10 and if take k=7 then we are considering the haming weight from 12 and so on.

Chapter 4

RESULTS AND DISCUSSION

4.1 Introduction

The analytical results are presented and discussed in this chapter. The bit error rate (BER) performance, sensitivities and penalties are calculated as functions of the relevant receiver and input parameter for direct detection OOK and M-ary WSK-DWDM schemes. Also the performance comparisons between the two different schemes (binary and M-ary) have been presented in details.

4.2 Results and Discussion

In order to determine the effect of Bit Error Rate (BER) on the performance of OOK and direct detection M-ary WSK-WDM schemes, it has been evaluated numerically the bit error rate (BER) performance as a function of average signal count per bit considering the effect of shot noise, thermal noise and FWM. The nominal values of the parameters which are used throught the calculation are given in Table 4.1.

First the bit error rate performance have been calculated for different coded and uncoded system, wavelength and optical bandwidth as a parameter and plotted against average signal input power per channel. Then the effect of M-ary system considered and the BER performance is evaluated for different parameters. The receiver sensitivity has been calculated for a bit error rate of 10^{-9} with the effect of FWM.

Table 4.1: Nominal Parameters of Optical Communication link

Parameter Name	Value
Bit Rate, R_b	10 Gbps
Temperature, T	300
Fiber attenuation, α	0.24 dB/Km
Responsivity, R	0.85 A/W
Channel Spacing, D_{ch}	20 GHz
Load Resistance, R_l	50 ohm

4.3: The plots/results of a binary WSK-DWDM system:

Without FWM & XPM:

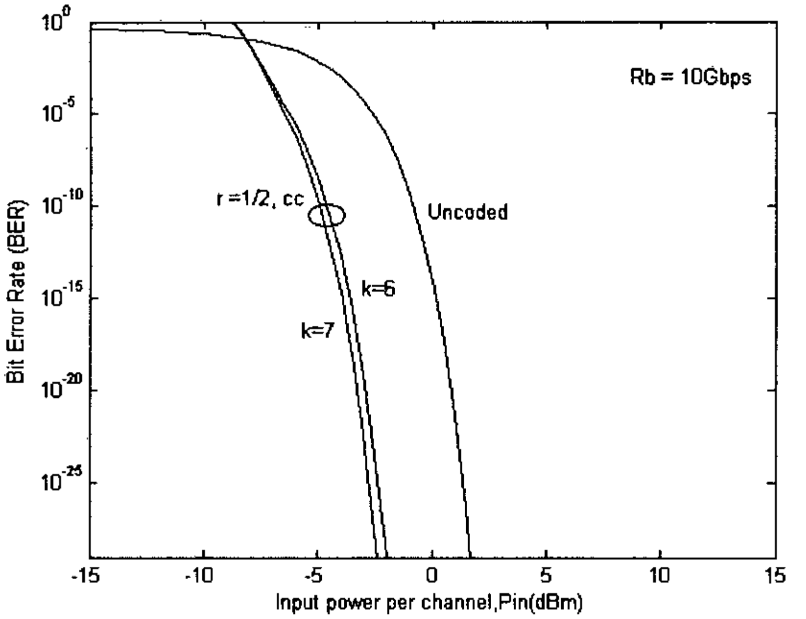


Fig 4.1: BER vs. Pin (dBm), coded and uncoded system for WSK-DWDM system.
(Br = 10 Gbps)

Following the analytical approach presented in section 3.2, the bit error rate performance results are evaluated at a data rate of 10Gbps per channel. Keeping the others parameters are constant, we compare the performance of the system with and without coding (convolution). Fig. 4.1 shows the plots of BER vs. Pin (dBm) with different constraint length (k). Table 4.2 it is found that, significant improvement of BER performance is achieved by applying convolution coding. For convolution code of rate ½, the coding gain is 5dB for constraint length k=6 and 6dB for k=7 at an uncoded BER of 10^{-9}.

Table 4.2: BER Improvement due to coding for WSK-WDM.

Pin (dBm)	Uncoded BER	BER (r=1/2, k=6)	BER (r=1/2, k=7)
-6	10^{-2}	10^{-4}	10^{-5}
-3	10^{-3}	10^{-15}	10^{-18}

<u>With FWM:</u>

Fig 4.2.shows the plot of BER vs. No. of channel (N) for coded and uncoded system at a constant input power (Pin=-2dBm) and different constraint length (k) at a rate of ½. The plot shows that the remarkable increase in number of channel for coded system than uncoded system. At a BER of 10^{-9} the number of channel used is more pronounced for Pin= -2dBm for coded system than uncoded system. The amount of improvement in channel due to coding shown in table 4.3.

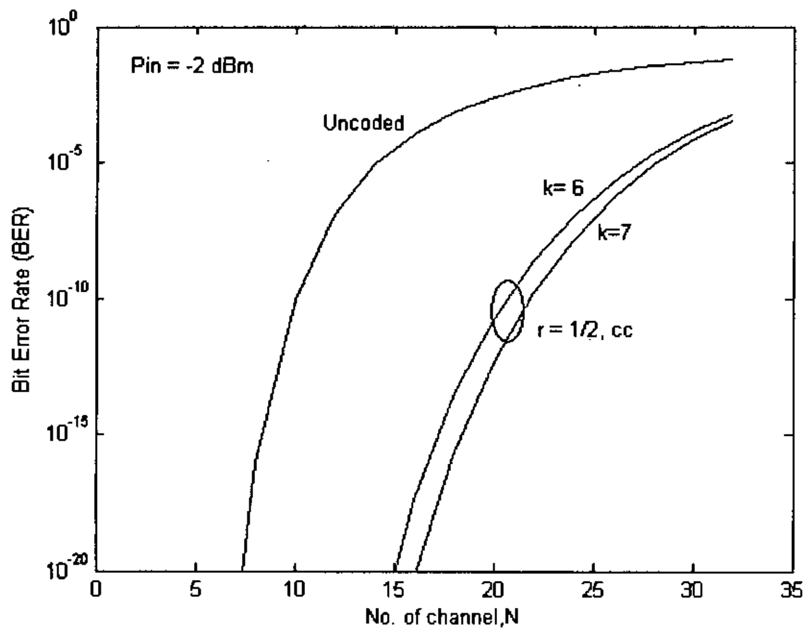


Fig 4.2: BER vs. No. of channel (N) at constant input power for WSK-DWDM system. (Br=10Gbps, Pin=-2dBm, r=1/2).

Fig 4.3 also shows the plot of BER vs. No. of channel (N) for coded and uncoded system at different input power. The plot shows that the remarkable increase in number of channel for coded system than uncoded system. When input power is increased then the allowable channel is decrease for a constant BER (10^{-9}).

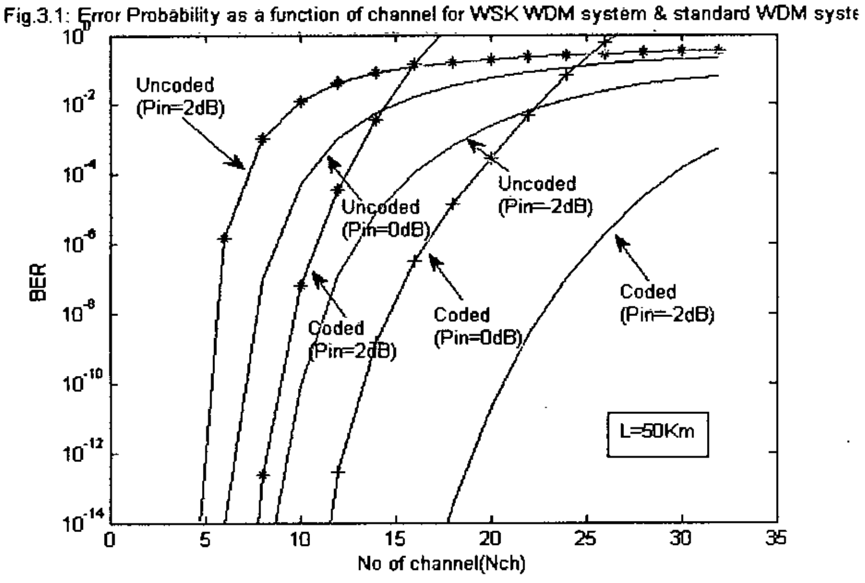


Fig 4.3: BER vs. No. of channel (N) for different input power for WSK-DWDM system. (Br=10Gbps, L=50km, r=1/2).

