PERFORMANCE ANALYSIS OF AN OPTICAL CROSS CONNECT AT DWDM SYSTEM

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Abstract

Performance analysis was carried out to find the effect of crosstalk in a WDM system. Firstly, analysis of BER was carried out without crosstalk. Then analysis of BER with crosstalk was done. Using equation for crosstalk, number of channels was plotted using matlab. System parameters were optimized for a particular crosstalk.

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Chapter 1

INTRODUCTION

OPTICAL wavelength division multiplexing (WDM) networks are very promising due to their large bandwidth, their large flexibility and the possibility to upgrade the existing optical fiber networks to WDM networks. WDM has already been introduced in commercial systems. All-optical cross connects (OXC), however, have not yet been used for the routing of the signals in any of these commercial systems. Several OXC topologies have been introduced, but their use has so far been limited to field trials, usually with a small number of input–output fibers and wavelength channels. The fact, that in practical systems many signals and wavelength channels could influence each other and cause significant crosstalk in the optical cross connect, has probably prevented the use of OXC's in commercial systems. The crosstalk levels in OXC configurations presented so far are generally so high that they give rise to a significant signal degradation and to an increased bit error probability. Because of the complexity of an OXC, different sources of crosstalk exist, which makes it difficult to optimize the component parameters for minimum total crosstalk. In this paper, the crosstalk with the bit error rate and without bit error rate is calculated and compared with each other, and the influence of the component crosstalk on the total crosstalk is identified. We present an analytical approximation for the total crosstalk level in a WDM system, which makes the component parameter optimization considerably easier.

This paper is divided into three chapters. In the first chapter Optical Fiber Communication process is explained. In the second chapter the analysis of crosstalk in WDM system with the system block designs. The third and the last part contains the results and discussions with graphical representations of various analysis that has been made through-out.

1.1: Introduction to Optical Communication

Optical communication is any form of telecommunication that uses light as a transmission medium. An optical communication system consists of a transmitter which encodes a message into an optical signal channel which carries the signal to its destination and a receiver which reproduces the message from the received optical signal.

Optical communication systems are used to provide high-speed communication connections. Optical communication is one of the newest and most advanced forms of communication by electromagnetic waves. In one sense, it differs from radio and microwave communication only in that the wavelengths employed are shorter (or equivalently, the frequencies employed are higher). However, in another very real sense it differs markedly from these older technologies because, for the first time, the wavelengths involved are much shorter than the dimensions of the devices which are used to transmit, receive, and otherwise handle the signals.

The advantages of optical communication are threefold. First, the high frequency of the optical carrier (typically of the order of 300,000 GHz) permits much more information to be transmitted over a single channel than is possible with a conventional radio or microwave system. Second, the very short wavelength of the optical carrier (typically of the order of 1 micrometer permits the realization of very small, compact components. Third, the highest transparency for electromagnetic radiation yet achieved in any solid material is that of silica glass in the wavelength region 1–1.5 μm. This transparency is orders of magnitude higher than that of any other solid material in any other part of the spectrum.

Optical communication in the modern sense of the term dates from about 1960, when the advent of lasers and light-emitting diodes (LEDs) made practical the exploitation of the wide-bandwidth capabilities of the light wave.

1.2: Optical Fibre

An optical fiber (or fibre) is a glass or plastic fiber that carries light along its length. Fiber optics is the overlap of applied science and engineering concerned with the design and application of optical fibers. Optical fibers are widely used in fiber-optic communications, which permits transmission over longer distances and at higher bandwidths (data rates) than other forms of communications. Fibers are used instead of metal wires because signals travel along them with less loss, and they are also immune to electromagnetic interference. Fibers are also used for illumination, and are wrapped in bundles so they can be used to carry images, thus allowing viewing in tight spaces. Specially designed fibers are used for a variety of other applications, including sensors and fiber lasers.

Light is kept in the core of the optical fiber by total internal reflection. This causes the fiber to act as a waveguide. Fibers which support many propagation paths or transverse modes are called multi-mode fibers (MMF), while those which can only support a single mode are called single-mode fibers (SMF). Multi-mode fibers generally have a larger core diameter, and are used for short-distance communication links and for applications where high power must be transmitted. Single-mode fibers are used for most communication links longer than 550 metres (1,800 ft).

Joining lengths of optical fiber is more complex than joining electrical wire or cable. The ends of the fibers must be carefully cleaved, and then spliced together either mechanically or by fusing them together with an electric arc. Special connectors are used to make removable connections.

Optical fibers can be used as sensors to measure strain, temperature, pressure and other quantities by modifying a fiber so that the quantity to be measured modulates the intensity, phase, polarization, wavelength or transit time of light in the fiber. In some buildings, optical fibers are used to route sunlight from the roof to other parts of the building (see non-imaging optics). Optical fiber illumination is also used for decorative applications, including signs, art, and artificial Christmas trees. Swarovski boutiques use optical fibers to illuminate their crystal showcases from many different angles while only employing one light source. Optical fiber is an intrinsic part of the light-transmitting concrete building product, LiTraCon.

Optical fiber is also used in imaging optics. A coherent bundle of fibers is used, sometimes along with lenses, for a long, thin imaging device called an endoscope, which is used to view objects through a small hole. Medical endoscopes are used for minimally invasive exploratory or surgical procedures. Industrial endoscopes are used for inspecting anything hard to reach, such as jet engine interiors.

In spectroscopy, optical fiber bundles are used to transmit light from a spectrometer to a substance which cannot be placed inside the spectrometer itself, in order to analyze its composition. A spectrometer analyzes substances by bouncing light off of and through them. By using fibers, a spectrometer can be used to study objects that are too large to fit inside, or gasses, or reactions which occur in pressure vessels.

Different Types of Fiber

Three basic types of fiber optic cable are used in communication systems:

1. Step-index multimode
2. Step-index single mode
3. Graded-index

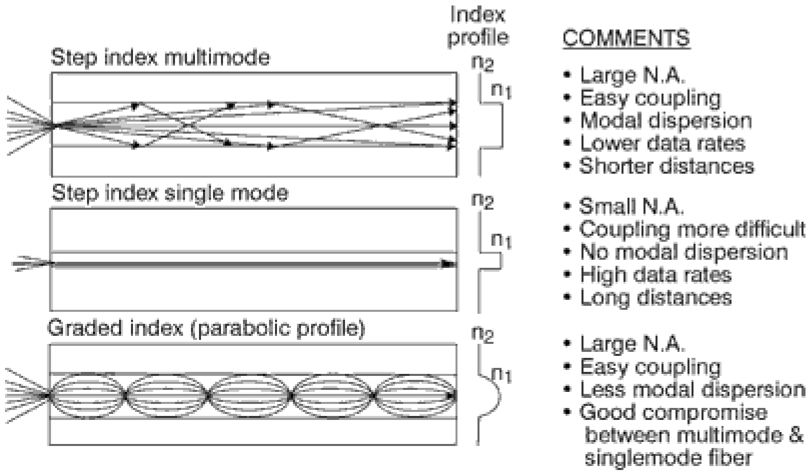


Figure1.2: Different types of fiber

Step-index multimode fiber has an index of refraction profile that steps from low to high to low as measured from cladding to core to cladding.

Single-mode step-index fiber allows for only one path, or mode, for light to travel within the fiber.

Graded-index fiber is a compromise between the large core diameter and N.A. of multimode fiber and the higher bandwidth of single-mode fiber.

An optical fiber consists of a core, cladding, and a buffer (a protective outer coating), in which the cladding guides the light along the core by using the method of total internal reflection. The core and the cladding (which has a lower-refractive-index) are usually made of high-quality silica glass, although they can both be made of plastic as well. Connecting two optical fibers is done by fusion splicing or mechanical splicing and requires special skills and interconnection technology due to the microscopic precision required to align the fiber cores. Two main types of optical fiber used in fiber optic communications include multi-mode optical fibers and single-mode optical fibers.

Optical fiber has two low-attenuation regions. Centered at approximately 1300 nm is a range of 200 nm in which attenuation is less than 0.5 dB/km. The total bandwidth in this region is about 25 T Hz. Centered at 1550 nm is a region of similar size with attenuation as low as 0.2 dB/km. Combined, these two regions provide a theoretical upper bound of 50 THz of bandwidth. By using these large low-attenuation areas for data transmission, the signal loss for a set of one or more wavelengths can be made very small, thus reducing the number of amplifiers and repeaters actually needed. Besides its enormous bandwidth and low attenuation, fiber also offers low error rates.

1.3: Optical Modulation Scheme

Optical Modulation is the addition of information (or the signal) to an electronic or optical signal carrier. Modulation is the process of transforming a message signal to make it easier to work with. It usually involves varying one waveform in relation to another waveform. Modulation can be applied to direct current (mainly by turning it on and off), to alternating current, and to optical signals. One can think of blanket waving as a form of modulation used in smoke signal transmission (the carrier being a steady stream of smoke). Morse code, invented for telegraphy and still used in amateur radio, uses a binary (two-state) digital code similar to the code used bymodern computers. For most of radio and telecommunication today, the carrier is alternating current (AC) in a given range of frequencies. Common modulation methods include:

Intensity modulation (IM):

In optical communications, intensity modulation (IM) is a form of modulation in which the optical power output of a source is varied in accordance with some characteristic of the modulating signal.

In intensity modulation, there are no discrete upper and lower sidebands in the usually understood sense of these terms, because present optical sources lack sufficient coherence to produce them. The envelope of the modulated optical signal is an analog of the modulating signal in the sense that the instantaneous power of the envelope is an analog of the characteristic of interest in the modulating signal. Recovery of the modulating signal is by direct detection, not heterodyning.

Frequency modulation (FM):

FM is the method in which the frequency of the carrier waveform is varied in small but meaningful amounts. It is a type of modulation where the frequency of the carrier is varied in accordance with the modulating signal. The amplitude of the carrier remains constant. In analog FM, the frequency of the AC signal wave, also called the *carrier*, varies in a continuous manner. Thus, there are infinitely many possible carrier frequencies. In *narrowband FM*, commonly used in two-way wireless communications, the instantaneous carrier frequency varies by up to 5 kilohertz (kHz, where 1 kHz = 1000 hertz or alternating cycles per second) above and below the frequency of the carrier with no modulation. In *wideband FM*, used in wireless broadcasting, the instantaneous frequency varies by up to several megahertz (MHz, where 1 MHz = 1,000,000 Hz). When the instantaneous input wave has positive polarity, the carrier frequency shifts in one direction; when the instantaneous input wave has negative polarity, the carrier frequency shifts in the opposite direction. At every instant in time, the extent of carrier-frequency shift (the *deviation*) is directly proportional to the extent to which the signal amplitude is positive or negative.

In digital FM, the carrier frequency shifts abruptly, rather than varying continuously. The number of possible carrier frequency states is usually a power of 2. If there are only two possible frequency states, the mode is called frequency-shift keying (FSK). In more complex modes, there can be four, eight, or more different frequency states. Each specific carrier frequency represents a
specific digital input data state.

FM modulation is a low-noise process and provides a high quality modulation technique which is used for music and speech in hi-fidelity broadcasts. There are several devices that are capable of generating FM signals, such as a VCO or a reactance modulator.

Phase modulation (PM):

Phase modulation is a method in which the natural flow of the alternating current waveform is delayed temporarily. It impressing data onto an alternating-current (AC) waveform by varying the instantaneous phase of the wave. This scheme can be used with analog or digital data.

In analog PM, the phase of the AC signal wave, also called the *carrier*, varies in a continuous manner. Thus, there are infinitely many possible carrier phase states. When the instantaneous data input waveform has positive polarity, the carrier phase shifts in one direction; when the instantaneous data input waveform has negative polarity, the carrier phase shifts in the opposite direction. At every instant in time, the extent of carrier-phase shift (the *phase angle*) is directly proportional to the extent to which the signal amplitude is positive or negative.

In digital PM, the carrier phase shifts abruptly, rather than continuously back and forth. The number of possible carrier phase states is usually a power of 2. If there are only two possible phase states, the mode is called *biphase modulation*. In more complex modes, there can be four, eight, or more different phase states. Each phase angle (that is, each shift from one phase state to another) represents a specific digital input data state.

