Performance Analysis Of A DWDM Optical Transport Network With Crosstalk

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By

Md.Fahmid-Ul-Islam -05310020

Md.Atiqul Haque Chowdhury -05310018

Muntakim Hussain -05210040

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ABSTRACT

Dense Wavelength Division Multiplexing (DWDM) that has dramatically increased the capacity of optical transmission systems. Its inherent advantages have made it the current favorite multiplexing technology for optical networks. In this paper, we have analyzed the performance of DWDM link that is corrupted by crosstalk for optical cross connect device.(OXC). Crosstalk is generated when a demultiplexer separates incoming wavelengths onto different output fibers. OXC is a device which is used for switching high speed optical signals. Analysis is included with different OXC configurations. We have shown bit error rate (BER) for OXC. We have also shown that the system suffers from a power penalty

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CHAPTER 1

INTRODUCTION

1.1 Introduction to Communication System

Communication is a process of transferring information from one entity to another. Communication processes are sign-mediated interactions between at least two agents which share a *repertoire* of signs and *semiotic* rules. Communication is commonly defined as "the imparting or interchange of thoughts, opinions, or information by speech, writing, or signs". Although there is such a thing as one-way communication, communication can be perceived better as a two-way process in which there is an exchange and progression of thoughts, feelings or ideas (energy) towards a mutually accepted goal or direction (information).

Communication is a process whereby information is enclosed in a package and is channeled and imparted by a sender to a receiver via some medium. The receiver then decodes the message and gives the sender a feedback. All forms of communication require a sender, a message, and a receiver. Communication requires that all parties have an area of communicative commonality. There are auditory means, such as speech, song, and tone of voice, and there are nonverbal means, such as body language, sign language, paralanguage, touch, eye contact, through media, i.e., pictures, graphics and sound, and writing.

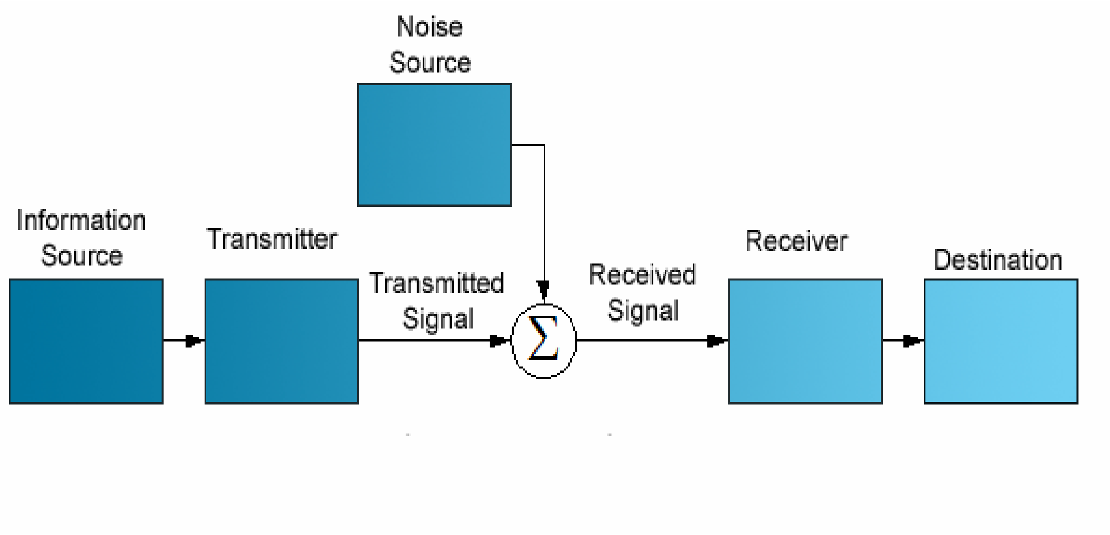


Figure1.1: Block diagram of communication system

1.2 Classifications of Communication System

In the present world, the communication system can be classified into two classes. They are-

- Analog system
- Digital system

1.2.1 Analog system

In this case 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**.** Figure 1.2 shows Block Diagram of Analog Optical Fiber Link.