Table 4.3: Improvement of channel (N) due to coding at constant input power (-2dBm) at BER=10^{-8} and BER=10^{-9}.

BER	Uncoded	Coded	
		K=6, r=1/2	k=7, r=1/2
10^{-8}	12	23	24
10^{-10}	10	20	22

Fig.4.4 shows the receiver sensitivity vs. no. of channel for coded and uncoded system at constant bit error rate (10^{-9}) and constant fiber length (L=50 km) with four wave mixing (FWM). The plot shows that at a constant channel, more input power is required for uncoded system than a coded system. As a result the receiver sensitivity is improved for the coded system.

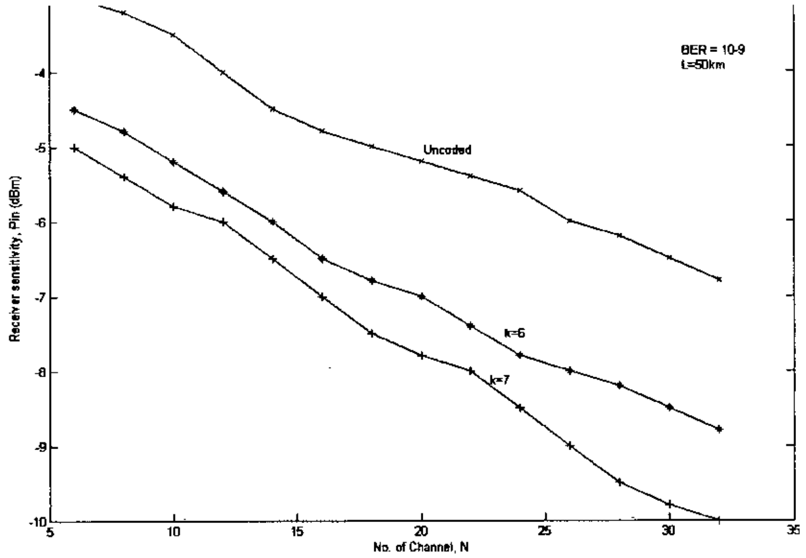


Fig: 4.4: Receiver sensitivity (Pinmax) vs. No. of channel (N) with and without coding and with FWM for WSK-DWDM system.

(Br=10Gbps, BER=10^{-9}, L=50km, Dch=20GHz, r=1/2)

Fig.4.5 shows the maximum allowable channel (N_{max}) vs. input power (P_{in}) for coded and uncoded system at constant bit error rate (10^{-9}) and constant fiber length (L=50 km) with four wave mixing (FWM). The plot shows that at a constant input power, more channel can be utilized for coded system than an uncoded system.

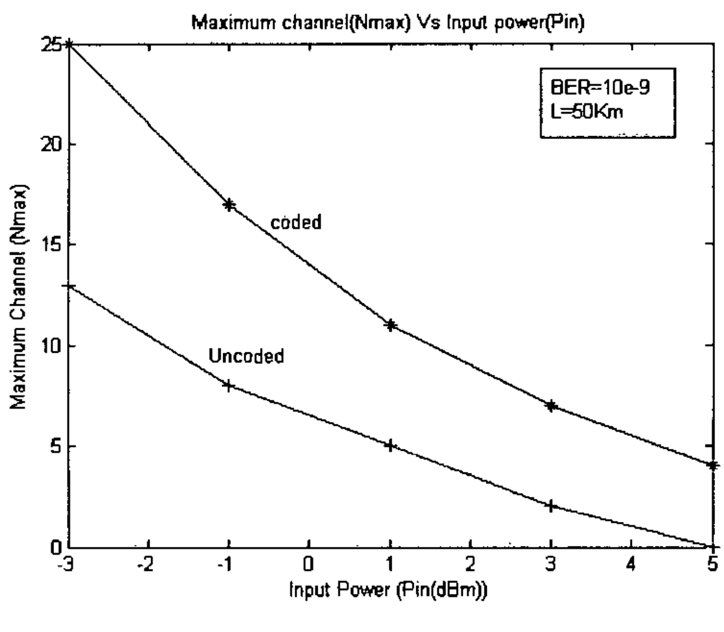


Fig: 4.5: N_{max} vs. P_{in} (dBm) with and without coding and with four wave mixing for WSK-DWDM system.

(Br=10Gbps, BER=10^{-9}, L=50km, Dch=20GHz, r=1/2)

Fig: 4.6.Shows the plots of BER vs. Pin (dBm) for uncoded and coded system with four wave mixing. It is noticed that BER performance is much better for coded system than uncoded system up to certain value of input power. After that the BER performance will start to degrade for both the system. For example at 0 dB input power, the BER for uncoded system is about 10^{-3} while for coded (k=6, r=1/2) system the BER is 10^{-11} and for coded (k=7, r=1/2) system the BER is 10^{-15}.

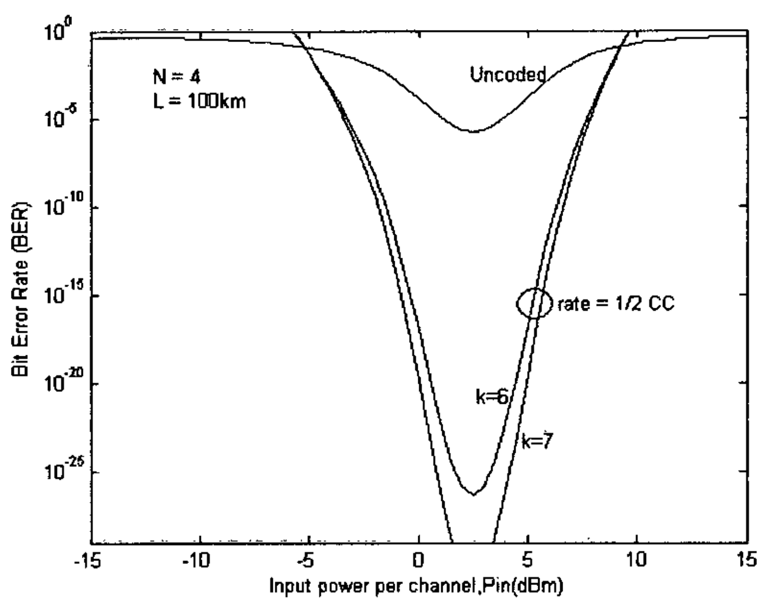


Fig: 4.6: BER vs. Pin (dBm) for coded and uncoded system with four wave mixing.
(N=4, L=100km, Br=10Gbps, r=1/2, Dch=20GHZ)

Fig: 4.7.shows the Bit Error Rate (BER) performance vs. Input power, Pin (dBm) with different no. of channel (N) at constant fiber length (L) and constant bit rate (R_b) with four wave mixing for coded system. It is observed that the bit error rate performance is degrading with increase in channel with constant fiber length. For, example, at 0 dB input power, the BER in the order of 10^{-15}, 10^{-9}, 10^{-6} for N=4, 8 and 16 respectively.