Digital Modulation:

Firstly, what is meant by digital modulation? Typically the objective of a digital communication system is to transport digital data between two or more nodes. In radio communications this is usually achieved by adjusting a physical characteristic of a sinusoidal carrier, either the frequency, phase, amplitude or a combination thereof. This is performed in real systems with a modulator at the transmitting end to impose the physical change to the carrier and a demodulator at the receiving end to detect the resultant modulation on reception

Frequency Shift Keyed (FSK)

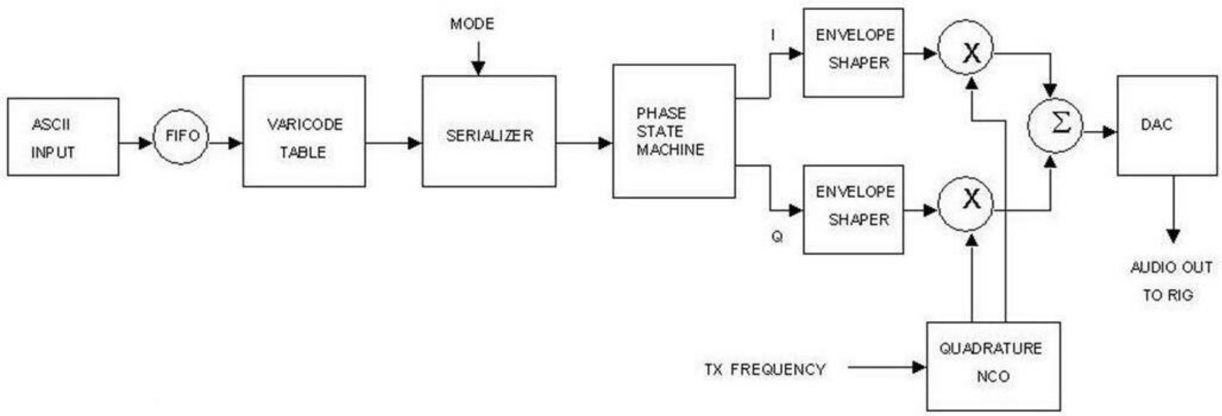
As previously stated applying modulation in wireless communications involves modifying the phase or amplitude, or both, of a sinusoidal carrier. One of the simplest, and widest used system, is frequency modulation. This exists in a great variety of forms, as will be discussed later, but in essence involves making a change to the frequency of the carrier to represent a different level. The generic name for this family of modulation is Frequency Shift Keying. FSK has the advantage of being very simple to generate, simple to demodulate and due to the constant amplitude can utilise a non-linear PA. Significant disadvantages, however, are the poor spectral efficiency and BER performance. This precludes its use in this basic form from cellular and even cordless systems.

Minimum Shift Keyed (MSK):

Minimum Shift Keying is FSK with a modulation index of 0.5. Therefore the carrier phase of an MSK signal will be advanced or retarded 90o over the course of each bit period to represent either a one or a zero. Due to this exact phase relationship MSK can be considered as either phase or frequency modulation. The result of this exact phase relationship is that MSK can’t practically be generated with a voltage controlled oscillator and a digital waveform. Instead an IQ modulation technique, as for PSK, is usually implemented. Coherent demodulation is usually employed for MSK due to the superior BER performance. This is practically achievable, and widely used in real systems, due to the exact phase relationship between each bit. The spectral characteristics and BER performance of MSK are considered later.

Phase Shift Keyed (PSK)

An alternative to imposing the modulation onto the carrier by varying the instantaneous frequency is to modulate the phase. This can be achieved simply by defining a relative phase shift from the carrier, usually equi-distant for each required state. Therefore a two level phase modulated system, such as Binary Phase Shift Keying, has two relative phase shifts from the carrier, + or - 90o. Typically this technique will lead to an improved BER performance compared to MSK. The resulting signal will, however, probably not be constant amplitude and not be very spectrally efficient due to the rapid phase discontinuities. Some additional filtering will be required to limit the spectral occupancy. Phase modulation requires coherent generation and as such if an IQ modulation technique is employed this filtering can be performed at baseband.



Binary Phase Shift Keyed (BPSK):

The simplest form of phase modulation is binary (two level) phase modulation. With theoretical BPSK the carrier phase has only two states, +/- p/2. Obviously the transition from a one to a zero, or vice versa, will result in the modulated signal crossing the origin of the constellation diagram resulting in 100% AM. Figure 5(a) below shows the theoretical spectra of a 1 Mbits BPSK signal with no additional filtering. Several techniques are employed in real systems to improve the spectral efficiency. One such method is to employ Raised Cosine filtering. Figure 4(b) below shows the improved spectral efficiency achieved by applying a raised cosine filter with b=0.5 to the baseband modulating signals. One potentially undesirable feature of BPSK that the application of a raised cosine filter will not improve is the 100% AM. In a real system the shaped signal will still require a linear PA to avoid spectral re-growth. Further hybrid versions of BPSK are used in real systems that combine constant amplitude modulation with phase modulation.

Quadrature Phase Shift Keyed (QPSK)

Higher order modulation schemes, such as QPSK, are often used in preference to BPSK when improved spectral efficiency is required.

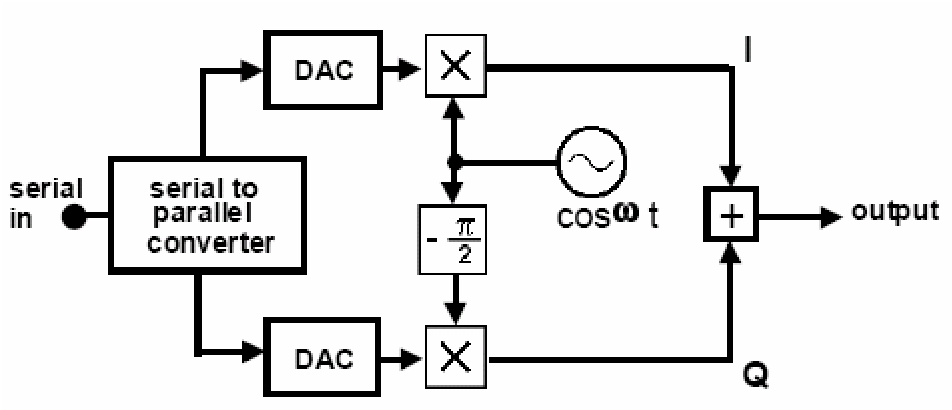


Figure 2: a QPSK modulator

1.4: Optical Multiplexing Schemes

Orthogonal frequency-division multiplexing (OFDM):

Orthogonal frequency-division multiplexing (OFDM) — essentially identical to Coded OFDM (COFDM) and Discrete multi-tone modulation (DMT) — is a frequency-division multiplexing (FDM) scheme utilized as a digital multi-carrier modulation method. A large number of closely-spaced orthogonal sub-carriers are used to carry data. The data is divided into several parallel data streams or channels, one for each sub-carrier. Each sub-carrier is modulated with a conventional modulation scheme (such as quadrature amplitude modulation or phase-shift keying) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth.

OFDM has developed into a popular scheme for wideband digital communication, whether wireless or over copper wires, used in applications such as digital television and audio broadcasting, wireless networking and broadband internet access.

The primary advantage of OFDM over single-carrier schemes is its ability to cope with severe channel conditions — for example, attenuation of high frequencies in a long copper wire, narrowband interference and frequency-selective fading due to multipath — without complex equalization filters. Channel equalization is simplified because OFDM may be viewed as using many slowly-modulated narrowband signals rather than one rapidly-modulated wideband signal. The low symbol rate makes the use of a guard interval between symbols affordable, making it possible to handle time-spreading and eliminate intersymbol interference (ISI). This mechanism also facilitates the design of Single Frequency Networks (SFNs), where several adjacent transmitters send the same signal simultaneously at the same frequency, as the signals from multiple distant transmitters may be combined constructively, rather than interfering as would typically occur in a traditional single-carrier system.

Wavelength-Division Multiplexing (WDM):

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 (colours) of laser light to carry different signals. This allows for a multiplication in capacity, in addition to enabling bidirectional communications over one strand of fiber. This is a form of frequency division multiplexing (FDM) but is commonly called wavelength division multiplexing.[1]

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 equivalent in this context.

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. The optical filtering devices used have traditionally been etalons, stable solid-state single-frequency Fabry-Perot interferometers in the form of thin-film-coated optical glass.

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.

In a simple WDM system each laser must emit light at a different wavelength, with all the lasers light multiplexed together onto a single optical fiber. After being transmitted through a high-bandwidth optical fiber, the combined optical signals must be demultiplexed at the receiving end by distributing the total optical power to each output port and then requiring that each receiver selectively recover only one wavelength by using a tunable optical filter. Each laser is modulated at a given speed, and the total aggregate capacity being transmitted along the high-bandwidth fiber is the sum total of the bit rates of the individual lasers. An example of the system capacity enhancement is the situation in which ten 2.5-Gbps signals can be transmitted on one fiber, producing a system capacity of 25 Gbps. This wavelength-parallelism circumvents the problem of typical optoelectronic devices, which do not have bandwidths exceeding a few gigahertz unless they are exotic and expensive. The speed requirements for the individual optoelectronic components are, therefore, relaxed, even though a significant amount of total fiber bandwidth is still being utilized.

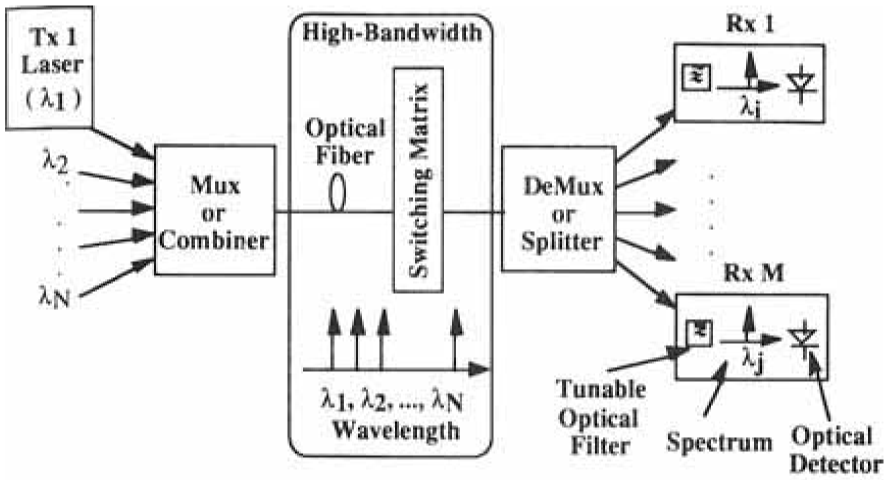


Figure 7: Diagram of a simple WDM system.

DWDM System:

Dense wavelength division multiplexing, or DWDM for short, refers originally to optical signals multiplexed within the 1550 nm band so as to leverage the capabilities (and cost) of erbium doped fiber amplifiers (EDFAs), which are effective for wavelengths between approximately 1525-1565 nm (C band), or 1570-1610 nm (L band). EDFAs were originally developed to replace SONET/SDH 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 through 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.

Components of DWDM system:

A DWDM system can be described as a parallel set of optical channels, each using a slightly different wavelength, but all sharing a single transmission medium or fiber.

Figure 5 illustrates the functionality of a multichannel DWDM transmission system when various 10 Gbps signals are fed to optical transmission modules. The optical output signals are converted to defined wavelengths in the 1550 nm window via wavelength transponders. An optical DWDM coupler (multiplexer) then 'bunches' these optical signals together on one fiber and forwards them as a multiplexed signal to an optical fiber amplifier (OFA). Depending on path length and type of fiber used, one or more OFAs can be used to boost the optical signal for long fiber spans. At termination on the receiving end, the optical signals are preamplified, then separated using optical filters (demultiplexer) before being converted into electrical signals in the receiver modules. For bidirectional transmission, this procedure must be duplicated in the opposite direction to carry the signals in that particular direction.

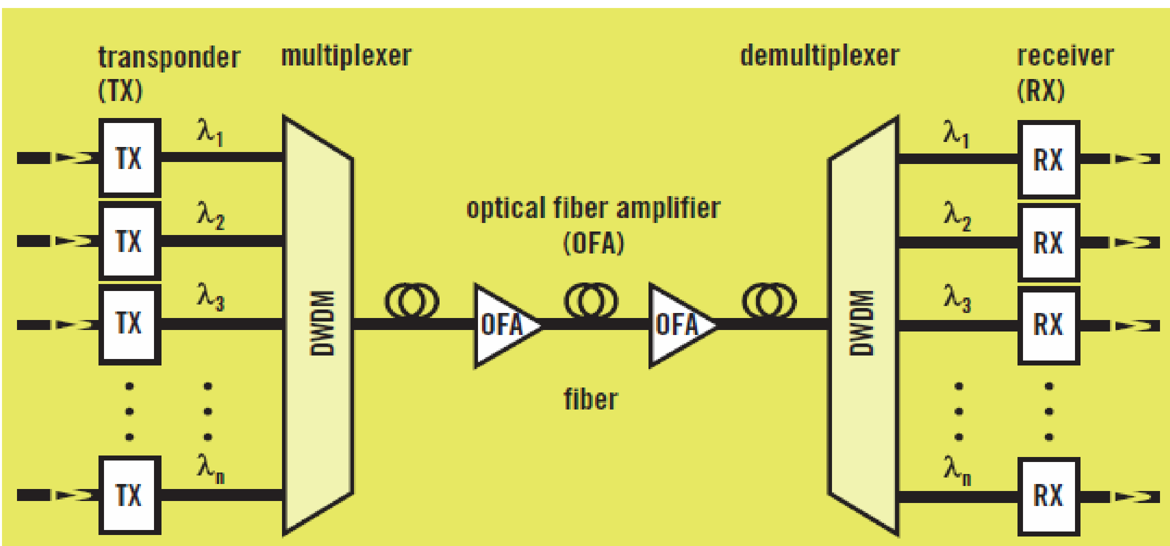


Figure: Multichannel DWDM transmission system

Transponder

Transponders receive optical signals and send them out carrying digital information at predefined wavelengths in accordance with the ITU-T guidelines (see reference table on pages 75 to 79) . A single channel transmitter typically consists of a high power distributed feedback (DFB) laser followed by a modulator and power amplifier (also referred to as a post-amplifier or booster). Direct modulation of the laser is only possible up to 2.5 Gbps. For higher transmission rates as a result of laser chirp, an external modulator must be used. DFB lasers offer greater precision than Fabry-Perot (FP) lasers, the latter of which emits harmonics close to the main peak rendering them unsuitable for DWDM systems. In DWDM systems both fixed and uneable laser sources can be utilized. In networks with dense channel spacing, transponder temperature must be stabilized. This can be enabled with the use of thermo-electric coolers.