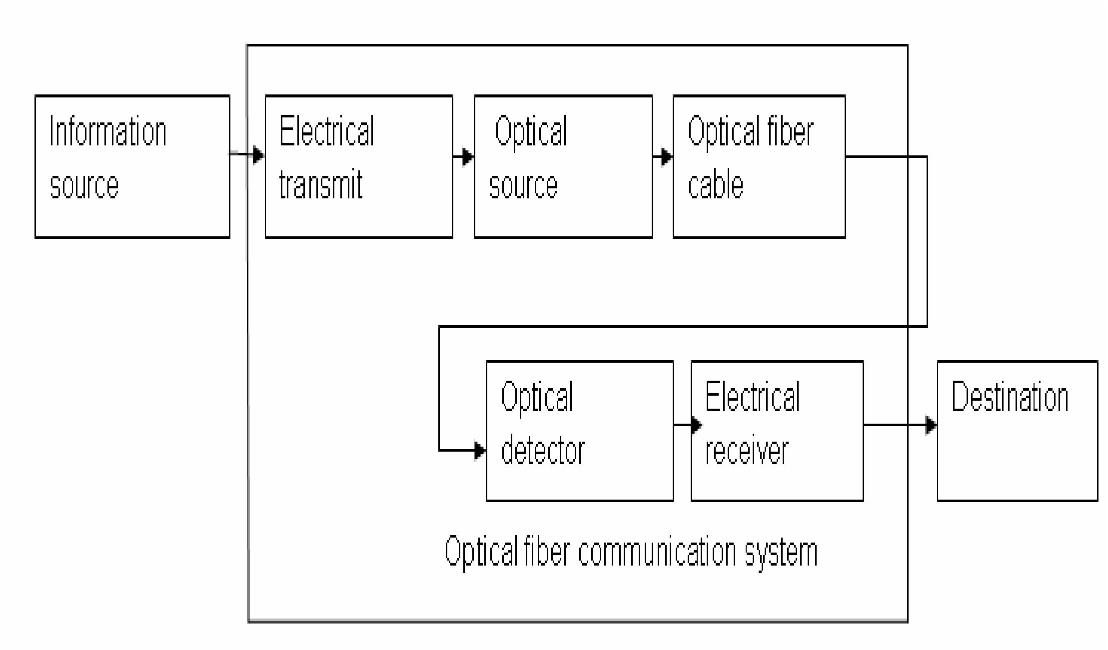


Figure1.2: Block diagram of Analog fiber link

Implement, analog modulation with an optical fiber communication system is less efficient, requiring a far higher signal to noise ratio at the receiver then digital modulation. Also the linearity needed for analog modulation is not always provided by semiconductor optical source, especially at the high modulation frequencies. And thereby an analog optical fiber communication links are generally limited to shorter distances and lower bandwidth then digital links.

1.2.2 Digital System

In digital optical fiber link, initially the input digital signal from the information source is suitable encoded for optical transmission. With digital modulation, however discrete changes in light intensity are obtained (i.e. on-off pulses). In here the laser drive circuit directly modulates the intensity of the semiconductor laser with the encoded digital signal. Hence a digital optical signal is launched in to 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 original digital information. Figure 1.2 shows the block diagram of digital optical fiber link:

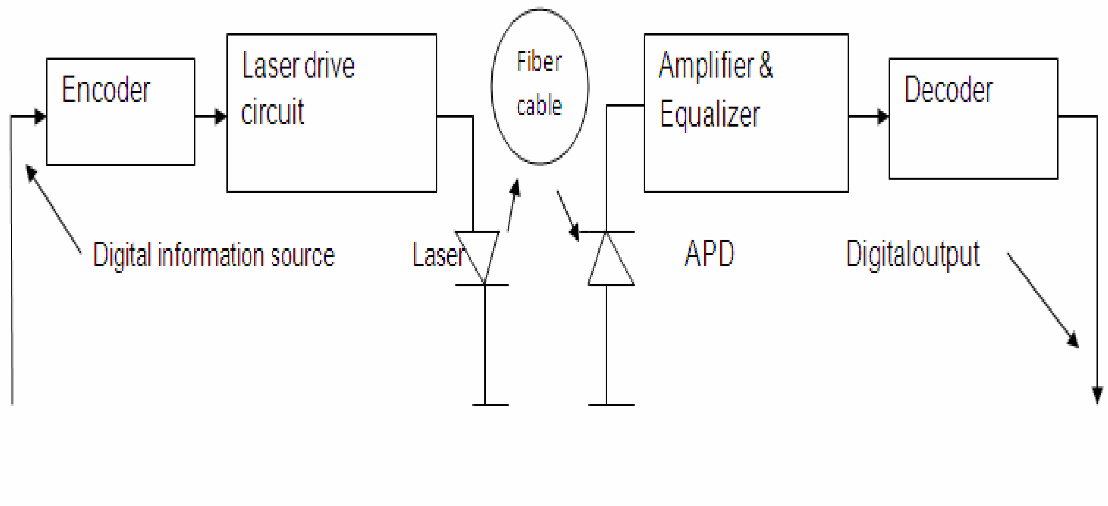


Figure1.3: Block diagram of Digital fiber link

1.2.2.1Wireless communication

Wireless communication is the transfer of information over a distance without the use of enhanced electrical conductors or "wires”. The distances involved may be short (a few meters as in television remote control) or long (thousands or millions of kilometers for radio communications). When the context is clear, the term is often shortened to "wireless". Wireless communication is generally considered to be a branch of telecommunications.