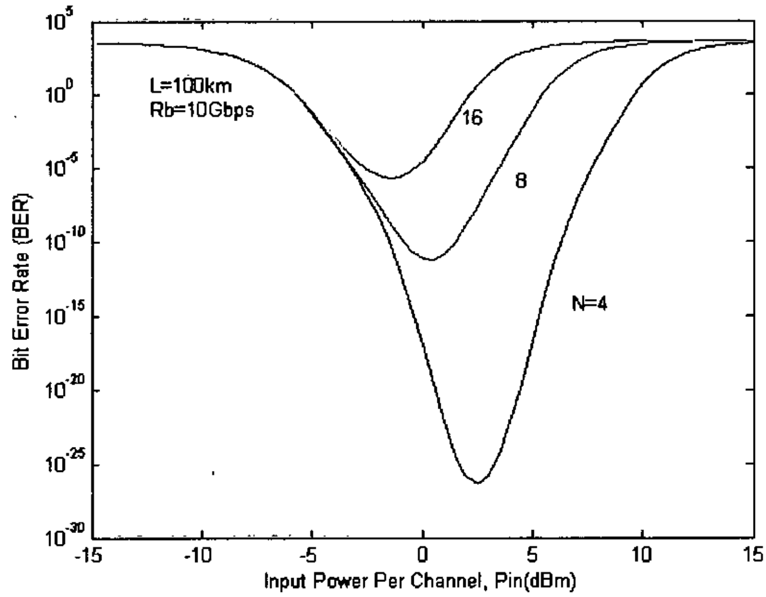


Fig: 4.7: Bit Error Rate (BER) vs. Input power per channel, Pin (dBm) for different no. of channel for WSK-DWDM.

(L=100km, Rb=10Gbps, Dch=20GHz, r=1/2, k=6)

Fig: 4.8shows the BER vs. Input power per channel, Pin (dBm) for different fiber length at a constant no. of channel and constant bit rate. It is observed that the system need more power with the increase of fiber length for same amount of BER. The amounts of power penalty suffered by the systems due to increase the fiber length at BER=10^{-9} are shown in Table 4.4.

Table 4.4: Power penalty (in dBm) due to fiber length at BER=10^{-9}.

BER=10^{-9}			
L	70km	80km	90km
Pin(dBm)	-8	-6	-2

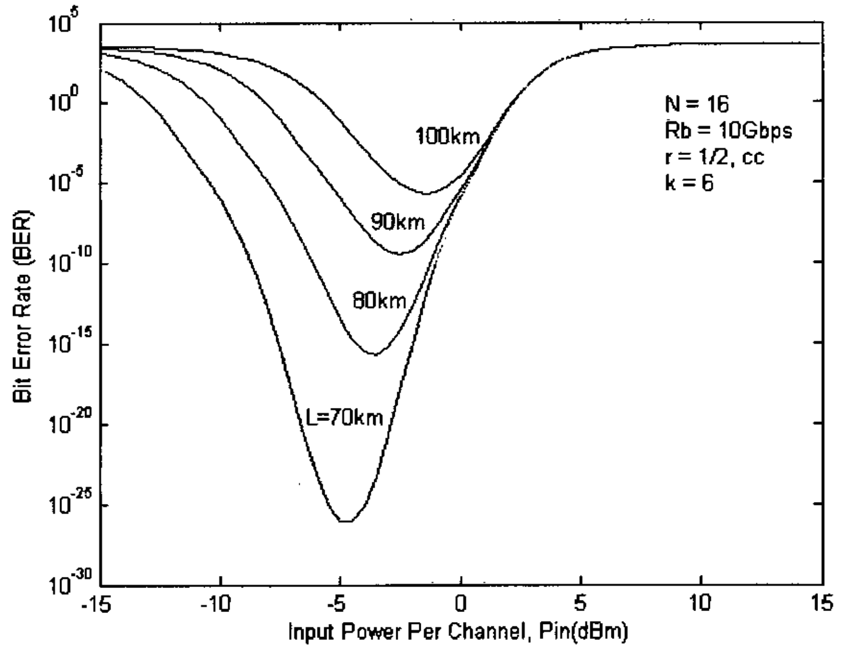


Fig: 4.8: BER vs. Pin (dBm) for different fiber length for WSK-DWDM with FWM.
(N=16, R_b=10Gbps, r=1/2, k=6, Dch=200GHz)

4.4: The plots/results of M-ary WSK-WDM system:

With FWM (uncoded):

Following the theoretical analysis presented in section 3.3, we evaluated the BER performance of WSK-DWDM system considering the effect of M-ary system. In this section, we observe the effect of BER performance for an uncoded system and compare the BER performance for binary and M-ary system with four wave mixing (FWM). From fig:4.9. It is observed that, significant improvement of BER performance is achieved for M-ary system than binary system with out coding at constant fiber length, channel and bit rate. Table 4.5. shows the BER performance improvement due to M-ary system at a given input power.

Table:4.5: BER Improvement for M-ary system than binary system for WSK-WDM system.

	Pin=0dBm	
BER	Binary	4-ary
	10^{-3}	10^{-16}

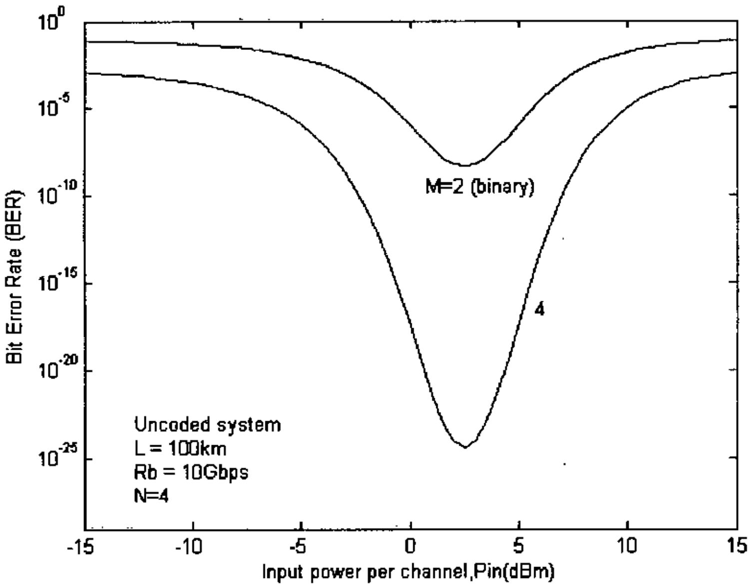


Fig: 4.9: BER vs. Pin(dBm) for binary and 4-ary uncoded system with FWM.

(L=100km, R_b = 10Gbps, N=4, uncoded, Dch=20GHz)

Fig: 4.10: shows the BER vs. input power per channel (Pin) with M=4, 8 and 16 at constant fiber length, channel and constant bit rate. We analyze the BER performance with different M value for uncoded system. It is observed that BER performance is more pronounced with increase in no. of ary (M) and results in BER floor. For example, at -15dB input power the BER for binary system is 10^{-2} while for uncoded M-ary the BER in order of 10^{-4}, 10^{-8} and 10^{-18} for M=4, 8, 16 respectively.

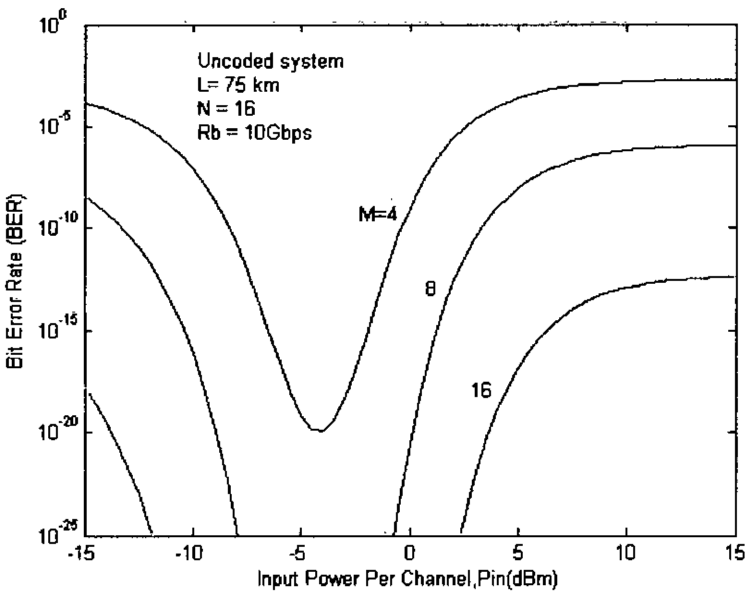


Fig: 4.10: BER vs. Input power per channel (Pin) for M-ary WSK-DWDM uncoded system.