Multiplexer (MUX)

MUX are deployed in DWDM systems to combine the signals at different wavelengths onto a single fiber through which they then travel simultaneously. Each wavelength carries its own information and represents a channel. An ideal MUX requires uniformly high transmission across the passband with a very high drop at the edge.

Fiber

The fiber is one of the most critical components of a DWDM system as it provides the physical transportation medium. Optical fibers consist of both core and cladding. The core is the inner,

light-guiding section and is surrounded by the cladding. As the refractive index of the core is higher than that of the cladding, light entering it at an angle – or numerical aperture – is fully reflected (almost 100 percent) off the core/cladding boundary and propagates down the length of the fiber. Optical fibers can be divided into multimode and singlemode fibers, each approximately the size of a human hair, with an outer diameter of 125 μm. Core size however differs. The diameter of multimode fibers range from between 50 μm and 62.5 μm, whilst for singlemode fibers it is between 7 and 10 μm. Light propagates down the fiber core in a stable path known as a mode. In multimode fibers, multiple paths arise making them unsuitable

for use in long haul DWDM transmission. In DWDM systems the fibers can be used either unidirectionally (signals transmitted in one direction only per fiber) or bidirectionally (signals

traveling in both directions).

Amplifier:

Amplifiers boost signals traveling down a fiber so they can cover longer spans. In the early stages of fiber optic telecommunications, lasers emitted relatively low power which led to the signal having to be frequently electrically regenerated (figure 7). These amplifiers receive the optical signal and convert it into an electrical signal (O/E conversion) which is then reshaped, retimed and amplified again. This is the so called 3R regenerator. Finally, the signal is converted back to an optical signal (E/O conversion). Optical fiber amplifiers (OFAs) can be used to provide a more economical solution. These can work solely in the optical domain, performing a 1R (optical reamplification only) regeneration. OFAs simultaneously amplify each wavelength of the DWDM signal without the need for demultiplexing and remultiplexing. One major advantage of OFAs is their transparency to signal speed and data type. Three types of OFAs are deployed in DWDM systems: erbium doped fiber amplifier (EDFA), semiconductor optical amplifiers (SOA) and Raman fiber amplifiers (RFA). In DWDM systems, the multiplexed signal has to be demultiplexed before each channel is regenerated, emitted by a laser and then multiplexed again. This is a process which is both complex and expensive.

Demultiplexer (DEMUX)

DEMUXs unscramble multiplexed channels before they are fed into their corresponding receivers. They work similarly to MUXs but operate in the reverse direction. It is common to preamplify optical signals before they are separated by the optical filters of the demultiplexer. The performance of a MUX or DEMUX is related to its capability to filter each incoming signal. The Bragg grating is currently the most popular technique used in DWDM systems.

Receiver

Receivers are used to convert optical signals into electrical signals. The light pulses transmitted over the optical fiber are received by a light sensitive device known as a photo diode which is made of semi-conductor material.

OCDMA

Optical communication systems in the optical fiber play a main part of the digital communications in backbone networks, high speed LAN, MAN and FTTH. The main advantages of the optical fiber communications are the high speed, large capacity and high reliability by the use of the broadband of the optical fiber. Asynchronous multiple access methods where network access is random and collisions occur, such as token passing and carrier sense multiple-access, are well suited to LAN's with low traffic demand. However, these asynchronous access methods suffer from cumulative delay as the traffic intensity increases. Also, contention protocols generally proposed for low traffic demands are not suitable if traffic delay is a major issue, e.g., in networks where information must be transmitted simultaneously. On the

other hand, synchronous accessing methods where transmissions are perfectly scheduled provide more successful transmissions than asynchronous methods. As a typical synchronous protocol, time division multiple access (TDMA) is an efficient multiple access protocol in networks with heavy traffic demands, since it can accommodate higher traffic demands and do not suffer from cumulative delay. However, in situations where the channel is sparsely used, TDMA is inefficient. As an alternate optical multiplexing technique, there is wavelength division multiple access (WDMA) which includes routing and switching functionality in addition to the transmission multiplex. The fundamental disadvantage in WDMA is that sophisticated hardware such as wavelength-controlled tunable lasers and high-quality narrowband tunable filters for each channel is required. Although WDMA can be used as a degree of design freedom with respect to routing and wavelength selection, usable wavelength might be limited due to the crosstalk caused by the nonlinearity within the optical fiber.

Optical CDMA is most suitable to be applied to high speed LAN to achieve contention-free, zero delay access, where
traffic tends to be bursty rather than continuous. Compared with TDMA, CDMA is attractive in other points. Channel assignment is much easier with CDMA. CDMA isolates irregular channels so that they do not influence other channels, while with TDMA, even one irregular channel, such as continuous emission from a transmitter, causes the failure of all other channels. Furthermore, CDMA can be efficiently used in conjunction with TDMA and WDMA on multimedia communication networks where multiple services with different traffic requirements are to be integrated. In optical CDMA, incoherent systems using narrow pulse laser sources are mainly implemented, since optical links have vast bandwidth and the optical components can produce very narrow pulse precisely in time and offer extra-high optical
signal processing. Thus, in optical CDMA, intensity-modulation/direct-detection (IMDD) is mainly used, where other arriving pulse sequences having positive pulses happen to overlap a pulse of the desired sequence, and produce multiple access interference (MAI). Since MAI is dominant compared to shot noise, dark current and thermal noise to degrade the performance, the suppression of MAI is the key issue in optical CDMA. Here, we summarize our recent results in optical CDMA, such as effective MAI suppression schemes and the embedded-modulation schemes with error correcting codes.

1.5 Limitations of WDM

Crosstalk will be one of the major limitations for the introduction of OXC in all optical networks. In this paper the influence of the components on the total OXC crosstalk is investigated.

Crosstalk:
Crosstalk occurs in devices that filter and separate wavelengths. A small
proportion of the optical power that should have ended up in a particular channel

(on a particular filter output) actually ends up in an adjacent (or another) channel. Crosstalk is critically important in WDM systems. When signals from one channel arrive in another they become noise in the other channel. This can have serious effects on the signal-to-noise ratio and hence on the error rate of the system. Crosstalk is usually quoted as the “worst case” condition. This is where the signal in one channel is right at the edge of its allowed band. Crosstalk is quoted as the loss in dB between the input level of the signal and its (unwanted) signal strength in the adjacent channel. A figure of 30 dB is widely considered to be an acceptable level for most systems.

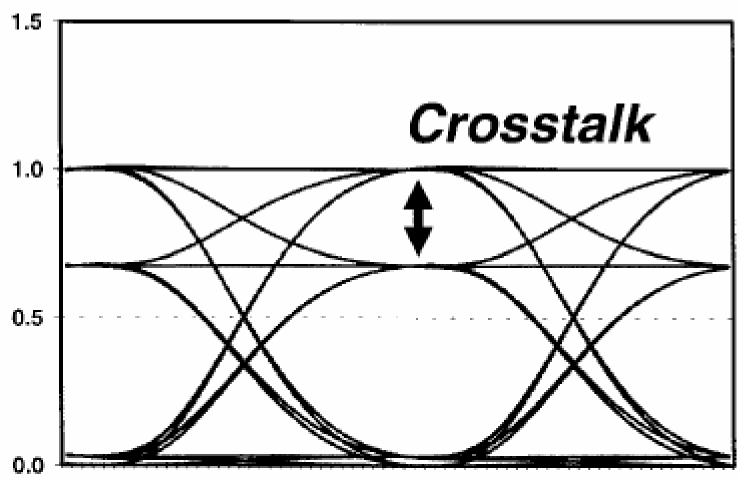


Fig. 8. Definition of crosstalk.

Types of crosstalk :

Different kinds of crosstalk exist, depending on their source. First one has to make a distinction between interband crosstalk and intraband crosstalk.

Interband crosstalk:

Interband crosstalk is the crosstalk situated in wavelengths outside the channel slot (Fig. 1.2) (wavelengths outside the optical bandwidth). This crosstalk can be removed with narrow-band filters and it produces no beating during detection, so it is less harmful. In a WDM networks, interband crosstalk appears from channels of different wavelengths.

Intraband Crosstalk

The crosstalk within the same wavelength slot is called intraband crosstalk.(fig 1.2). It cannot be removed by an optical filter and therefore accumulates through the network. Since it cannot be removed, one has to prevent the crosstalk. In this paper intraband crosstalk is studied since the network performance will be limited by this kind of crosstalk. Intraband crosstalk occurs when the signal and the interferer has the closely-valued wavelengths. Intraband however, can be coherent or incoherent crosstalk. If the signal crosstalk mixing takes place within the laser coherence length, then intraband crosstalk is defined as coherent. Otherwise incoherent crosstalk will appear.

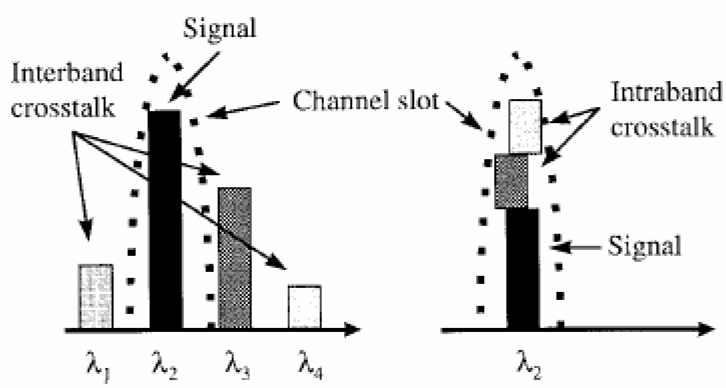


Fig. 5. Interband and intraband crosstalk.

Moreover, within the intraband crosstalk, a distinction between incoherent and coherent crosstalk has to be made. These types of crosstalk are not well defined in literature and therefore a definition is given here. To make a distinction between both types of intraband crosstalk one has to look at the consequences. The interference of the signal channel and the crosstalk channel at the detector results in a beat term.

Coherent crosstalk

The crosstalk is called coherent crosstalk if the total crosstalk is dominated by this beat. It is seen that coherent crosstalk is less harmful to system performance than incoherent crosstalk.

Incoherent Crosstalk

If this beat term is very small compared with the total crosstalk, it is called incoherent.This difference will be illustrated hereafter.

1.6: Objective of the Thesis Work

Performance Analysis is carried out to find the effect of crosstalk due to optical cross connect in a DWDM system considering a WDM based optical cross connect (OXC). An analysis is carried out to find the amount of crosstalk due to OXC. The bit error rate performance degradation due to crosstalk is evaluated for OXC parameter and number of wavelengths per fiber. The optimum parameters such as optimum number of channels and hops are determined.

Chapter – 2

ANALYSIS OF CROSSTALK IN WDM SYSTEM

This chapter presents the influence of Crosstalk in system performance. Firstly the block diagrams representing the system block diagram and WDM system with Hops. Secondly, analysis of Bit Error Rate without Crosstalk, which is in ideal case, is given. Then analysis of Bit Error Rate with Cross talk using equations in both the cases is given.