It encompasses various types of fixed, mobile, and portable two-way radios, cellular telephones, personal digital assistants (PDAs), and wireless networking. Other examples of *wireless technology* include GPS units, garage door openers and or garage doors, wireless computer mice, keyboards and headsets, satellite television

Wireless communication can be via:

- Radio frequency communication
- Microwave communication
- Infrared (IR) short-range communication

1.3 Radio Frequency (RF) communication

Radio frequency (RF) radiation is a subset of electromagnetic radiation with a wavelength of 100 km to 1 mm, which is a frequency of 3 kHz to 300 GHz, respectively. This range of electromagnetic radiation constitutes the radio spectrum and corresponds to the frequency of alternating current electrical signals used to produce and detect radio waves. RF can refer to electromagnetic oscillations in either electrical circuits or radiation through air and space. Like other subsets of electromagnetic radiation, RF travels at the speed of light.

In order to receive radio signals, for instance from AM/FM radio stations, a radio antenna must be used. However, since the antenna will pick up thousands of radio signals at a time, a radio tuner is necessary to tune in to a particular frequency (or frequency range). This is typically done via a resonator (in its simplest form, a circuit with a capacitor and an inductor). The resonator is configured to resonate at a particular frequency (or frequency band), thus amplifying sine waves at that radio frequency, while ignoring other sine waves. Usually, either the inductor or the capacitor of the resonator is adjustable, allowing the user to change the frequency at which it resonates. The resonant frequency of tuned circuit is given by the formula $f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$ where f is the frequency in Hertz, L is inductance in Henries, and C is capacitance in Farads.

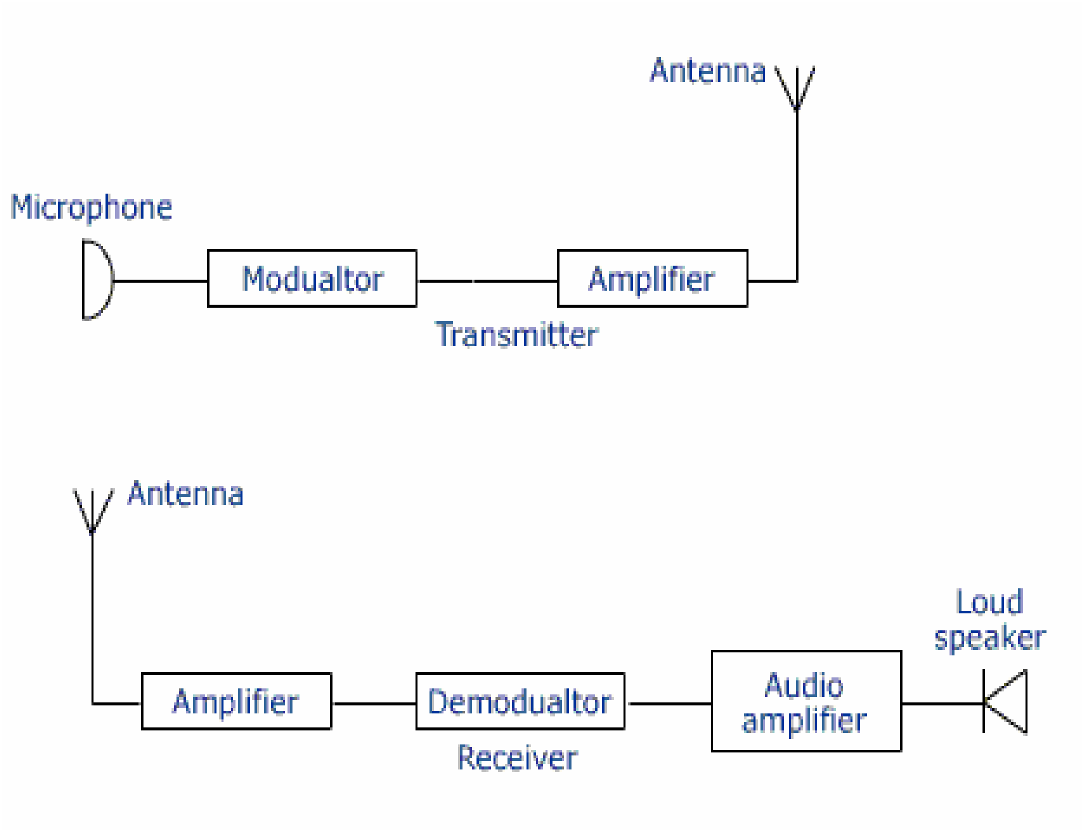


Figure1.4: Block diagram of Radio Frequency communication

1.3.1 Special properties of RF electrical signals

Electrical currents that oscillate at RF have special properties not shared by direct current signals.