(L=75km, N=16, R_b = 10Gbps, Dch=20GHz, uncoded system) fig: 4.11: BER vs. input power per channel , Pin (dBm) with different channel spacing. It is noticed that the WSK-WDM system suffers almost the same amount of power penalty for lower values of input power at constant BER. But at higher values of input power the amount of power penalty increase with increase in channel spacing.

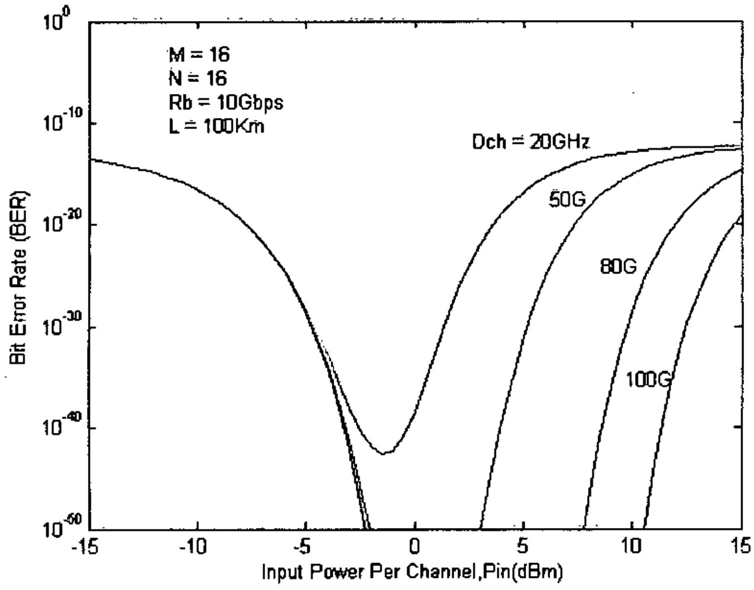


Fig: 4.11: BER vs. Pin(dBm) for WSK-DWDM system at different channel spacing. (M=16, N=16, L=100km, R_b = 10Gbps, uncoded system)

Fig4.12. illustrate the receiver sensitivity or power penalty comparison with different fiber length for multiple ary. The plots shows that the amount power penalty with increase in fiber length for a constant ary system. The table 5.3.4. shows the amount of power penalty with different fiber length at 4-ary system. The performance analyze is for uncoded system at constant BER (10^{-9}) with four wave mixing (FWM).

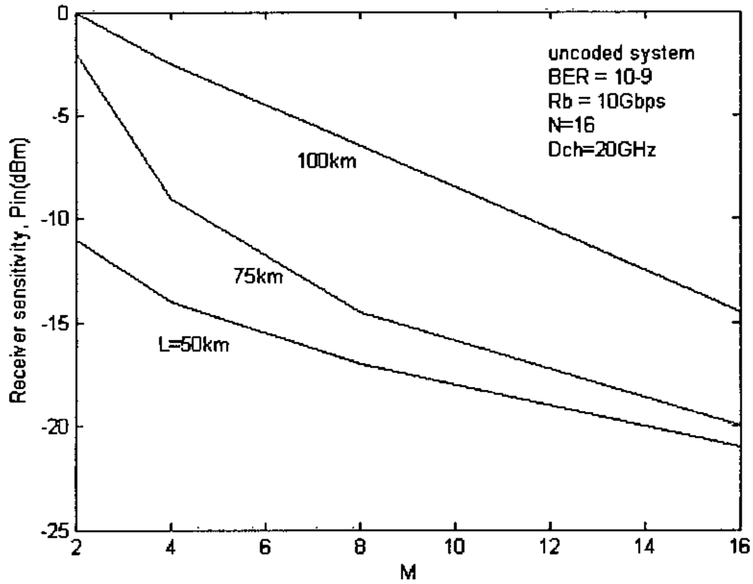


Fig: 4.12: Receiver sensitivity vs. M for WSK-WDM system at different fiber length. (BER= 10^{-9}, R_b = 10Gbps, N=16, D_{ch} = 20GHz, uncoded system.)

Table: 4.6: Amount of power penalty with increase in fiber length for WSK-WDM uncoded 4-ary system.

BER=10^{-9}, M=4			
L	50km	75km	100km
Pin(dBm)	-14	-8	-2

<u>M-WSK: With FWM and XPM</u>

Fig4.13. shows the XPM power vs. probe power in dBm. The XPM power is increased with the increase in probe power.

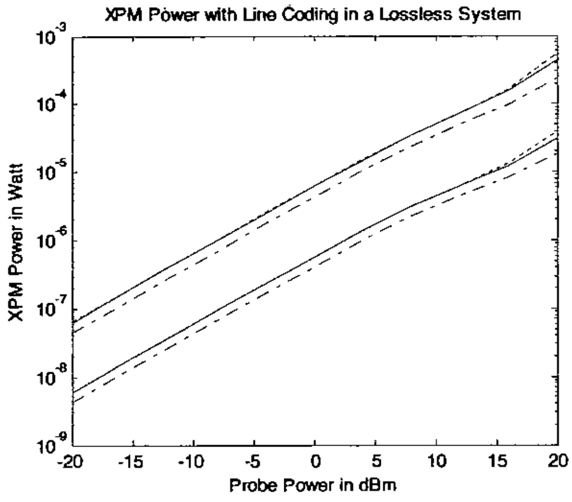


Fig 4.13: XPM Power (Watt) vs. Pin (dBm) for a WSK-DWDM system
(R_b = 10Gbps, N=16, D_{ch} = 20GHz, uncoded system.)

Fig 4.14: shows the BER vs. input power (P_{in}) with XPM and without XPM for uncoded system. It has been noticed that the BER performance is degrade with the effect of XPM. The system suffers additional power penalty due to XPM. For example, the penalty is found to be for M=4, Pin=-15dB (Without XPM) and Pin=-9dB (with XPM).

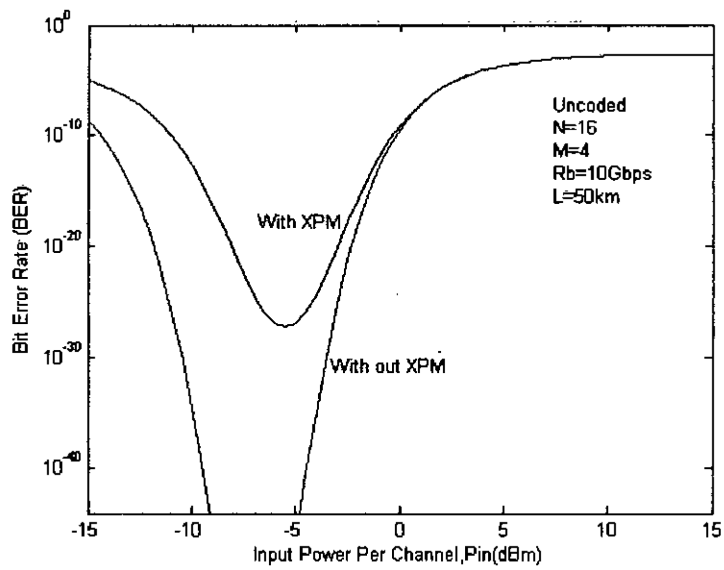


Fig 4.14: BER vs. Pin(dBm) with XPM and without XPM.
(L=50km, Rb = 10Gbps, N=16, M=4, uncoded, Dch=20GHz)

Fig 4.15 & 4.16 illustrate the BER performance for uncoded binay and 4-ary system with XPM for different fiber length. It is noticed that with the increase in fiber length the BER performance is degrade when XPM is introduce. Additional power penalty for increase in fiber length.