2.1.1 WDM SYSTEM BLOCK DIAGRAM

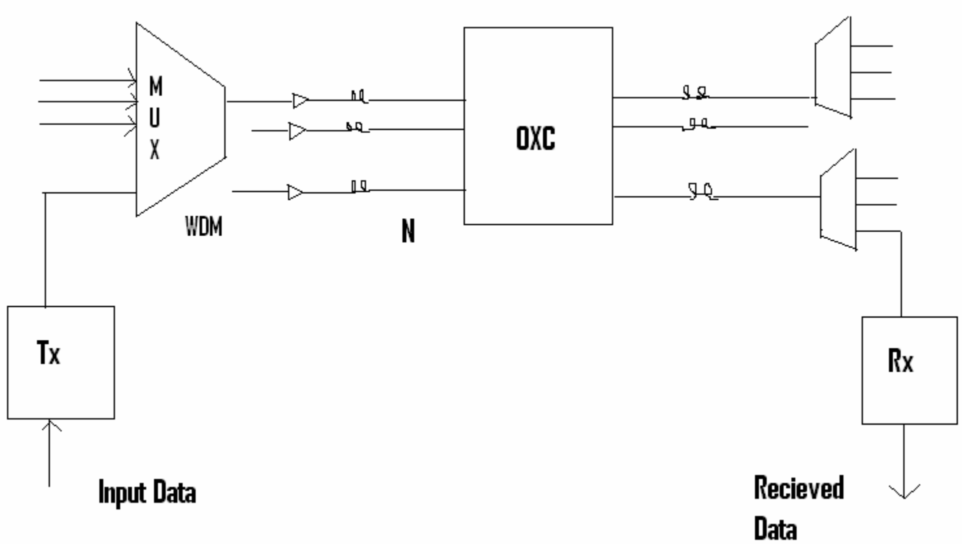
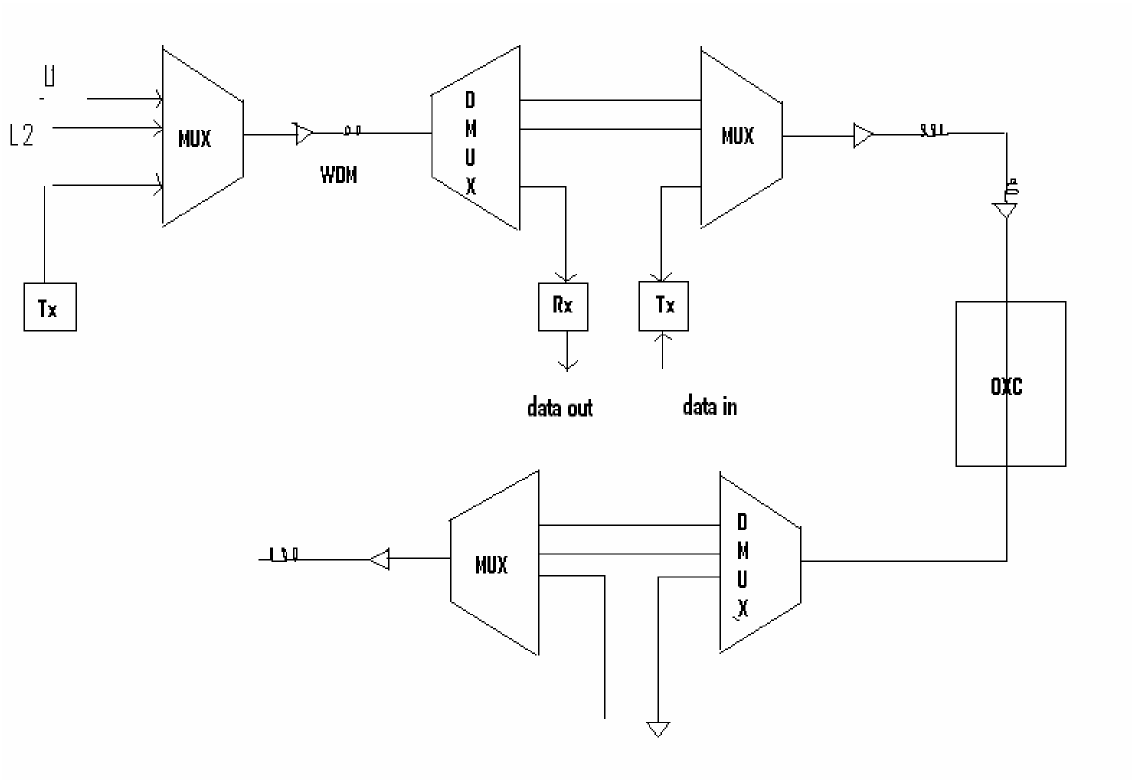


Fig 1: System Block Design

The above block diagram shows a simple WDM system. Here L numbers of signals are multiplexed in a channel in a multiplexer from transmitters. N number of channels are going through Optical Cross connect and each channel are demultiplexed using a demultiplexer and the receiver receives the desired signal.

2.1.2 SYSTEM BLOCK DIAGRAM WITH HOPS



The above diagram shows a WDM system block diagram with hops. Here three hops are shown. L number of signals are multiplexed and passed through a optical fiber. Which is demultiplexed to get the desired signal and a new signal is multiplexed by the transmitter. The signal passes through optical fiber again. This way hops are used.

2.1.3 BLOCK DIAGRAM OF OPTICAL CROSSCONNECT

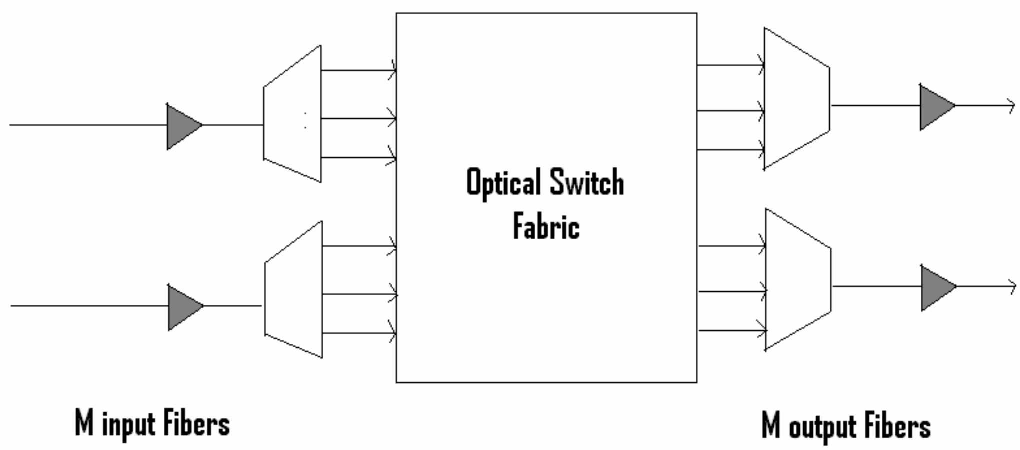


Fig: Schematic illustration of a conventional OXC node

The above diagram shows an optical cross connect where M input fibers are coming. The cross connect switches the signal to the desired location to pass on the other side to be demultiplexed.

2.1.4 BLOCK DIAGRAM OF OXC CROSSTALK

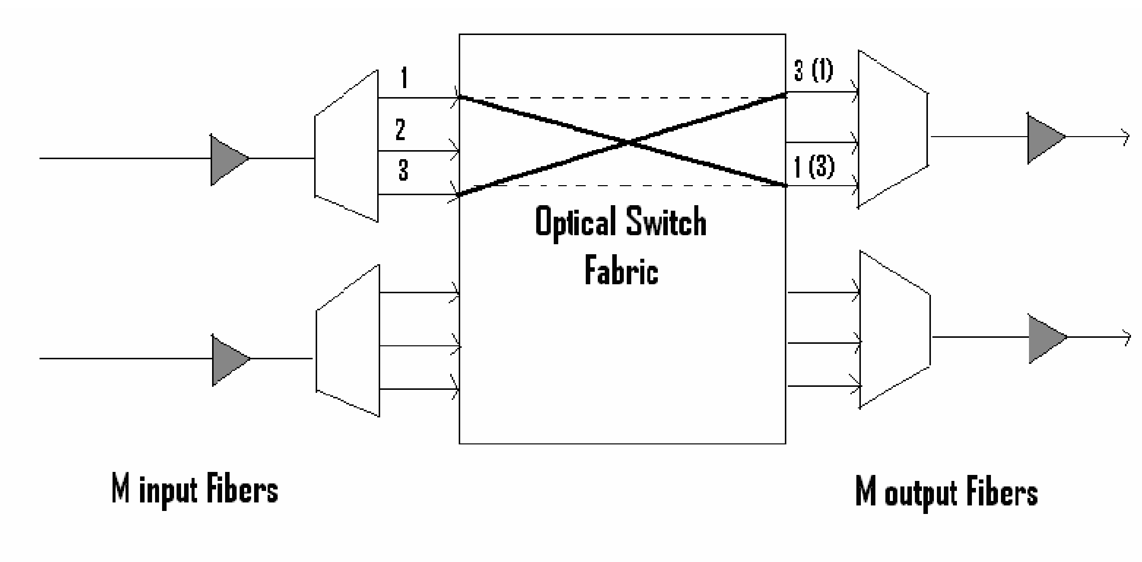


Fig: Schematic illustration of a conventional OXC node

The above diagram shows the crosstalk in the Optical switch. In the switch, signal from input 1 is connected with output 3. And signal from input 3 is connected to output 1. But it can be seen that in output 3, a little portion of input 3 has entered along with the signal 1. Similarly at output 1 a little portion of input 1 has entered along with the signal 3. this unwanted portion of signal that enters in the output of the Optical Cross connect is the crosstalk due to OXC.

2.2 Analysis of Bit Error Rate without Crosstalk

Bit Error Rate can be calculated with and without Crosstalk using some equations.
In this section the ideal case is shown. So Crosstalk is taken to be zero. Equation for crosstalk is given is the next section.
Bit Error Rate: The number of bit errors that occur within the space of one second. This measurement is one of the prime considerations in determining signal quality. The higher the data transmission rate the greater the standard.

The BER is an indication of how often data has to be retransmitted because of an error. Too high a BER may indicate that a slower data rate would actually improve overall transmission time for a given amount of transmitted data since the BER might be reduced, lowering the number of packets that had to be resent.

For most practical WDM networks, this requirement of BER is 10^{-12} (~ 10^{-9} to 10^{-12}), which means that a maximum one out of every 10^{12} bits can be corrupted during transmission. Therefore, BER is considered an important figure of merit for WDM networks; all designs are based to adhere to that quality.

BER in WDM system is calculated by the equation:

$$BER = .5\ \mathrm{erfc}\,(Q/\sqrt{2}) \qquad \text{(eq. 1)}$$

Here Q is a function proportional to the receiver signal-to-noise ratio (SNR).

It is expressed as:

$$Q = (R_b * P_s)\ \hat{}2 / \sqrt{(\sigma_{ase}\hat{}2 + \sigma_c\hat{}2)} \qquad \text{(eq. 2)}$$

R_b = Bit Rate; in telecommunications and computing, bitrate (sometimes written bit rate, data rate or as a variable *R* or f_b) is the number of bits that are conveyed or processed per unit of time. The bit rate is quantified using the bits per second (bit/s or bps) unit.

P_s = Signal power in dbm.

σ_c = Crosstalk.

σ_{ase} = ASE (amplified spontaneous emission) noise induced by parametric gain and spontaneous Raman scattering in optical fiber Ramen amplifier.

It is an unwanted noise

$$\sigma_{ase} = \sqrt{((G-1)*n_{sp}*h*\nu*\beta o)}$$

Here

G = Gain

n_{sp} = Spontaneous Emission Factor or Population-Inversion Factor

h = Planck's constant = 6.634*10^-34

ν = Frequency of the signal = c/L

c = speed of light = 3*10^8

L= wavelength

βo = Band Width a measure of the width of a range of frequencies, measured in hertz.

In ideal case, $\sigma_c = 0$; which is with no cross talk, equation 2 becomes:

$$Q = (R_d * P_s)^2/\sigma_{ase} \qquad [\sigma_c = 0 \text{ for ideal case}]$$

For different values of bandwidth, BER without crosstalk can be calculated using Eq. 1 for the above equation of Q. Bandwidth can be 2* R_b, 4* R_b, 6* R_b etc.

For Amplitude Modulated signal the Bit Error Rate can be approximated from Gaussian equation as:

$$BER = \int_Q^{\infty} \left(e^{-x^2/2} / \sqrt{2\pi} \right) dx$$

2.3 Analysis of Bit Error Rate with Crosstalk

In practical case zero crosstalk is not possible. So BER is calculated with equation 1 taking in the value of σ_c

$$BER = .5 \, \text{erfc}(Q/\sqrt{2}) \qquad \text{(eq. 1)}$$

Here Q is a function proportional to the receiver signal-to-noise ratio (SNR).

It is expressed as:

$$Q = (R_d * P_s)^2/\sqrt{(\sigma_{ase}^2 + \sigma_c^2)} \qquad \text{(eq. 2)}$$

Here

R_b = Bit Rate; in telecommunications and computing, bitrate (sometimes written bit rate, data rate or as a variable R or f_b) is the number of bits that are conveyed or processed per unit of time. The bit rate is quantified using the bits per second (bit/s or bps) unit.

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It is an unwanted noise

$$\sigma_{ase} = \sqrt{((G-1)*n_{sp}*h*\nu*\beta_o)}$$

Here

G = Gain

b = bit ratio of signal peak power

n_{sp} = Spontaneous Emission Factor or Population-Inversion Factor

h = Planck's constant = 6.634*10^-34

ν = Frequency of the signal = c/L

c = speed of light = 3*10^8

L= wavelength

β_o = Band Width.

Putting in the values in equation 2, we can find the value of Q and putting this value in equation 1 we can calculate the value of BER in WDM system.

For the same input power crosstalk can be calculated for different number of channels and hops using the equation:

$$\sigma^2 = M*b^2*R_d^2*P_s^2*(2*\acute{\varepsilon}_{adj} + (N-3)\,\acute{\varepsilon}_{nonad} + X_{switch})$$

Where

M = Number of Hops.

b = Ratio of signal peak power.

N = Number of channels.

R_d = Detector responsivity.

P_s = Input Power

$\acute{\varepsilon}_{ad}$ = Effective adjacent channel crosstalk.

$\acute{\varepsilon}_{nonad}$ = Effective Non adjacent channel crosstalk.

X_{switch} = Crosstalk value (in linear units) of the optical switch fabric.

In order to calculate Power Penalty from in-band Crosstalk, we first calculate the power for without crosstalk then for with crosstalk. The difference between the two gives the Power Penalty.