- *The ease with which they can ionize air to create a conductive path through air, which is exploited by 'high frequency' units used in electric arc welding.*
- *RF current cannot penetrate deeply into electrical conductors but flows along the surface of conductors; this is known as the skin effect.*
- *It has the ability to appear to flow through paths that contain insulating material, like the dielectric insulator of a capacitor. The degree of effect of these properties depends on the frequency of the signals.*

1.3.2 Radio spectrum

Radio spectrum refers to the part of the electromagnetic spectrum corresponding to radio frequencies – that is, frequencies lower than around 300 GHz (or, equivalently, wavelengths longer than about 1 mm).Different parts of the radio spectrum are used for different radio transmission technologies and applications.

Designation		Frequency	Wavelength
ELF	extremely low frequency	3Hz to 30Hz	100'000km to 10'000 km
SLF	super low frequency	30Hz to 300Hz	10'000km to 1'000km
ULF	ultraslow frequency	300Hz to 3000Hz	1'000km to 100km
VLF	very low frequency	3kHz to 30kHz	100km to 10km
LF	low frequency	30kHz to 300kHz	10km to 1km
MF	medium frequency	300kHz to 3000kHz	1km to 100m
HF	high frequency	3MHz to 30MHz	100m to 10m
VHF	very high frequency	30MHz to 300MHz	10m to 1m
UHF	ultrahigh frequency	300MHz to 3000MHz	1m to 10cm
SHF	super high frequency	3GHz to 30GHz	10cm to 1cm
EHF	extremely high frequency	30GHz to 300GHz	1cm to 1mm

Table 1.1: Radio Spectrums

1.4 Microwave (MW) Communication

Portion of the electromagnetic spectrum that is situated between radio waves and infrared radiation. Microwaves have wavelengths ranging from 30 cm to 1 mm, corresponding to frequencies from about 1 gigahertz (10^9 Hz) to 1 terahertz (10^{12} Hz). They are the principal carriers of television, telephone, and data transmissions between stations on Earth and between the Earth and satellites.

1.4.1 Microwave sources

- Vacuum tube devices operate on the ballistic motion of electrons in a vacuum under the influence of controlling electric or magnetic fields, and include the magnetron, klystron, traveling-wave tube (TWT), and gyration.
- Solid-state sources include the field-effect transistor (at least at lower frequencies), tunnel diodes, Gunn diodes, and IMPATT diodes.
- The sun also emits microwave radiation; most of it is blocked by the atmosphere.

1.4.2 Applications

Areas in which microwave radiation is applied include radar, communications, radiometry, medicine, physics, chemistry, and cooking food.

- Radar: Radar is used in military applications, commercial aviation, remote sensing of the atmosphere, and astronomy. The high antenna directivity and the excellent propagation characteristics of microwaves in the atmosphere make this the preferred band for radar applications.
- Space Communication: There is at least 100 times as much frequency space available for communications in the microwave band as in the entire spectrum below microwaves. The high directivity also makes possible communication to satellites and deep-space probes.

- Radiology: Applications of microwaves in medicine include (1) thermography, the measurement of tissue temperature; (2)

hyperthermia, microwave heating used in the treatment of cancer and in the treatment of hypothermic subjects; and (3) biomedical imaging, the use of microwaves to study the structure of tissue beneath the skin.

- Remote sensing: A microwave radiometer is a sensitive receiver which measures the noise power received by an antenna; from this measurement, the noise temperature of the source object can be determined. Radiometers are used extensively for remote sensing.

1.5 Optical communication

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

The advantages of optical communication are three types:

- 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.

- The very short wavelength of the optical carrier (typically of the order of 1 micrometer) permits the realization of very small, compact components.

- The highest transparency for electromagnetic radiation yet achieved in any solid material is that of silica glass in the wavelength region 1–1.5 micrometer. This transparency is orders of magnitude higher than that of any other solid material in any other part of the spectrum.

Forms of optical communication:

- Optical fiber communications
- Free-space optical communication

1.5.1: Optical fiber communication

Optical fiber communication is the most common type of channel for optical communications; however, other types of optical waveguides are used within communications gear, and have even formed the channel of very short distance (e.g. chip-to-chip, intra-chip) links in laboratory trials.