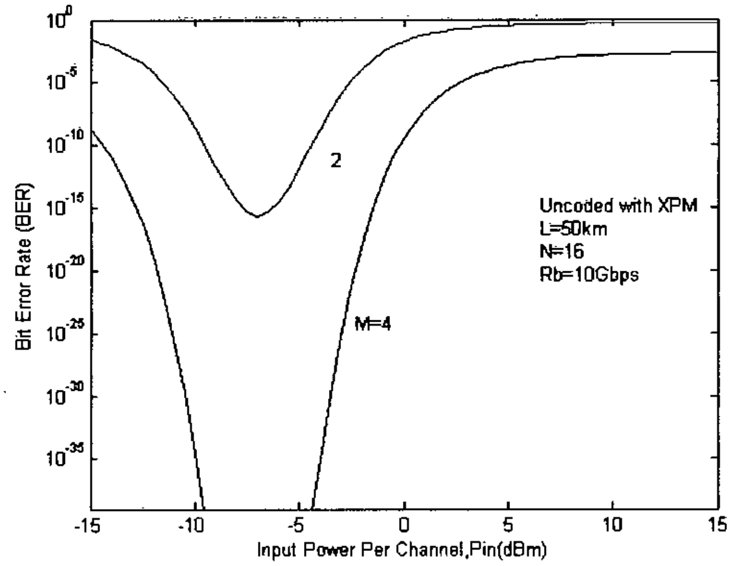


Fig 4.15: BER vs. Pin(dBm) for binary and 4-ary uncoded system with XPM and FWM. (L=50km, Rb = 10Gbps, N=4, uncoded, Dch=20GHz)

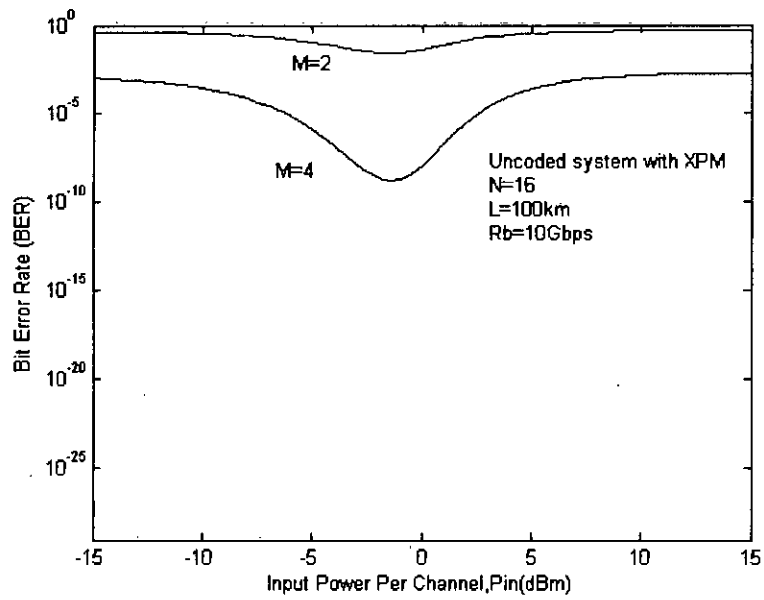


Fig 4.16: BER vs. Pin(dBm) for binary and 4-ary uncoded system with FWM. (L=100km, Rb = 10Gbps, N=16, uncoded, Dch=20GHz)

Fig 4.17: shows the BER vs. input power (P_{in}) with different XPM power. The BER performance will detoriate with increase in XPM power. At lower valu of XPM power the required input powers is less and for higher XPM power the required input power higher. So there is a remarkable power penalty with the increase in XPM power.

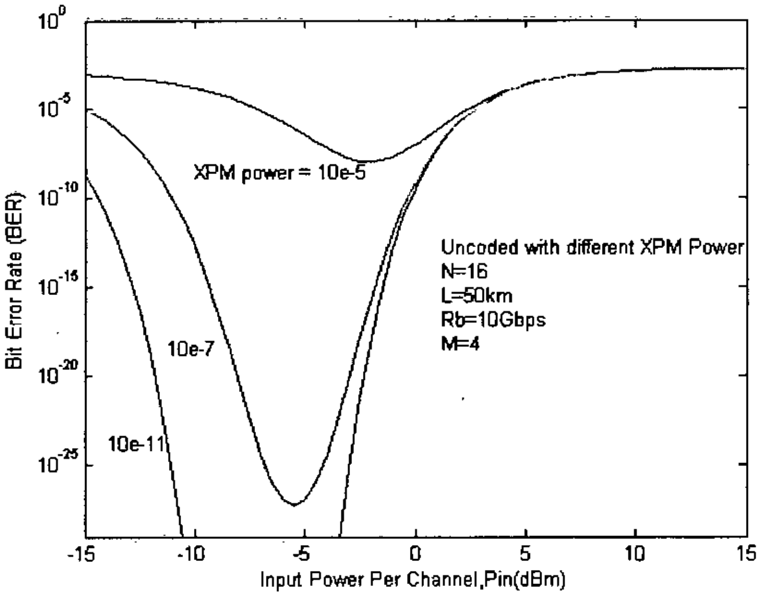


Fig 4.17: BER vs. Pin(dBm) for for different XPM power.
(L=100km, R_b = 10Gbps, N=16, uncoded, D_{ch}=20GHz)

<u>M-WSK: With Convolution coding</u>

Fig 4.18 & Fig 4.19 shows the BER vs. input power (P_{in}) for coded M-WSK system..It is clear that there is a remarkable improvement in BER performance for coded system than an uncoded system.

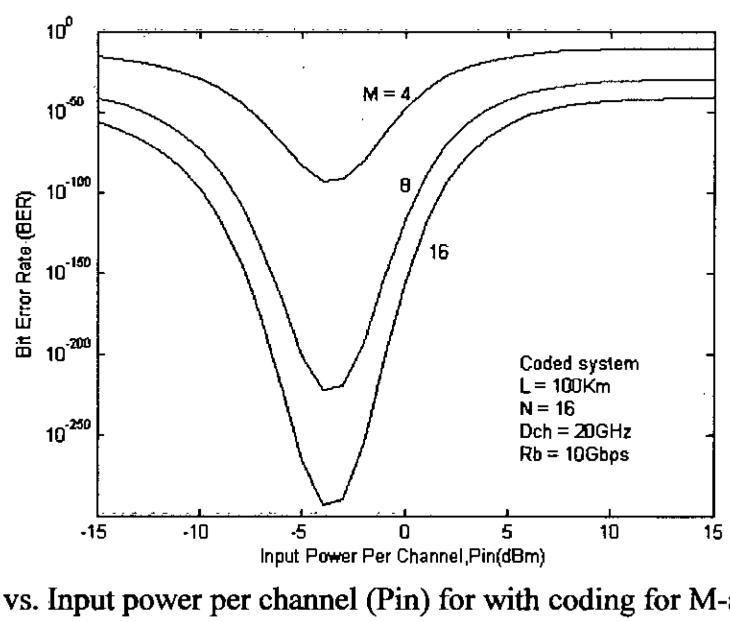


Fig 4.18: BER vs. Input power per channel (Pin) for with coding for M-ary WSK-DWDM.
(L=75km, N=16, Rb = 10Gbps, Dch=20GHz, coded system)

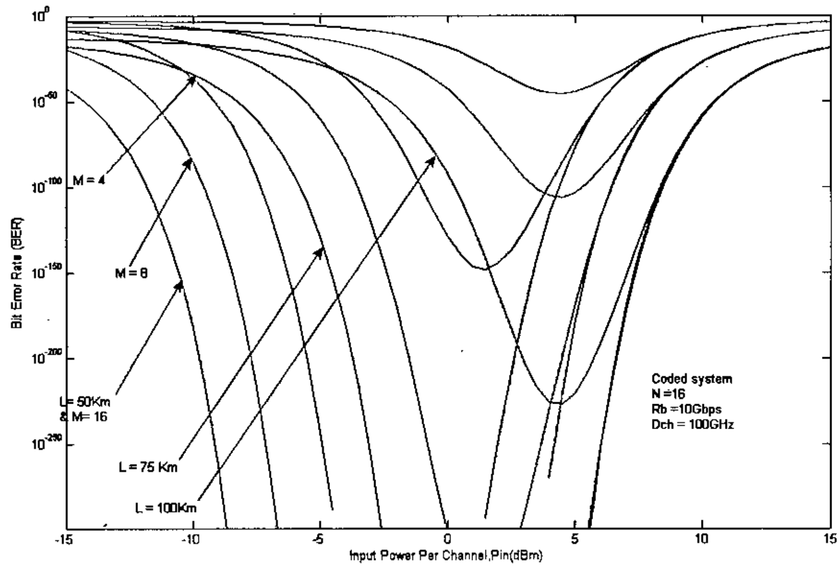


Fig 4.19: BER vs. Input power per channel (Pin) with coding for M-ary WSK-DWDM. (different length, N=16, Rb = 10Gbps, Dch=100GHz, coded system)

Table 4.7: BER improvement due to coding for M-WSK system.