3.0) RESULTS AND DISCUSSION

BER without crosstalk

Figure 1

BER or bit error rate is plotted as a function of input power (Pin) in dbm in Figure: 1.

$$BER = 0.5\, erfc\,(\frac{Q}{\sqrt{2}})$$

Where Q is Signal Noise Ratio. To calculate BER first we need to find out Q.

$$Q = \frac{(R_b\, P_s)^2}{\sqrt{(\sigma_{ase}{}^2 + \sigma_c{}^2)}}$$

Here,

R_b = bit rate

P_s = input power in dbm

σ_{ase} = crosstalk of amplifier spontaneous emission

σ_c = crosstalk, here σc is zero since this has been calculated for without crosstalk.

σ_{ase} is calculated from this equation-

$$\sigma ase^2 = (G-1)Nsp\ h\ m\ B$$

Where

G= gain

N_{sp} = open emission factor

h= planks constant

B= bandwidth

Values taken for Figure1:

B= 2Rb

Nsp=1.8

G= 20 db

H= 6.63*10^(-34)

BER or Bit Error Rate is plotted as a function of input power (Pin) in dbm in Figure: 1 Here the value of Rb(bit rate) is 10GHz. The Pin is taken from range -8 dbm to 100 dbm.

The resulting graph of BER VS Pin is plotted bellow. It is seen that without crosstalk the BER increase with increase in Pin.

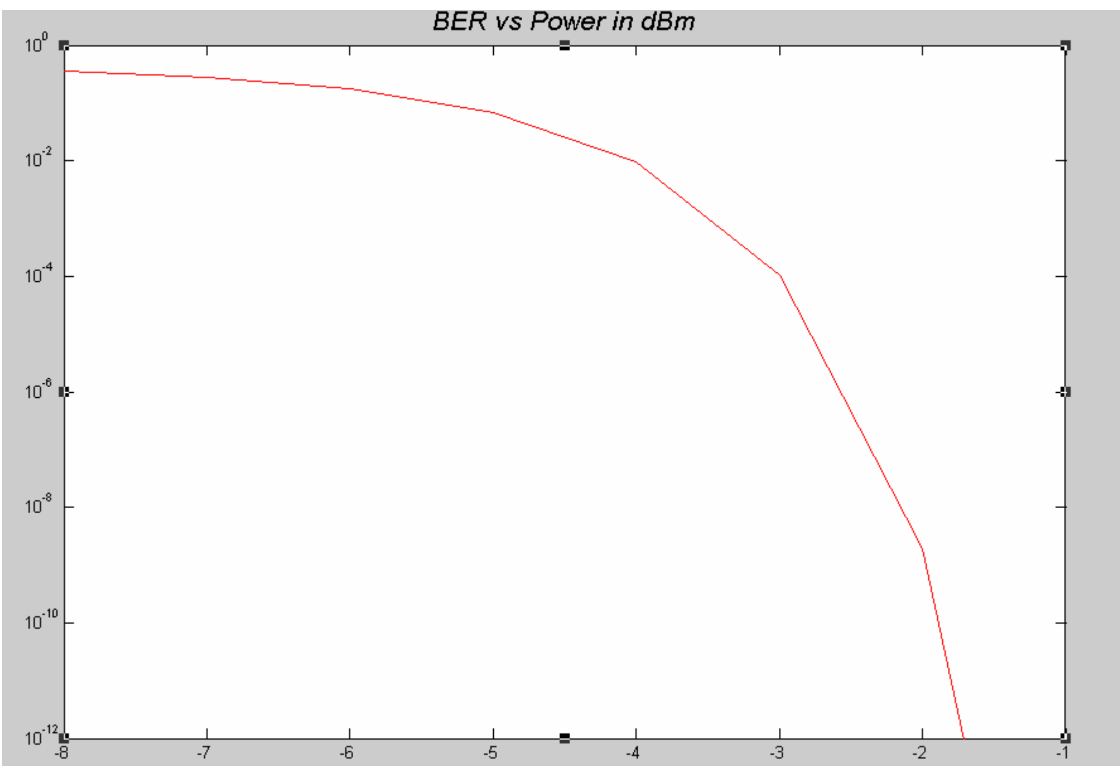


Figure 1: Bit Error Rate (BER) VS Input power (Pin)

Figure 2

This is the plot of BER vs power in dbm for different bandwidths. Here for without crosstalk different values of bandwidth(B) is taken and has been shown in graph. The input power is taken from range -8 dbm to -1 dbm. Then the corresponding values of BER are plotted against Pin for the corresponding different values of B.

BER is calculated from the equation-

$$BER = 0.5\, erfc\,(\frac{Q}{\sqrt{2}})$$

Q is calculated from the equation-

$$Q = \frac{(Rb\ Ps)^2}{\sqrt{(\sigma ase^2 + \sigma c^2)}}$$

Crosstalk in amplified spontaneous emission is calculated from the equation-

$$\sigma_{ase}{}^2 = (G-1)Nsp\ h\ m\ B$$

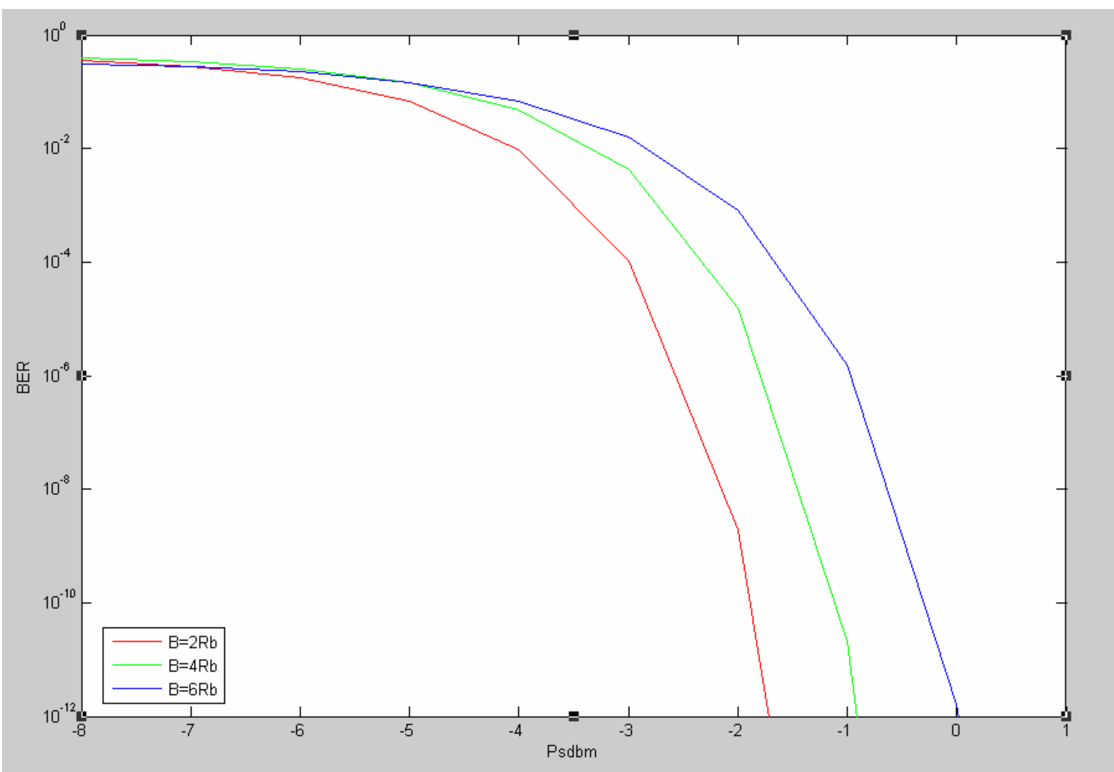


Figure 2: BER vs input power for different Bandwidth.

The resulting graph of BER VS Pin is plotted above. We have plotted this graph for three different bandwidths. It is seen that the BER increases with increase in Pin. It is also shown that to use more bandwidth we need more input power. For example, when we use 4*Rb as our bandwidth, we need -1.2dbm power where we need 0.1 dbm input power to use 6*Rb as bandwidth. At the same time BER also increase with increase in bandwidth.

BER with Crosstalk

Figure 3:

BER or bit error rate is plotted as a function of input power (Pin) in dbm in Figure: 3.

$$BER = 0.5\, erfc\,(\frac{Q}{\sqrt{2}})$$

Where Q is Signal Noise Ratio. To calculate BER first we need to find out Q.

$$Q = \frac{(Rb\ Ps)^2}{\sqrt{({\sigma_{ase}}^2 + {\sigma_c}^2)}}$$

Here,

Rb= bit rate

Ps= input power in dbm

σ_{ase} = crosstalk of amplifier spontaneous emission

σ_c= crosstalk

ε_{ase} is calculated from this equation-

$${\sigma_{ase}}^2 = (G - 1)Nsp * h * m * B$$

Where

G= gain

Nsp= open emission factor

h= planks constant

B= bandwidth

M=c/L; c is the speed of light and L is wavelength.

Values taken for Figure1:

L=1550

C=3.8*10^(3)

B= 2Rb

Nsp=1.8

G=1

H=6.63*10^(-34)

σ_{ase}^2= 0.0001

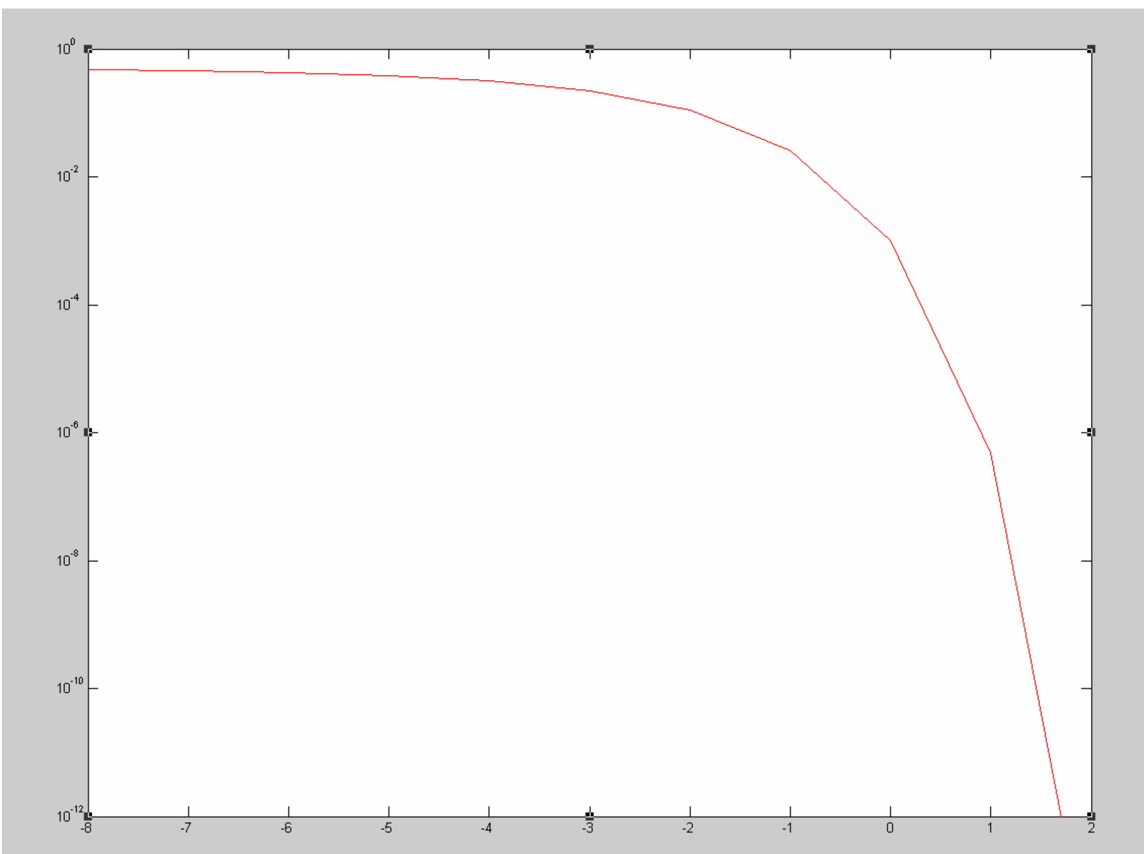


Figure 3: BER vs Input power in dbm

In this graph we have plotted BER against Input power in dbm when crosstalk is available.

Figure 4

Now we have plotted the graph of BER against input power in dbm for different crosstalk. Different values of crosstalk have been taken here for a fixed bandwidth and analysis the graphs for different crosstalk. The input power is taken from range -5dbm to 20dbm.