1.5.1.1Components of optical fiber communication:

Optical transmitters:

The transmitters in optical fiber links are generally light-emitting diodes (LED) or laser diodes. Infrared light, rather than visible light is used more commonly, because optical fibers transmit infrared wavelengths with less *attenuation and dispersion. The signal encoding is typically simple intensity modulation,*

Optical receivers:

Semiconductor photodiodes are used for the receivers in virtually all optical communication systems. There are two basic types of photodiodes in use:

- *Photodiodes where, reverse biased junction is applied*
- *Avalanche photodiodes*

1.5.2: Free-space optical communication

Free Space Optics (FSO) is an optical communication technology that uses light propagating in free space to transmit data between two points. The technology is useful where the physical connections by the means of fiber optic cables are impractical due to high costs or other.

Applications:

- LAN-to-LAN connections on campuses at Fast Ethernet or Gigabit Ethernet speeds.
- Converged Voice-Data-Connection.
- For communications between spacecraft, including elements of a satellite constellation etc.

1.5.3: Fiber optics

Fiber Optical Cable is a method of transmitting information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information. Optical fibers have largely replaced copper wire communications in core networks in the developed world.

A technology that uses glass (or plastic) threads (fibers) to transmit data. A fiber optic cable consists of a bundle of glass threads, each of which is capable of transmitting messages modulated onto light waves.

Advantages:

- Fiber optic cables have a much greater bandwidth than metal cables. This means that they can carry more data.
- Fiber optic cables are less susceptible than metal cables to interference.
- Fiber optic cables are much thinner and lighter than metal wires.
- Data can be transmitted digitally (the natural form for computer data) rather than analogically.

Applications of fiber optics:

- *Optical fiber is used by many telecommunications companies to transmit telephone signals*
- *Internet communication*
- *Cable television*
- *Submarine communications cable*

Technology:

Main technologies are related with fiber optics, are given below:

- *Transmitter, Receiver, Fiber, Amplifier, Encoder, Decoder, Multiplexer, De-multiplexer, Attenuations, Dispersion, regeneration*

1.6 Optical Multiplexing Schemes

Multiplexing is sending multiple signals or streams of information on a carrier at the same time in the form of a single, complex signal and then recovering the separate signals at the receiving end. In analog transmission, signals are commonly multiplexed using frequency-division multiplexing (FDM), in which the carrier bandwidth is divided into sub channels of different frequency widths, each carrying a signal at the same time in parallel. In digital transmission, signals are commonly multiplexed using time-division multiplexing (TDM), in which the multiple signals are carried over the same channel in alternating time slots.

Types of multiplexing:

- Frequency Division Multiplexing (FDM)
- Time Division Multiplexing (TDM)
- Wavelength Division Multiplexing (WDM)
- Code Division Multiplexing (CDM)

1.6.1 Frequency Division Multiplexing (FDM)

In communication systems, Frequency Division Multiplexing (FDM) is a method in which each signal is allocated a frequency slot within the overall line/transmission bandwidth, In other words the total available frequency bandwidth on the transmission line is divided into frequency channels and each information signal occupies one of these channels the signal will have exclusive use of this frequency slot all the time (i.e. each subscriber occupies his/her own slot). Before transmission, the individual information signals are shifted up in frequency as shown on the following figure.

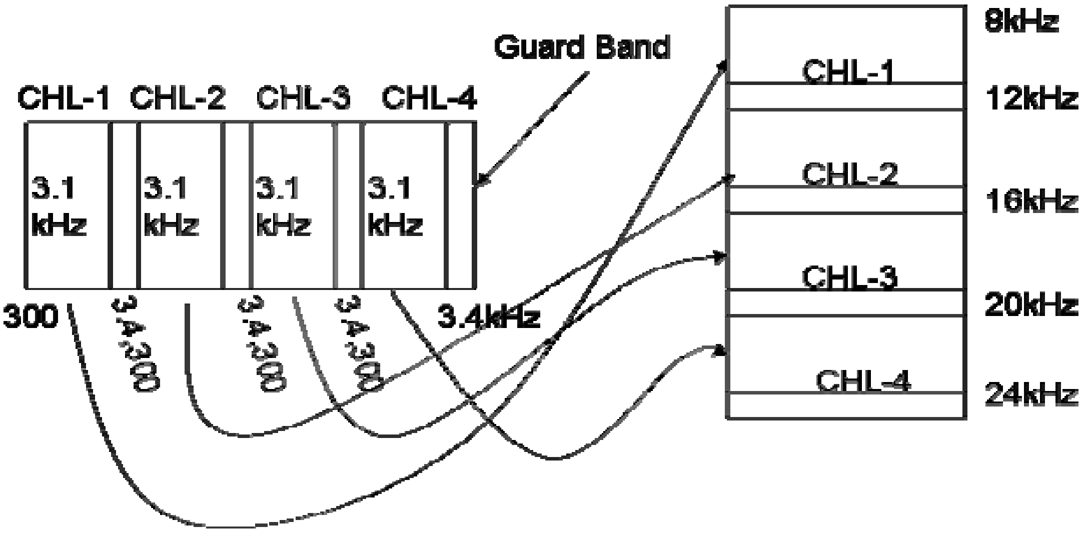


Figure1.5: Basic Frequency Division Multiplexing Profile

Figure above shows four telephone speech channels. The bandwidth of each speech is restricted to the range 300 – 3400Hz (called commercial speech bandwidth). This gives a bandwidth of 3400-300 = 3.1 kHz for each channel as shown in the above figure. Guard bands prevent interference between channels. The information signals are shifted up in frequency as shown on the right with a channel spacing of 4 kHz.