P_{in} (dBm)	M=4		M=8	
	Uncoded BER	R=1/2, K=6 BER	Uncoded BER	R=1/2, K=6 BER
-15	10^{-4}	10^{-20}	10^{-8}	10^{-48}
-10	10^{-7}	10^{-30}	10^{-18}	10^{-65}

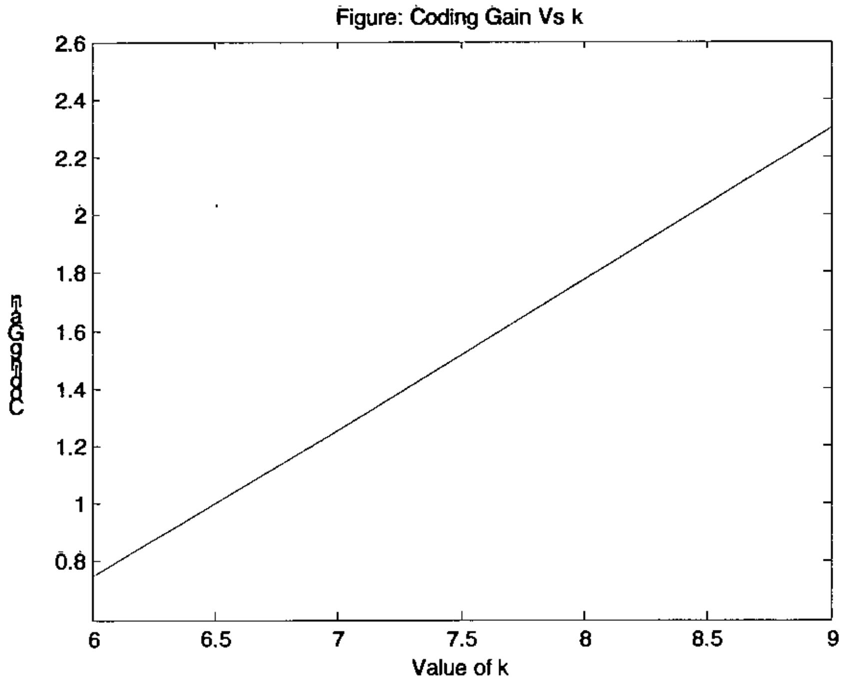


Fig 4.20: Coding Gain (CG) vs. value of K (constraint length) WSK-WDM system

This graph represents the relation between the coding gain we gathered from the previous figure and the value of k. Here we plotted the graph for k= 6, 7, 8 and the gain= 0.75dB, 1.25 dB, 2.3 dB.

Chapter 5

CONCLUSIONS AND FUTURE WORK

5.1: Conclusion

A detailed analytical approach is presented to evaluate the BER performance of WSK-DWDM in presence of XPM & FWM. The WSK-WDM system exhibits promising features that will be useful for future high speed, long distance optical networks.

FWM & XPM becomes the major source of non-linear effects causing interchannel crosstalk and channel power depletion and thereby degrading the system performance. It has been observed that the performance of WSK-DWDM system without coding is not satisfactory; rather the performance is further deteriorated when input power per channel is high. WSK-WDM can provide better performance by applying error correction coding like convolution coding.

A remarkable improvement in system performance can be achieved even for an uncoded system for M-ary WSK (M-WSK) system than binary system. This system offers much better performance: it gives much lower BER; maximum allowable input power per channel is much higher than that of other systems.

There is a significant reduction in the effect of FWM & XPM at higher order M-WSK system compared to binary. Significant amount of coding gain as well as increase in allowable input power are obtained due to rate-1/2 convolution coding compared to the system without coding.

5.2: Future Work

Further research can be carried out to find the effectiveness of line coding schemes as well as turbo codes with M-ary WSK (M-WSK) to minimize the effect of FWM.

Further research can also be initiated to find the performance of optical code division multiple access (O-CDMA) with M-ary WSK modulation.

Study can be carried out to find the effectiveness of unequal channel spacing method of minimizing FWM along with M-ary WSK (M-WSK).

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Appendix-A

Bit Error Rate (BER) for binary WSK-WDM system:

The probability of error or bit error rate (BER) is given by-

$$BER(P_e) = 0.5\,erfc[SNR] \quad \text{(A.1)}$$

where, signal-to-noise ration,

$$SNR(r) = \frac{I_s}{\sigma\sqrt{2}}$$

where, $I_s = R_d P_s(r)$

and, $\sigma = \sqrt{P_{th} + P_{shot} + P_{FWM}}$

Where,

$$P_{th} = Thermal\ noise = \frac{4kTB}{R_L}$$

and, $P_{shot} = shot\ Noise = 2eI_s B$

where,

$B = Bandwidth$

$e = electron\ charge$

$$P_{FWM} = \frac{1024\ \pi^2}{n^4 \lambda^2 c^2}\left[\frac{D\chi_{1111}\ L_{eff}}{A_{eff}}\right]^2 P_i P_j P_k e^{-\alpha L}\eta\ .$$

and,

$$P_{XPM} = 2\gamma_1 P_1(0) P_2(\omega) e^{-\alpha L} e^{-\frac{j\omega L}{V_{g1}}}$$

$$\left\{\frac{1}{a^2+(b+q)^2}\left[a.\sin(bL)-(b+q).\cos(bL)+\right.\right.$$

$$\left.[a.\sin(qL)+(b+q).\cos(qL)]\exp(-\alpha L)\right]$$

$$\frac{1}{a^2+(b-q)^2}\left[a.\sin(bL)-(b-q).\cos(bL)+\right.$$

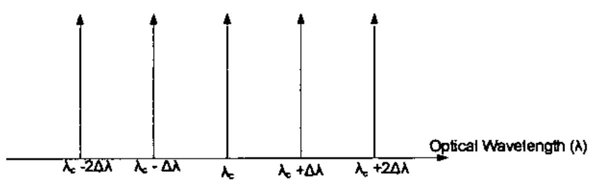
$$\left.\left.[-a.\sin(qL)+(b-q)\cos(qL)]\exp(-\alpha L)\right]\right\}$$

Appendix-B

Bit Error rate (BER) M-ray WSK-WDM system:

In orthogonal MWSK, the M=2k district symbols are represented by M-WSK waveforms

$S_m(t) = ACos(W_m t + \phi_m)$, where, m = 1, 2, ..., M (B.1)



where

$$W_m = 2\pi f_m = \frac{2\pi C}{\lambda_m}$$

ϕ_m = initial phase

A = Signal amplitude

$T_s = KT_b$ = Signaling interval

T_b = bit duration

$E_s = \frac{A^2 T_s}{2}$ = Signal Energy

= Energy/symbol

Cohereat:

To derive the average probability of symbol error, we assume that the signal (S, H) was sent and received signal

r(t)=S_1 (t)+ n(t)

—

Where,

n(t)=AWGN with zero mean.