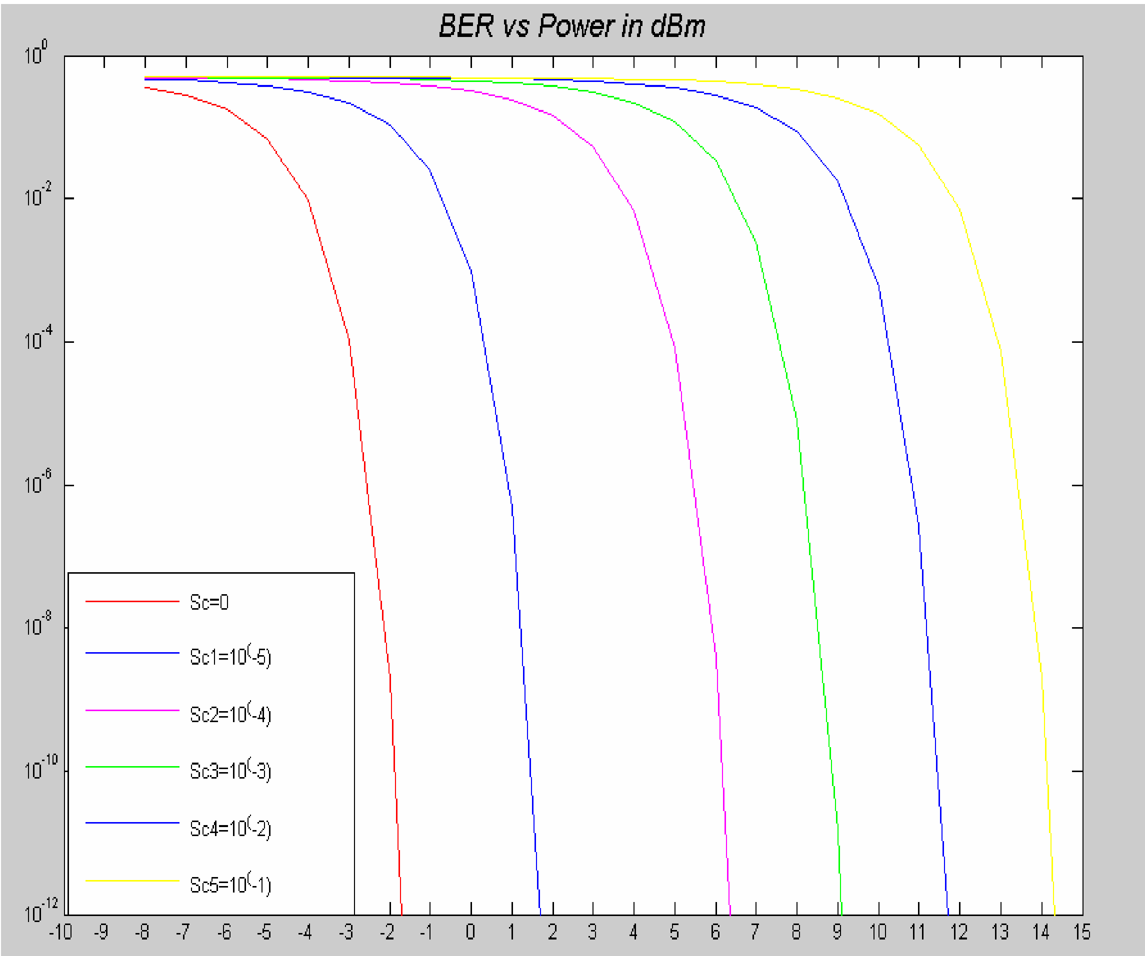


Figure 4: BER vs input power in dbm for different crosstalk.

Here we show that BER increase for increasing crosstalk. For using more input power we get more crosstalk. For example, when 1.8 dbm ia used as input power, the crosstalk is $10^{(-5)}$ and for 9.1dbm input power, crosstalk is $10^{(-3)}$. At the same time BER is also increasing.

Figure 5

Figure below shows Crosstalk plotted against number of channel using in WDM system. Here we calculated crosstalk from the equation-

$$\sigma^2 = Mb^2R^2{P_s}^2[2\varepsilon_{adj} + (N-3)\varepsilon_{nonadj} + X_{switch}]$$

Where,

M= number of hop

B= bit ratio of signal peak power

R= detector resistance

Ps= input power

ε= effective adjacent and effective nonadjacent

N= number of channel

X= switch

Values taken for figure 5:

B= 1

R= 0.85

X= 1

The input power is taken from the range -8dbm to 20 dbm. Effective adjacent and non adjacent both are taken 0.5. We have plotted this graph for 2 hoops and 10 channels.

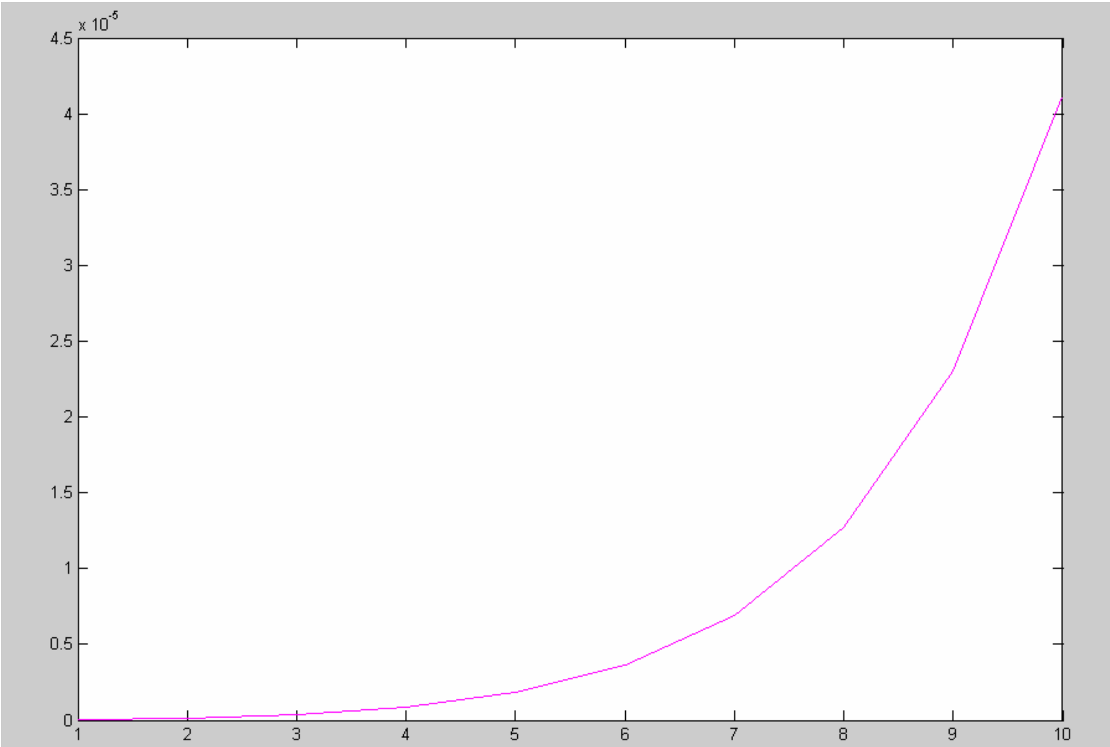


Figure 5: crosstalk vs number of channel

From this graph it can be said that crosstalk increase if we use more channels.

Figure 6:

The graph of crosstalk vs number of channel is plotted for different number of hops. At first crosstalk can be find out from the formula $\sigma^2 = Mb^2R^2P_s^{\,2}[2\varepsilon_{adj} + (N-3)\varepsilon_{nonadj} + X_{switch}]$

In this graph we have changed the value of M for the same input power, which is -8dbm to 20 dbm and for 10 channels.

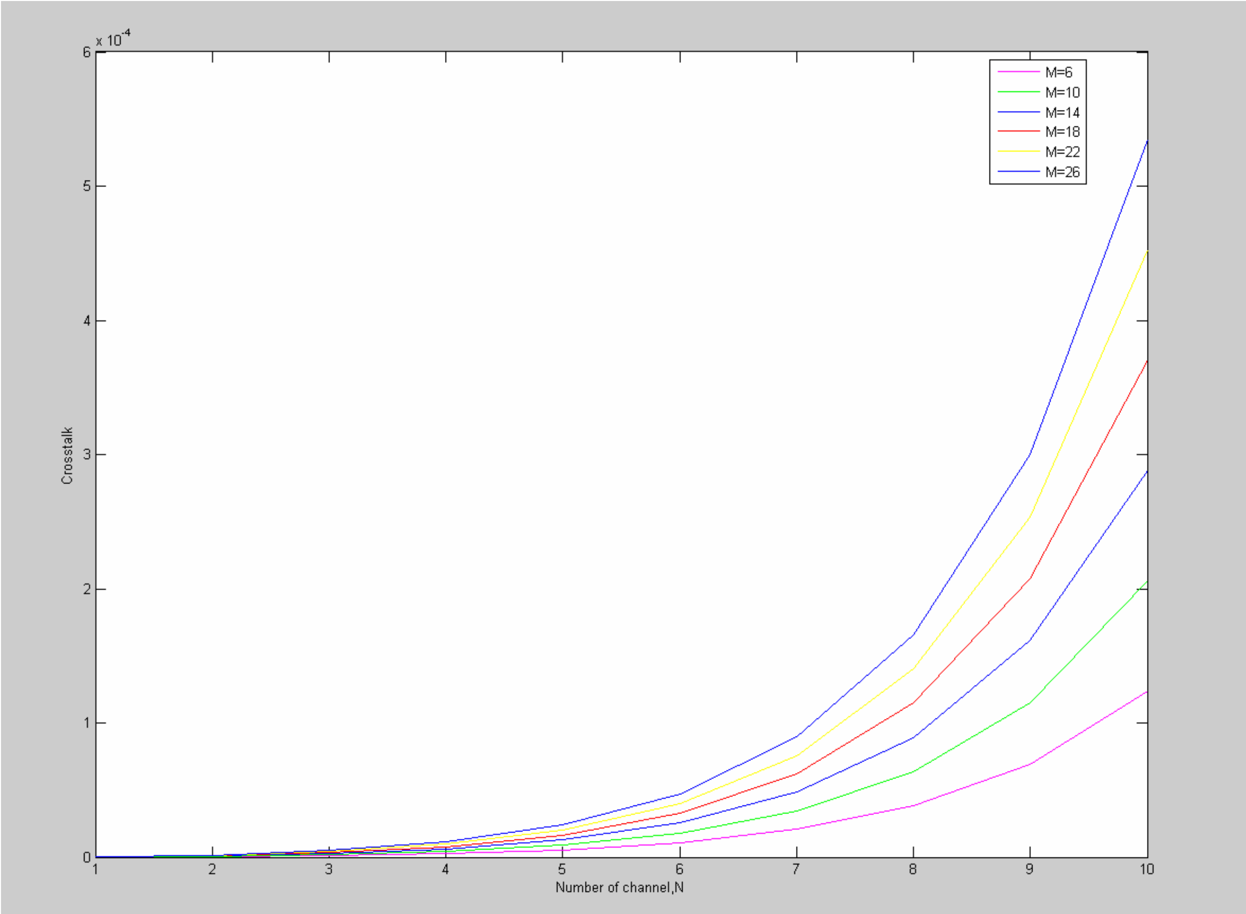


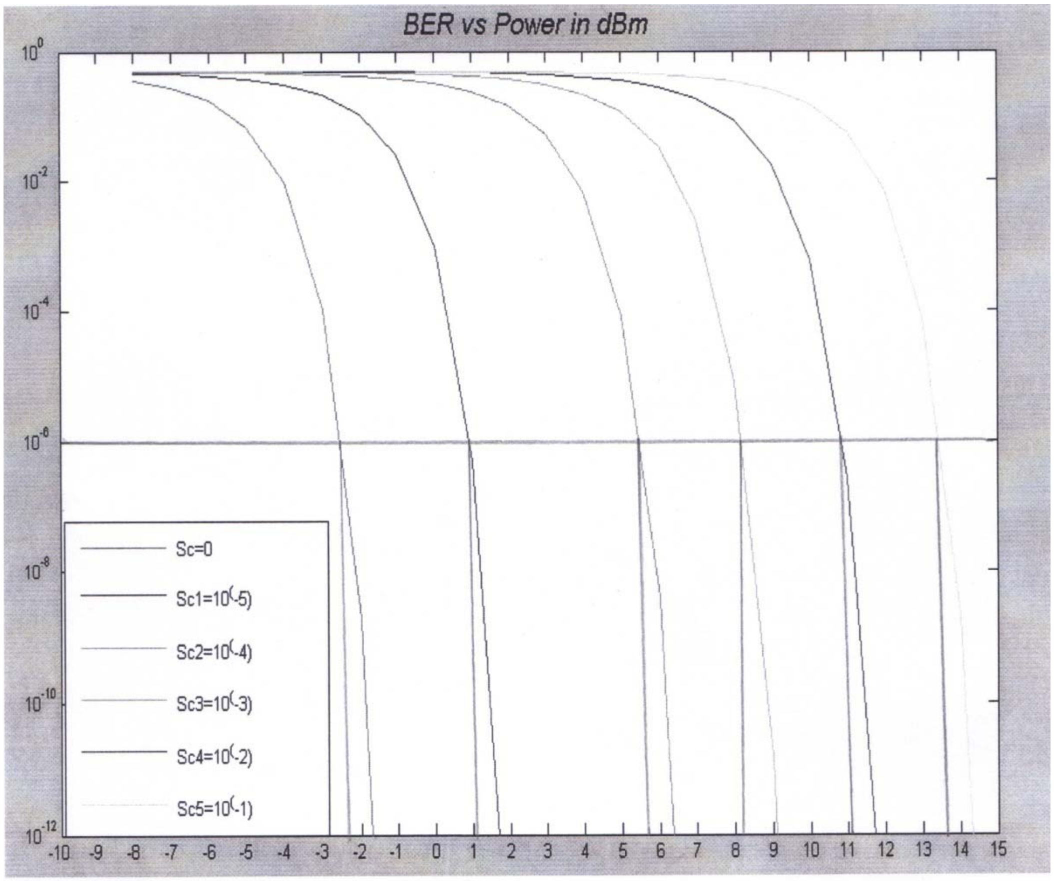
Figure 6: crosstalk vs number of channels

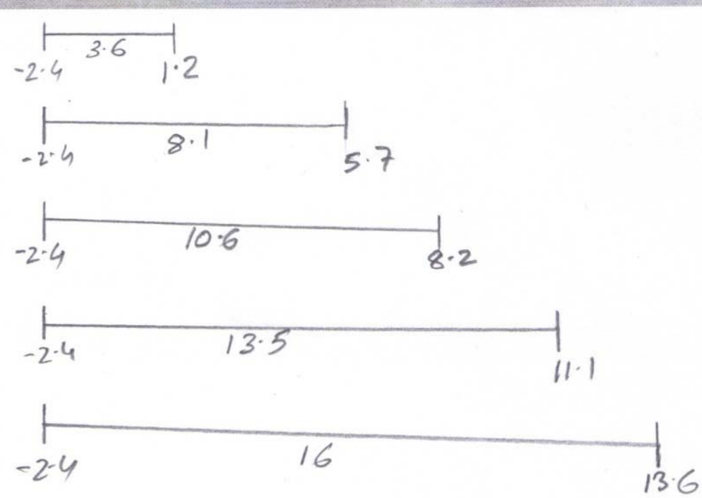
It can be said that if we increase the number of hop then crosstalk also increases. Another way it can be analyzed that for a fixed number of crosstalk if we use more hops, the number of channel decrease and in another way we can use more channels for less hops.