1.6.2 Time Division Multiplexing (TDM)

Time Division Multiplexing (TDM) allows multiple conversations to take place by the sharing of medium or channel in time. A channel is allocated the whole of the line bandwidth for a specific period of time. This means that each subscriber is allocated a time slot. When we discuss Pulse Code Modulation (PCM), we talk about sampling a signal in time. This is also done in Time Division Multiplexing (TDM). If we have a number of analog signals, each signal is sampled first. Then, the samples from each are combined and the composite signal is transmitted. Sampling is an essential component in TDM.

Individual channels are sampled at higher rates [normally 8 kHz (i.e. 8 samples per cycle of 1 kHz)]. The samples are converted into digital signals and a series of zeros and ones is transmitted on the line.

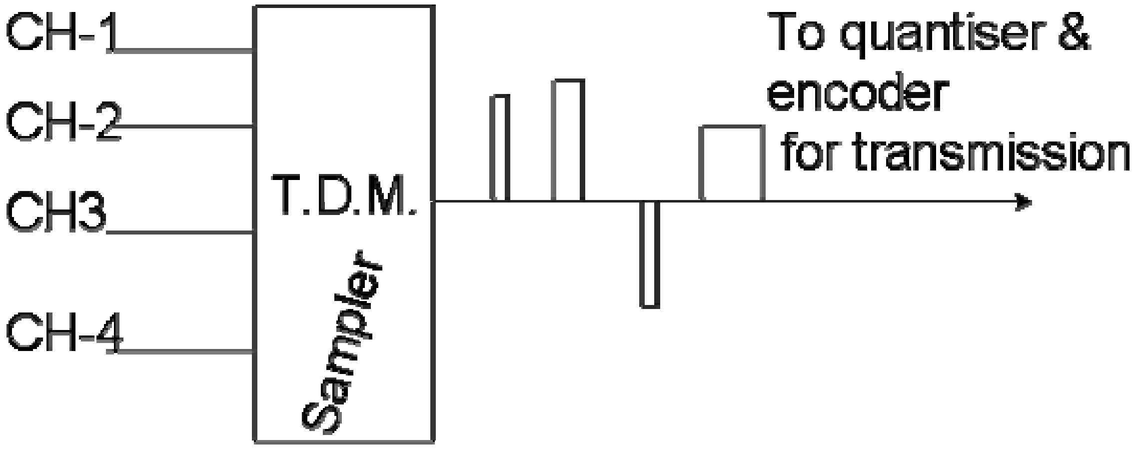


Figure1.6: Basic Time Division Multiplexing (TDM) System

1.6.3 Code Division Multiplexing (CDM)

Code division multiplexing (CDM) allows signals from a series of independent sources to be transmitted at the same time over the same frequency band. This is accomplished by using orthogonal codes to spread each signal over a large, common frequency band. At the receiver, the appropriate orthogonal code is then used again to recover the particular signal intended for a particular user.

The key principle of CDM is spread spectrum. Spread spectrum is a means of communication with the following features:

- Each information-bearing signal is transmitted with a bandwidth in excess of the minimum bandwidth necessary to send the information.
- The bandwidth is increased by using a spreading code that is independent of the information.
- The receiver has advance knowledge of the spreading code and uses this knowledge to recover the information from the received, spread-out signal.

Spread spectrum seems incredibly counterintuitive. We've spent most of this book studying ways to transmit information using a minimum of bandwidth. Why should we now study ways to intentionally increase the amount of bandwidth required to transmit a signal? By the end of this chapter you will see that spread spectrum is a good technique for providing secure, reliable, private communication in an environment with multiple transmitters and receivers. In fact, spread spectrum and CDM are currently being used in an ever-increasing number of commercial cellular telephone systems.

1.6.4 Wavelength Division Multiplexing (WDM)

Wavelength-division multiplexing (WDM) is a method of combining multiple signals on laser beams at various infrared (IR) wavelengths for transmission along fiber optic media. Each laser is modulated by an independent set of signals. Wavelength-sensitive filters, the IR analog of visible-light color filters, are used at the receiving end.