Where,

$S_1 = E_s + n_1$

$S_m = n_m$,m=2,3........M

$n_m = \int_0^{T_s} n(t) S_m(t) dt$

The output of photo detector (PD):

$$i_m = R_d \left|S_m(t) + S_{fwm}(t)\right|^2 \qquad (B.2)$$

$$= R_d \left|S_m(t)\right|^2 + R_d \left|S_{fwm}(t)\right|^2$$

$$= R_d \left|\left\{\sqrt{2P_s}\cos(\omega_m t + \phi)\right\}\right|^2 + R_d \left|P_{th}\right| + R_d \left|P_{sh}\right| + R_d \left|P_{fwm}\right| + R_d \left|P_{XPM}\right|, \ where, S_m(t) = \sqrt{2P_s}\cos(\omega_m t + \phi)$$

Considering only FWM & XPM,

$$= R_d \left|\left\{\sqrt{2P_s}\cos(\omega_m t + \phi)\right\}\right|^2 + R_d \left|\frac{1024\pi^2}{n^4\lambda^2 c^2}\left[\frac{D\chi_{1111} L_{eff}}{A_{eff}}\right]^2 P_i P_j P_k e^{-\alpha L}\eta\right| + R_d \left|P_{XPM}\right|, where\ m = 2,3,4........$$

$$= R_d\, 2P_s \cos^2(\omega_m t + \phi) + R_d \left|\frac{1024\pi^2}{n^4\lambda^2 c^2}\left[\frac{D\chi_{1111} L_{eff}}{A_{eff}}\right]^2 P_i P_j P_k e^{-\alpha L}\eta\right| + R_d \left|P_{XPM}\right|$$

$$= R_d P_s [1 + \cos 2(\omega_m t + \phi)] + R_d \left|\frac{1024\pi^2}{n^4\lambda^2 c^2}\left[\frac{D\chi_{1111} L_{eff}}{A_{eff}}\right]^2 P_i P_j P_k e^{-\alpha L}\eta\right| + R_d \left|P_{XPM}\right|$$

$$= R_d P_s + R_d P_s \cos 2(\omega_m t + \phi) + R_d \left|\frac{1024\pi^2}{n^4\lambda^2 c^2}\left[\frac{D\chi_{1111} L_{eff}}{A_{eff}}\right]^2 P_i P_j P_k e^{-\alpha L}\eta\right| + R_d \left|P_{XPM}\right| \qquad (B.3)$$

Then we can write,

When m=1, then $i_1 = R_d P_s + n_1$

And, $i_m = n_m$, *where* $m = 2,3,4.......M.$

Where, n is AWGN with zero mean.

The signal to noise ratio (SNR):

$$SNR = \frac{R_d P_S}{\sigma_0} \qquad (B.4)$$

Where, $\sigma_0 = \sqrt{P_{th} + P_{sh} + P_{FWM} + P_{s-fwm} + P_{XPM}}$

and,

$$P_{th} = Thermal\ noise = \frac{4KTB}{R_L}$$

$$P_{sh} = Shot\ noise = 2\, e\, I_S\, B$$

$$P_{FWM} = R_d^{\,2} \cdot \left[\frac{1024\Pi^2}{n^4 \lambda^2 c^2} \left[\frac{D\chi_{1111} L_{eff}}{A_{eff}} \right]^2 P_i P_j P_k e^{-\alpha L} \eta \right].$$

$$P_{s-fwm} = 2(R_d\, P_{fwm})(R_d\, P_s)$$

$$= 2\, R_d^{\,2}\, P_{fwm} P_s.$$

$$P_{XPM} = 2\gamma_1\, P_1(0)\, P_2(\omega)\, e^{-\alpha L}\, e^{-\frac{j\omega L}{V_{g1}}}$$

$$\left\{ \frac{1}{a^2 + (b+q)^2} [a.\sin(bL) - (b+q).\cos(bL) + \right.$$

$$[a.\sin(qL) + (b+q).\cos(qL)]\exp(-\alpha L)]$$

$$\frac{1}{a^2 + (b-q)^2} [a.\sin(bL) - (b-q).\cos(bL) +$$

$$\left. [-a.\sin(qL) + (b-q)\cos(qL)]\exp(-\alpha L)] \right\}$$

The probability density function of S_m, given that S_1 (t) was sent is

$$P(\frac{S_m}{S_1}) = \frac{e^{-\frac{[(S_m - \delta_{1m} E_s)^2}{E_s N_0}}}{\sqrt{\Pi E_s N_0}} \qquad (B.5)$$

$$P(\frac{S_m}{S_1}) = \frac{e^{-\{\frac{S_m - \delta_{1m} E_s)^2}{E_s N_0}}}{\sqrt{\Pi E_s N_0}}$$

Thus the probability that the demodulator will make an impact decision is simply

$$P_{e1} = 1 - P_r(\frac{S_2 \langle S_1 \cap S_3 \langle S_1 \cap \ldots\ldots \cap S_m \langle S_1}{S_1}) \qquad (B.6)$$

$$= 1 - \int_{-\infty}^{\infty}\int_{-\infty}^{S_1} \ldots\ldots\ldots\ldots \int_{-\infty}^{S_1} P(\frac{S_1, S_2 \ldots\ldots S_M}{S_1}) ds_1 dr ds_M$$

Now

$$P(\frac{S_1, S_2, \ldots\ldots\ldots S_M}{S_1}) = \prod_{m=1}^{M} P(\frac{S_m}{S_1})$$

$$P_{e1} = 1 - \int_{-\infty}^{\infty}\left[\int_{-\infty}^{S_1} P\left(\left(\frac{S_M}{S_1}\right) dS_M\right)\right]^{M-1} P\left(\frac{S_1}{S_1}\right) dS_1 \qquad \text{(B.7)}$$

Now,

$$\int_{-\infty}^{S_1} P\left(\left(\frac{S_M}{S_1}\right) dS_M\right) = 1 - \int_{S_1}^{\infty} \frac{e^{-\frac{S_M{}^2}{E_S N_0}}}{\sqrt{\pi E_S N_0}} dS_M$$

$$Let, x = \sqrt{\frac{2}{E_S N_0}}\ S_m$$

$$\int_{-\infty}^{S_1} P(S_M / S_1) dS_m = 1 - \int_{\sqrt{\frac{2}{E_S N_0}} S_1}^{\infty} \frac{e^{-\frac{x^2}{2}}}{\sqrt{2\pi}} dx$$

$$= 1 - Q(\sqrt{\frac{2}{E_S N_0}}\ S_1)$$

By substitution we get,

$$P_{e1} = 1 - \int_{-\infty}^{\infty}\left[1 - Q\left(\sqrt{\frac{2}{E_S N_o}}\ .S_1\right)\right]^{M-1} \frac{e^{-\frac{(S_1 - E_S)^2}{E_S N_o}}}{\sqrt{\pi E_S N_o}} dS_1$$

Now, *let*, $y = \sqrt{\frac{2}{E_S N_0}}\ (S_1 - E_s)$, then P_{e1} becomes,

$$P_{e1} = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty}\left[1 - Q\left(y + \sqrt{\frac{2E_S}{N_o}}\right)\right]^{M-1} e^{(\frac{-y^2}{2})} dy$$

Let, $y_1 = 1 - Q\left(y + \sqrt{\frac{2E_s}{N_0}}\right)^{M-1} = 1 - Q\left(y + \frac{R_d\, P_s}{\sigma_0}\right)^{M-1}$

where, $Q(y) = \frac{1}{\sqrt{2\pi}} \int_y^{\infty} e^{(\frac{-y^2}{2})} dy$ = Gaussian Integral Function = $0.5\, erfc(\frac{y}{\sqrt{2}})$.

$$y_2 = e^{-\frac{y^2}{2}}$$

so, $P_{e1} = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} [y_1\, y_2]\, dy$

We can write, the probability of BER for WSK-WDM system,

$$P_{e1} = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} [1 - Q(y + \frac{R_d P_S}{\sigma_O})]^{M-1}\; e^{(\frac{-y^2}{2})\, dy} \qquad \text{(B.8)}$$

where, $\sigma_0 = \sqrt{P_{th} + P_{shot} + P_{fwm} + P_{s-fwm}}$.