Figure 6

Now from the figure 4, for one bit error rate we can find the power penalty from the input power.

Power penalty is the difference between two powers. So for calculating power penalty we need to calculate the difference of input power with crosstalk from the power without crosstalk.


BER vs Power in dBm
Sc=0
Sc1=10(-5)
Sc2=10(-4)
Sc3=10(-3)
Sc4=10(-2)
Sc5=10(-1)


3·6
-2·4
1·2
8·1
-2·4
5·7
10·6
-2·4
8·2
13·5
-2·4
11·1
16
-2·4
13·6

Here we have taken $10^{(-6)}$ Bit error rate and calculated the power penalty corresponding of this value. We got input power -2.4 dbm when crosstalk is zero. For 0.00001 crosstalk power penalty is 3.6 db , for 0.0001 crosstalk we got 8.1db as power penalty. Power penalty is 10.6 db when crosstalk is 0.001, power penalty 13.5 db for crosstalk 0.01 and by using crosstalk 0.1 we got 16 db power penalties.

Figure 7

Power penalty vs crosstalk is plotted here.

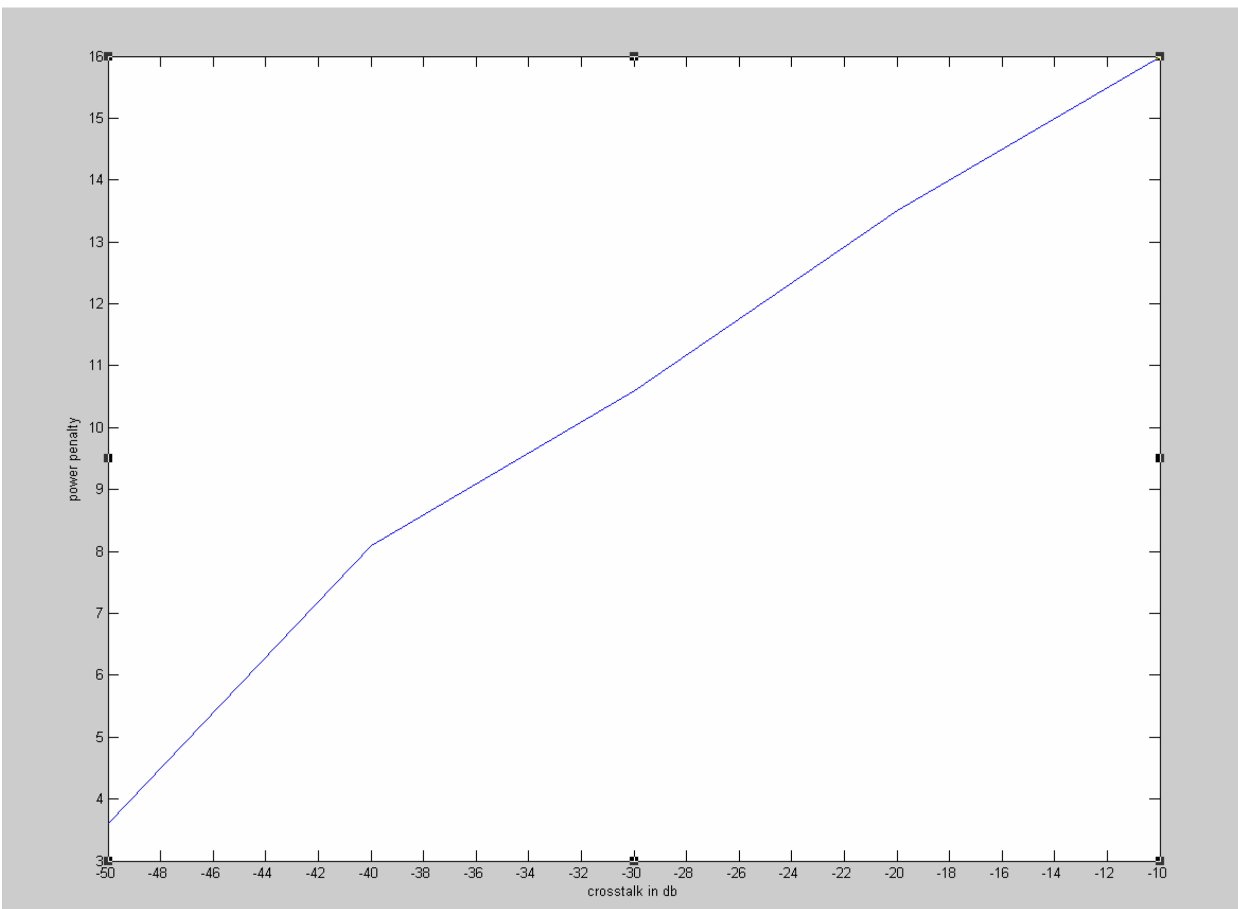


Figure7 : power penalty vs crosstalk

From this graph we can be able to find out the crosstalk for different power penalty.

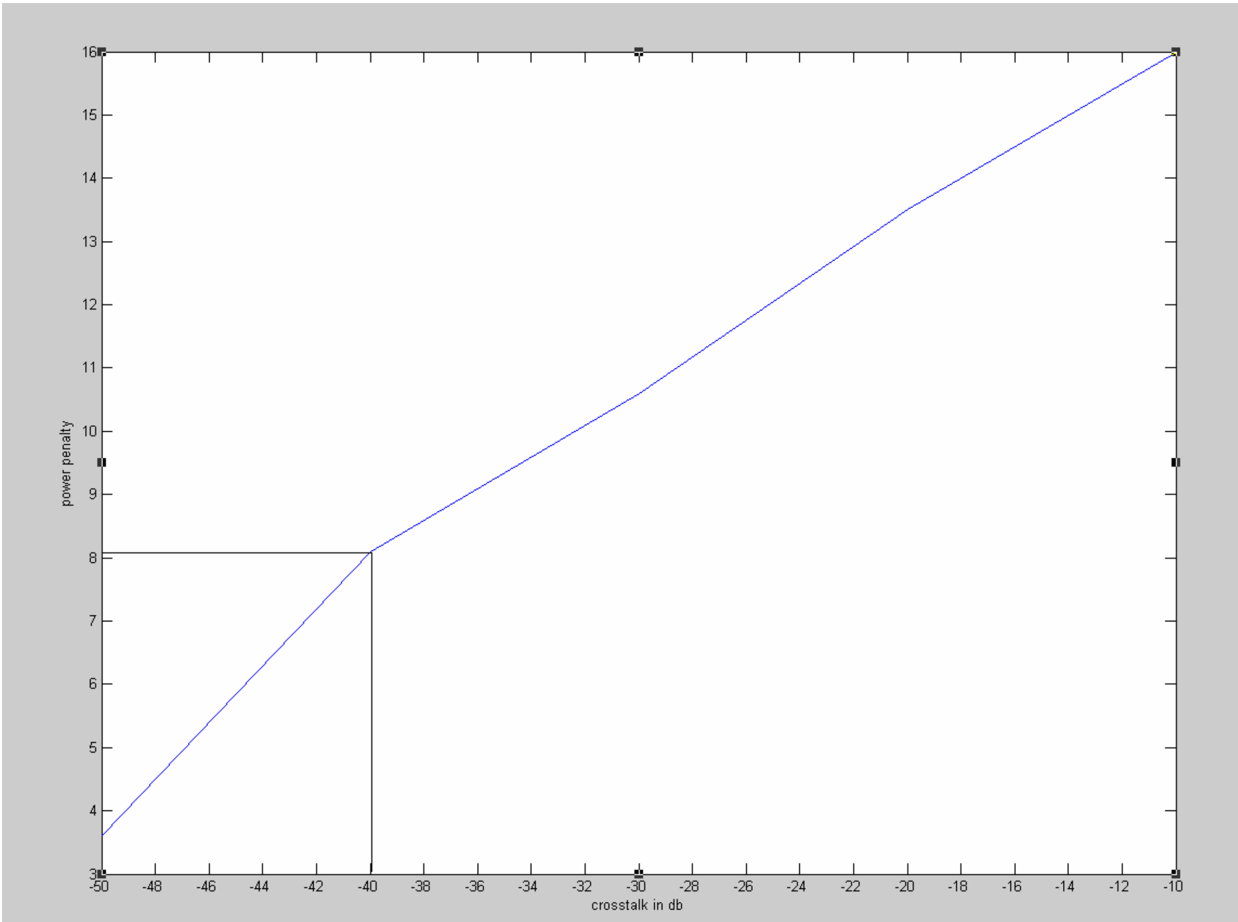
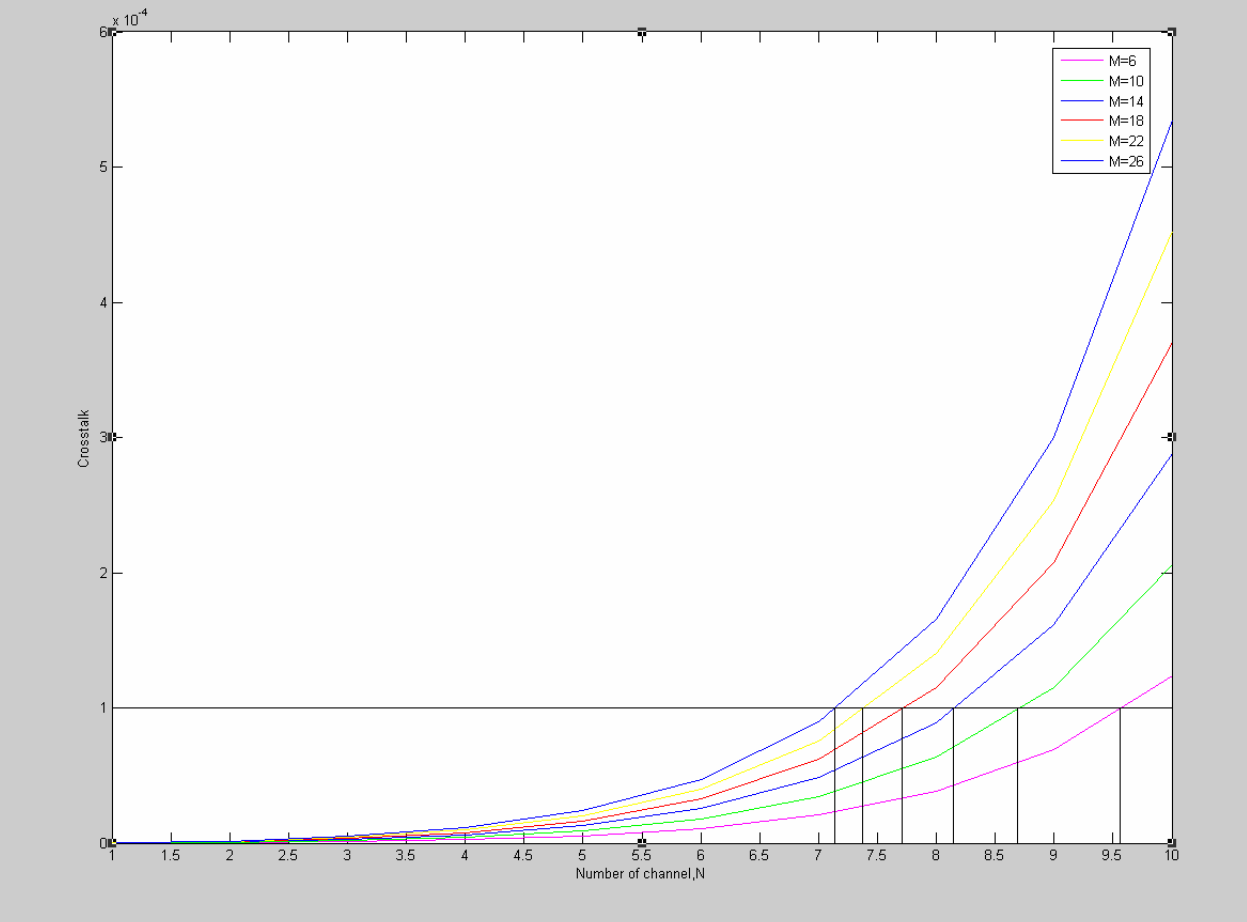


Figure: power penalty vs crosstalk.