WDM is similar to frequency-division multiplexing (FDM). But instead of taking place at radio frequencies (RF), WDM is done in the IR portion of the electromagnetic (EM) spectrum. Each IR channel carries several RF signals combined by means of FDM or time-division multiplexing (TDM). Each multiplexed IR channel is separated, or demultiplexed, into the original signals at the destination. Using FDM or TDM in each IR channel in combination with WDM of several IR channels, data in different formats and at different speeds can be transmitted simultaneously on a single fiber.

In early WDM systems, there were two IR channels per fiber. At the destination, the IR channels were demultiplexed by a dichroic (two-wavelength) filter with a cutoff wavelength approximately midway between the wavelengths of the two channels. It soon became clear that more than two multiplexed IR channels could be demultiplexed using cascaded dichroic filters, giving rise to coarse wavelength-division multiplexing (CWDM) and dense wavelength-division multiplexing (DWDM). In CWDM, there are usually eight different IR channels, but there can be up to 18. In DWDM, there can be dozens. Because each IR channel carries its own set of multiplexed RF signals, it is theoretically possible to transmit combined data on a single fiber at a total effective speed of several hundred gigabits per second (Gbps).

The use of WDM can multiply the effective bandwidth of a fiber optic communications system by a large factor. But its cost must be weighed against the alternative of using multiple fibers bundled into a cable. A fiber optic repeater device called the erbium amplifier promises to make WDM a cost-effective long-term solution to the bandwidth exhaustion problem.

Impetus behind WDM system

- Development of optoelectronics device & components
- Recent progress in integrated optics technology
- Low loss optical fiber

The key system features of WDM

- Capacity update
- Transparency
- Wavelength routing
- Wavelength switching

WDM application

- WANs: fiber links => WDM => DWDM links
- Undersea links : amplifier => high maintenance cost and it can’t put to many fiber
- DWDM highly successful in long haul market
- Bandwidth demand is low and more dynamic

Advantages of WDM

- Large bandwidth and capacity
- Multiple channel at different wavelength
- Low transition cost
- Signal security
- Potential low transmission cost per channel
- WDM technology can also provide fiber redundancy

Disadvantage of WDM

- Less electrical power
- Expensive connection
- Expensive amplifiers

WDM in transmission system

Theoretically, the full data transmission capacity of fiber would be exploited with a single data channel of very high data rate, corresponding to a very large channel bandwidth. However, given the enormous available bandwidth (tens to terahertz) of the low loss transmission window of silica single-mode fibers, this would lead to a data rate which is far higher than what can be handled by optoelectronics sender and receiver.

Various types of dispersion in the transmission fiber would have very detrimental effects on such wide-bandwidth channels, so that the transmission distance would be strongly restricted. WDM solves these problems by keeping the transmission rates of each channel at reasonably low levels and achieving a high total data rate by combining several or many channels. Two different version of WDM can be defined below:

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

1.6.4.1 Coarse Wavelength Division Multiplexing (CWDM)

Coarse wavelength division multiplexing (CWDM) is a method of combining multiple signals on laser beams at various wavelengths for transmission along fiber optic cables, such that the number of channels is fewer than in dense wavelength division multiplexing (DWDM) but more than in standard wavelength division multiplexing (WDM).

CWDM systems have channels at wavelengths spaced 20 nanometers (nm) apart, compared with 0.4 nm spacing for DWDM. This allows the use of low-cost, uncooled lasers for CWDM. In a typical CWDM system, laser emissions occur on eight channels at eight defined wavelengths: 1610 nm, 1590 nm, 1570 nm, 1550 nm, 1530 nm, 1510 nm, 1490 nm, and 1470 nm. But up to 18 different channels are allowed, with wavelengths ranging down to 1270 nm.

The energy from the lasers in a CWDM system is spread out over a larger range of wavelengths than is the energy from the lasers in a DWDM system. The tolerance (extent of wavelength imprecision or variability) in a CWDM laser is up to ± 3 nm, whereas in a DWDM laser the tolerance is much tighter. Because of the use of lasers with lower precision, a CWDM system is less expensive and consumes less power than a DWDM system. However, the maximum realizable distance between nodes is smaller with CWDM.

Advantage:

- Maximizes the existing fiber network, allowing you to meet additional service requirements without adding additional fiber.

- Enables out-of-band testing: simply dedicate a separate wavelength for testing and monitoring.
- Installs easily and maintenance is just as simple.

CHAPTER 2

Dense Wavelength Division Multiplexing (DWDM)

2.1 Dense Wavelength Division Multiplexing (DWDM) System

Dense wavelength division multiplexing (DWDM) is a technology that puts data from different sources together on an optical fiber, with each signal carried at the same time on its own separate light wavelength. Using DWDM, up to 80 (and theoretically more) separate wavelengths or channels of data can be multiplexed into a light stream transmitted on a single optical fiber. Each channel carries a time division multiplexed (TDM) signal. In a system with each channel carrying 2.5 Gbps (billion bits per second), up to 200 billion bits can be delivered a second by the optical fiber. DWDM is also sometimes called wave division multiplexing (WDM).