and, $$\begin{aligned} P_{s-fwm} &= 2(R_d\, P_{fwm})(R_d\, P_s) \\ &= 2\, R_d^{\,2}\, P_{fwm}\, P_s. \end{aligned}$$

$$P_{e1} = 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \left[1 - Q(y + \sqrt{\frac{2E_s}{\sigma_0}}) \right]^{M-1} e^{(\frac{-y^2}{2})\, dy}, \text{ Where, } \frac{R_d\, P_s}{\sigma_0} = \sqrt{\frac{2E_s}{\sigma_0}}$$

$$P_{e1} = 1 - \frac{1}{\sqrt{2\pi}} \left[\int_{-\infty}^{\infty} e^{-\frac{y^2}{2}} dy - \int_{-\infty}^{\infty} e^{-\frac{y^2}{2}} Q(y + \sqrt{\frac{2E_s}{\sigma_0}})\, dy \right]^{M-1}$$

$$P_{e1} = 1 - \frac{1}{\sqrt{2\pi}} \left[\sqrt{2\pi} - \int_{-\infty}^{\infty} e^{-\frac{y^2}{2}} Q(y + \sqrt{\frac{2E_s}{\sigma_0}})\, dy \right]^{M-1}$$

for, M=2 (binary):

$$P_{e1} = 1 - \frac{1}{\sqrt{2\pi}} \left[\sqrt{2\pi} - \int_{-\infty}^{\infty} e^{-\frac{y^2}{2}} Q(y + \sqrt{\frac{2E_s}{\sigma_0}})\, dy \right] \qquad \text{(B.9)}$$

$$P_{e1} = 1 - 1 + \frac{1}{\sqrt{2\pi}} \left[\int_{-\infty}^{\infty} e^{-\frac{y^2}{2}} Q(y + \sqrt{\frac{2E_s}{\sigma_0}})\, dy \right]$$

$$P_{e1} = \frac{1}{\sqrt{2\pi}} \left[\int_{-\infty}^{\infty} e^{-\frac{y^2}{2}} Q(y + \sqrt{\frac{2E_s}{\sigma_0}})\, dy \right]$$

Appendix-C

Weigh Spectrum of convolutional encoders:

Hamming Weight d	W(d) for R=1/2	W(d) for R=1/3
10	3.6×10^{01}	-
11	0	-
12	2.11×10^{02}	-
13	0	-
14	1.404×10^{03}	-
15	0	1.1
16	1.633×10^{04}	1.6
17	0	1.9
18	7.7433×10^{04}	2.8
19	0	5.5
20	5.0269×10^{05}	9.6
21	0	1.69×10^{02}
22	3.322763×10^{06}	3.38×10^{02}
23	0	6.36×10^{02}
24	2.129291×10^{07}	1.276×10^{03}
25	0	2.172×10^{03}
26	1.3436491×10^{08}	-

Appendix-D

ABSCISSAS AND WEIGHT FACTORS FOR HERMITE INTEGRATION

$$\int_{-\infty}^{\infty} e^{-x^2} f(x)\,dx \approx \sum_{i=1}^{n} w_i f(x_i)$$

$$\int_{-\infty}^{\infty} g(x)\,dx \approx \sum_{i=1}^{n} w_i e^{x_i^2} g(x_i)$$

Abscissas $= \pm x_i$ (Zeros of Hermite Polynomials) Weight Factors $= w_i$

$\pm x_i$	w_i	$w_i e^{x_i^2}$
	$n=2$	
0.70710 67811 86548	(-1)8.86226 92545 28	1.46114 11826 611
	$n=3$	
0.00000 00000 00000	(0)1.18163 59006 04	1.18163 59006 037
1.22474 48713 91589	(-1)2.95408 97515 09	1.32393 11752 136
	$n=4$	
0.52464 76232 75290	(-1)8.04914 09000 55	1.05996 44828 950
1.65068 01238 85785	(-2)8.13128 35447 25	1.24022 58176 958
	$n=5$	
0.00000 00000 00000	(-1)9.45308 72048 29	0.94530 87204 829
0.95857 24646 13819	(-1)3.93619 32315 22	0.98658 09967 514
2.02018 28704 56086	(-2)1.99532 42059 05	1.18148 86255 360
	$n=6$	
0.43607 74119 27617	(-1)7.24629 59522 44	0.87640 13344 362
1.33584 90740 13697	(-1)1.57067 32032 29	0.93558 05576 312
2.35060 49736 74492	(-3)4.53000 99055 09	1.13690 83326 745
	$n=7$	
0.00000 00000 00000	(-1)8.10264 61755 68	0.81026 46175 568
0.81628 78828 58965	(-1)4.25607 25261 01	0.82868 73032 836
1.67355 16287 67471	(-2)5.45155 82819 13	0.89718 46002 252
2.65196 13568 35233	(-4)9.71781 24509 95	1.10133 07296 103
	$n=8$	
0.38118 69902 07322	(-1)6.61147 01255 82	0.76454 41286 517
1.15719 37124 46780	(-1)2.07802 32581 49	0.79289 00483 864
1.98165 67566 95843	(-2)1.70779 83007 41	0.86675 26065 634
2.93063 74202 57244	(-4)1.99604 07221 14	1.07193 01442 480
	$n=9$	
0.00000 00000 00000	(-1)7.20235 21560 61	0.72023 52156 061
0.72355 10187 52838	(-1)4.32651 55900 26	0.73030 24527 451
1.46855 32892 16668	(-2)8.84745 27394 38	0.76460 81250 946
2.26658 05845 31843	(-3)4.94362 42755 37	0.84175 27014 787
3.19099 32017 81528	(-5)3.96069 77263 26	1.04700 35809 767

$\pm x_i$	w_i	$w_i e^{x_i^2}$
	$n=10$	
0.34290 13272 23705	(- 1)6.10862 63373 53	0.68708 18539 513
1.03661 08297 89514	(- 1)2.40138 61108 23	0.70329 63231 049
1.75668 36492 99882	(- 2)3.38743 94455 48	0.74144 19319 436
2.53273 16742 32790	(- 3)1.34364 57467 81	0.82066 61264 048
3.43615 91188 37738	(- 6)7.64043 28552 33	1.02545 16913 657
	$n=12$	
0.31424 03762 54359	(- 1)5.70135 23626 25	0.62930 78743 695
0.94778 83912 40164	(- 1)2.60492 31026 42	0.63962 12320 203
1.59768 26351 52605	(- 2)5.16079 85615 88	0.66266 27732 669
2.27950 70805 01060	(- 3)3.90539 05846 29	0.70522 03661 122
3.02063 70251 20890	(- 5)8.57368 70435 88	0.78664 39394 633
3.88972 48978 69782	(- 7)2.65855 16843 56	0.98969 90470 923
	$n=16$	
0.27348 10461 3815	(- 1)5.07929 47901 66	0.54737 52050 378
0.82295 14491 4466	(- 1)2.80647 45852 85	0.55244 19573 675
1.38025 85391 9888	(- 2)8.38100 41398 99	0.56321 78290 882
1.95178 79909 1625	(- 2)1.28803 11535 51	0.58124 72754 009
2.54620 21578 4748	(- 4)9.32284 00862 42	0.60973 69582 560
3.17699 91619 7996	(- 5)2.71186 00925 38	0.65575 56728 761
3.86944 79048 6012	(- 7)2.32098 08448 65	0.73824 56222 777
4.68873 89393 0582	(-10)2.65480 74740 11	0.93687 44928 841
	$n=20$	
0.24534 07083 009	(- 1)4.62243 66960 06	0.49092 15006 667
0.73747 37285 454	(- 1)2.86675 50536 28	0.49384 33852 721
1.23407 62153 953	(- 1)1.09017 20602 00	0.49992 08713 363
1.73853 77121 166	(- 2)2.48105 20887 46	0.50967 90271 175
2.25497 40020 893	(- 3)3.24377 33422 38	0.52408 03509 486
2.78880 60584 281	(- 4)2.28338 63601 63	0.54485 17423 644
3.34785 45673 832	(- 6)7.80255 64785 32	0.57526 24428 525
3.94476 40401 156	(- 7)1.08606 93707 69	0.62227 86961 914
4.60368 24495 507	(-10)4.39934 09922 73	0.70433 29611 769
5.38748 08900 112	(-13)2.22939 36455 34	0.89859 19614 532