For example, it can be said that for 8.1 power penalty relative crosstalk is -40 db, which is 0.0004. in this way we can find crosstalk for a given power penalty.

After finding the amount of crosstalk we can find the number of channels and number of hops can be used for that particular crosstalk from figure 6 which is crosstalk vs number of channels.

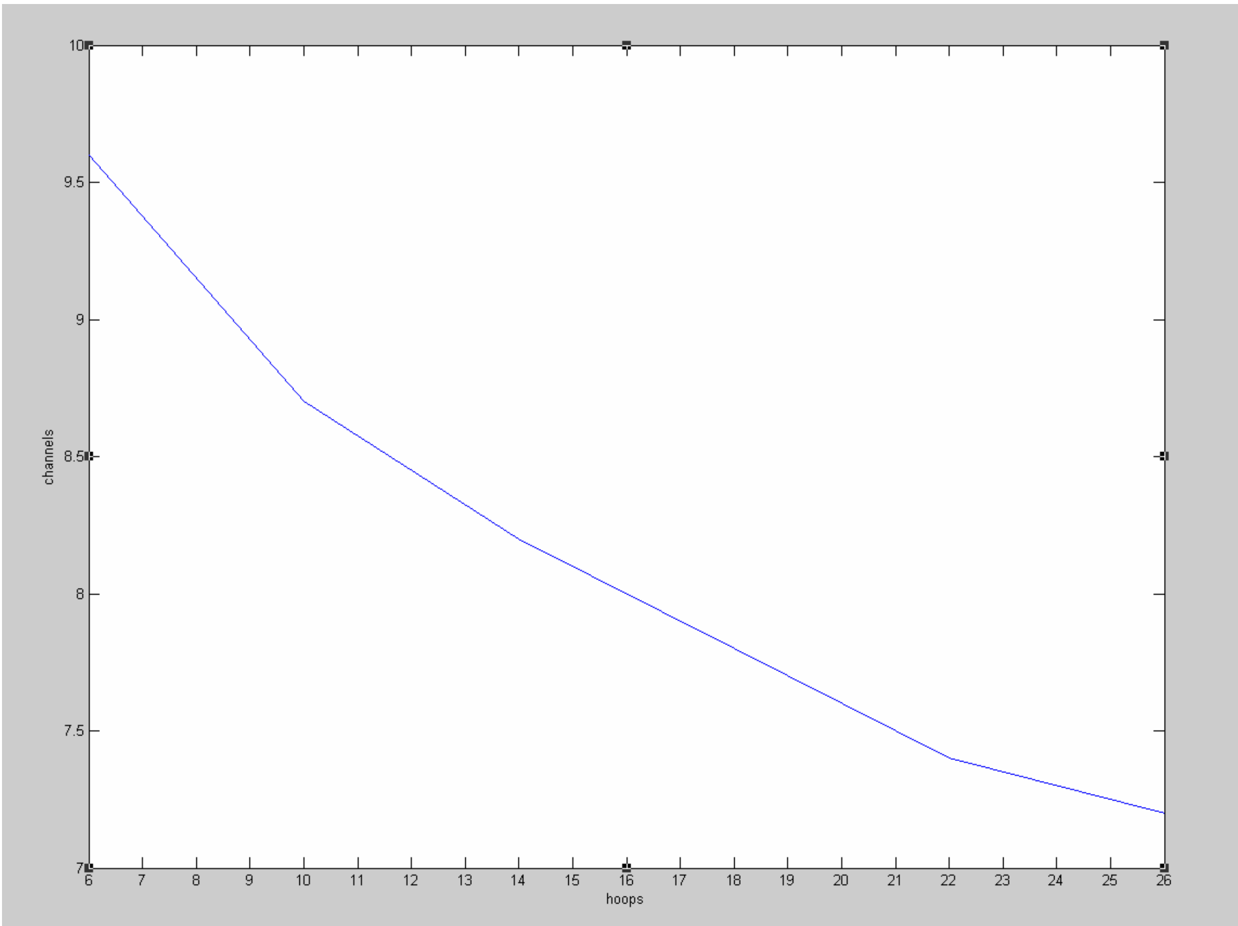


For this graph we are able to find out the number of channels and hops for related crosstalk. For example for power penalty 8.1db we got the corresponding crosstalk to be -40db which is 10^(-4). From the above graph, we can find combinations of hops and channels. Here, the combinations are :

Hoops	Channels
6	9.6 = 10(approx.)
10	8.7 = 9 (approx.)
14	8.2 = 8 (approx.)
18	7.8 = 8 (approx.)
22	7.4 = 7 (approx.)
26	7.2 = 7 (approx.)

Figure 8

Numbers of channel are plotted against number of hops.



This graph can be plotted manually too. Which is given below. This graph shows different combinations of hops and channels for a crosstalk 10 ^ (-4) which we got for power penalty 8.1 db. From this graph any combination can be used for this power penalty.

Similarly, we can plot a graph for hops and channels for any power penalty and corresponding crosstalk. Therefore a relationship between hops and channels is established using this graph.

Chapter 4

Conclusion and Future works

In this thesis paper, we have used some basic equations to optimize the relation between hoops and channels. No new equation were derived or used to form this relationship. The graph was plotted manually using the graphs plotted with the basic equations of BER and Crosstalk in matlab software. At first a graph for BER vs. Pin was plotted using BER equation. Then a graph of crosstalk vs. number of channels was plotted for different number of hops. From this graph power penalty was found out. This power penalty was used to plot a graph of power penalty vs. crosstalk. From this graph we have taken a particular crosstalk. And from the graph of crosstalk vs. channel, the combination of hoops and channels were found out. Which were plot manually to get the final graph. The graphs are shown in the Result section.

In this final graph, we have shown that for a particular Power Penalty, combination of hoops and channels can be plotted. The user can use any combination as required by the system.

Hence, we can conclude that by this process we can find number of hoops and channels for a given Power penalty.

Further research can be carried out to evaluate the performance of a WDM network with OXC using different topologies of the OXC and to find a topology with optimum system performance.

Work can be carried out to evaluate the performance of a WDM system with bi-directional OXC and find the limitations due to crosstalk and optimum system parameters.

Work can be carried out with precoding techniques to minimize the effect of Bit noise due to crosstalk and signal in a WDM system.

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‘Performance Limitations of Optical Cross Connect without Wavelength Converter due to Crosstalk’ by M. S, Islam, S.P. Majumder, Ngee Thiam Sim

‘Crosstalk in WDM Communication’ by Idelfonso Tafur Monry, EdwardbTangdiongga

Wikipedia.

MATLAB code of BER vs Input Power in dbm graph for different Bandwidth

```
Psdbm=[-8:1:1]
for i=1:10
    Ps(i)=10^(Psdbm(i)/10)*10^-3
end
L=1550*10^-9
c=3*10^8
m=c/L
G=10^(20/10);
Nsp=1.8;
h=6.63*10^(-34);
Rb=10*10^9;
B0=2*Rb;
 Sase=sqrt((G-1)*Nsp*h*m*B0)
Sc=0;
y = 10*log10(Rb)
for j=1:10
Q(j)=(y*Ps(j))^2/sqrt(Sase^2+Sc^2)
BER(j)=0.5*erfc(Q(j)/(sqrt(2)))
end
B0=4*Rb;
 Sase1=sqrt((G-1)*Nsp*h*m*B0)
Sc1=0;
y1 = 10*log10(Rb)
for k=1:10
```

```
Q1(k)=(y1*Ps(k))^2/sqrt(Sase1^2+Sc1^2)
BER1(k)=0.5*erfc(Q1(k)/(sqrt(2)))
end
B0=6*Rb;
 Sase2=sqrt((G-1)*Nsp*h*m*B0)
Sc2=0;
y2 = 10*log10(Rb)
for v=1:10
Q2(v)=(y*Ps(v))^2/sqrt(Sase^2+Sc^2)
BER2(v)=0.5*erfc(Q(v)/(sqrt(v)))
end
semilogy(Psdbm,BER,'r')
hold on
semilogy(Psdbm,BER1,'g')
hold on
semilogy(Psdbm,BER2,'b')
legend('B=2Rb','B=4Rb','B=6Rb',3)
xlabel('Psdbm')
ylabel('BER')
```

MATLAB code of BER vs Input Power in dbm graph for different Crosstalk

```
Psdbm=[-8:1:100]


for i=1:length(Psdbm)

    Ps(i)=10^(Psdbm(i)/10)*10^-3

end


L=1550*10^-9

c=3*10^8

m=c/L

G=10^(20/10);

Nsp=1.8;

h=6.63*10^(-34);

Rb=10*10^9;

B0=2*Rb;

 Sase=sqrt((G-1)*Nsp*h*m*B0)

Sc=0;

y = 10*log10(Rb)



for j=1:length(Psdbm)

Q(j)=(y*Ps(j))^2/sqrt(Sase^2+Sc)

BER(j)=0.5*erfc(Q(j)/(sqrt(2)))

end

B0=2*Rb;
```

```
 Sase1=sqrt((G-1)*Nsp*h*m*B0)
Sc1=10^(-4);
y1 = 10*log10(Rb)


for k=1:length(Psdbm)
Q1(k)=(y1*Ps(k))^2/sqrt(Sase1^2+Sc1)
BER1(k)=0.5*erfc(Q1(k)/(sqrt(2)))
end

B0=2*Rb;
 Sase2=sqrt((G-1)*Nsp*h*m*B0)
Sc2=10^(-3);
y2 = 10*log10(Rb)

for v=1:length(Psdbm)
Q2(v)=(y2*Ps(v))^2/sqrt(Sase2^2+Sc2)
BER2(v)=0.5*erfc(Q2(v)/(sqrt(v)))
end
B0=2*Rb;
 Sase3=sqrt((G-1)*Nsp*h*m*B0)
Sc3=10^(-2);
y3 = 10*log10(Rb)

for u=1:length(Psdbm)
```

```
Q3(u)=(y3*Ps(u))^2/sqrt(Sase3^2+Sc3)

BER3(u)=0.5*erfc(Q3(u)/(sqrt(u)))

end

B0=2*Rb;

 Sase4=sqrt((G-1)*Nsp*h*m*B0)

Sc4=10^(-1);

y4 = 10*log10(Rb)


for o=1:length(Psdbm)

Q4(o)=(y4*Ps(o))^2/sqrt(Sase4^2+Sc4)

BER4(o)=0.5*erfc(Q4(o)/(sqrt(o)))

end


semilogy(Psdbm,BER,'r')

hold on

semilogy(Psdbm,BER1,'b')

hold on

semilogy(Psdbm,BER2,'m')

hold on

semilogy(Psdbm,BER3,'g')

hold on

semilogy(Psdbm,BER4)

legend('Sc=0','Sc1=10^(-4)','Sc2=10^(-3)','Sc3=10^(-2)','Sc4=10^(-1)',5)


title('\it{BER vs Power in dBm}','FontSize',16)
```

MATLAB code of Crosstalk vs Number of channels

```
M=6;
Rd=0.85;
b=1;
eadj=0.5;
enonad=0.5;
Psdbm=[-5:1:100]
for i=1:length(Psdbm)
   Ps(i)=10^(Psdbm(i)/10)*10^-3
end
X=0.01;
n=1:10
S=zeros(1,length(n))
for j=1:length(n)
   S(j)=(M*b^2*Rd^2*Ps(j)^2*(2*eadj+(n(j)-3)*enonad+X))

end
M=10;
n=1:10
S1=zeros(1,length(n))
for k=1:length(n)
   S1(k)=(M*b^2*Rd^2*Ps(k)^2*(2*eadj+(n(k)-3)*enonad+X))

end
```

```
M=14;
n=1:10
S2=zeros(1,length(n))
for l=1:length(n)
   S2(l)=(M*b^2*Rd^2*Ps(l)^2*(2*eadj+(n(l)-3)*enonad+X))

end
M=18;
n=1:10
S3=zeros(1,length(n))
for o=1:length(n)
   S3(o)=(M*b^2*Rd^2*Ps(o)^2*(2*eadj+(n(o)-3)*enonad+X))

end
M=22;
n=1:10
S4=zeros(1,length(n))
for u=1:length(n)
   S4(u)=(M*b^2*Rd^2*Ps(u)^2*(2*eadj+(n(u)-3)*enonad+X))

end
M=26;
n=1:10
S5=zeros(1,length(n))
for v=1:length(n)
```

```
    S5(v)=(M*b^2*Rd^2*Ps(v)^2*(2*eadj+(n(v)-3)*enonad+X))

end

plot(n,S,'m')
hold on
plot(n,S1,'g')
hold on
plot(n,S2,'b')
hold on
plot(n,S3,'r')
hold on
plot(n,S4,'y')
hold on
plot(n,S5)
legend('M=6','M=10','M=14','M=18','M=22','M=26',6)
```