Since each channel is demultiplexed at the end of the transmission back into the original source, different data formats being transmitted at different data rates can be transmitted together. Specifically, Internet (IP) data, Synchronous Optical Network data (SONET), and asynchronous transfer mode (ATM) data can all be traveling at the same time within the optical fiber. DWDM promises to solve the "fiber exhaust" problem and is expected to be the central technology in the all-optical networks of the future.

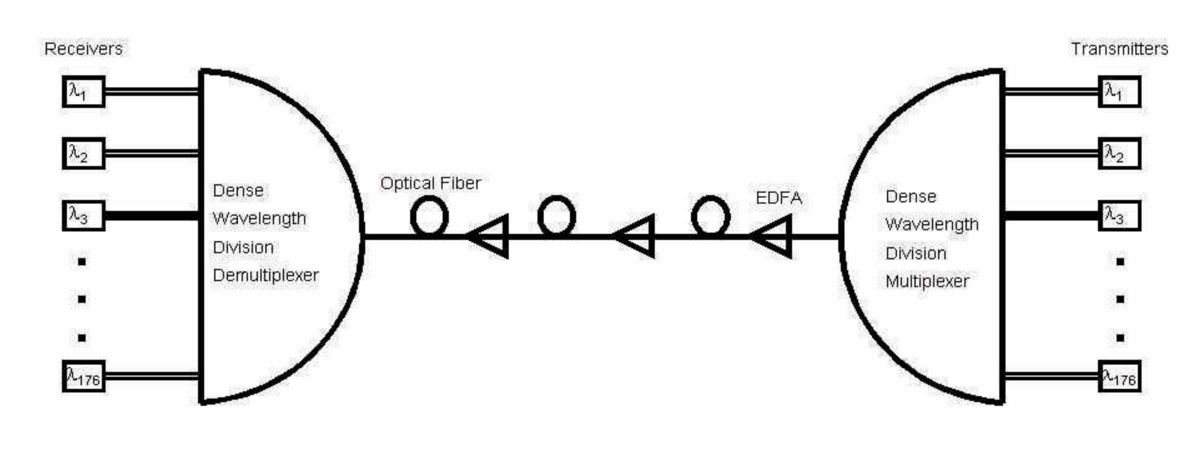


Figure2.1: Block Diagram of a basic or typical DWDM System

Advantage:

From both technical and economic perspectives, the ability to provide potentially unlimited transmission capacity is the most obvious advantage of DWDM technology. The current investment in fiber plant can not only be preserved, but optimized by a factor of at least 32. As demands change, more capacity can be added, either by simple equipment upgrades or by increasing the number of lambdas on the fiber, without expensive upgrades. Capacity can be obtained for the cost of the equipment, and existing fiber plant investment is retained.

Bandwidth aside, DWDM's most compelling technical advantages can be summarized as follows:

- **Transparency**—Because DWDM is a physical layer architecture, it can transparently support both TDM and data formats such as ATM, Gigabit Ethernet, ESCON, and Fiber Channel with open interfaces over a common physical layer.
- **Scalability**—DWDM can leverage the abundance of dark fiber in many metropolitan area and enterprise networks to quickly meet demand for capacity on point-to-point links and on spans of existing SONET/SDH rings.
- **Dynamic provisioning**—Fast, simple, and dynamic provisioning of network connections give providers the ability to provide high-bandwidth services in days rather than months.

2.2 Limitations of DWDM System

Even after the vast use of dense wavelength division multiplexing (DWDM), there are some limitations of the system. They are:

- Dispersion
- Cross-phase modulation(XPM)
- Crosstalk etc.

2.2.1 Dispersion:

The invention is the novel use of dispersion compensation in a long haul wavelength division multiplexed high capacity optical transport system which has very many (400-2000) channels packed extremely closely together (e.g. 5-10 GHz channel spacing), in order to greatly reduce the deleterious effects of four-wave mixing. It has been discovered that the exact distribution of fiber dispersion along the optical link (the ‘dispersion map’) strongly influences the degree of four-wave mixing, and hence the degradation in transmission quality. In particular, by carefully designing the dispersion map of the optical fiber link it is possible to significantly reduce the effects of four-wave mixing, allowing total system capacities and reaches to be achieved that would otherwise have not been possible. It should be noted that the use of such a dispersion map may not provide the optimum net system dispersion. However, the inclusion of additional dispersion compensating modules at the end of a link allows for the conventional benefit of the use of dispersion compensation without reducing the beneficial effect of decreased four-wave mixing.

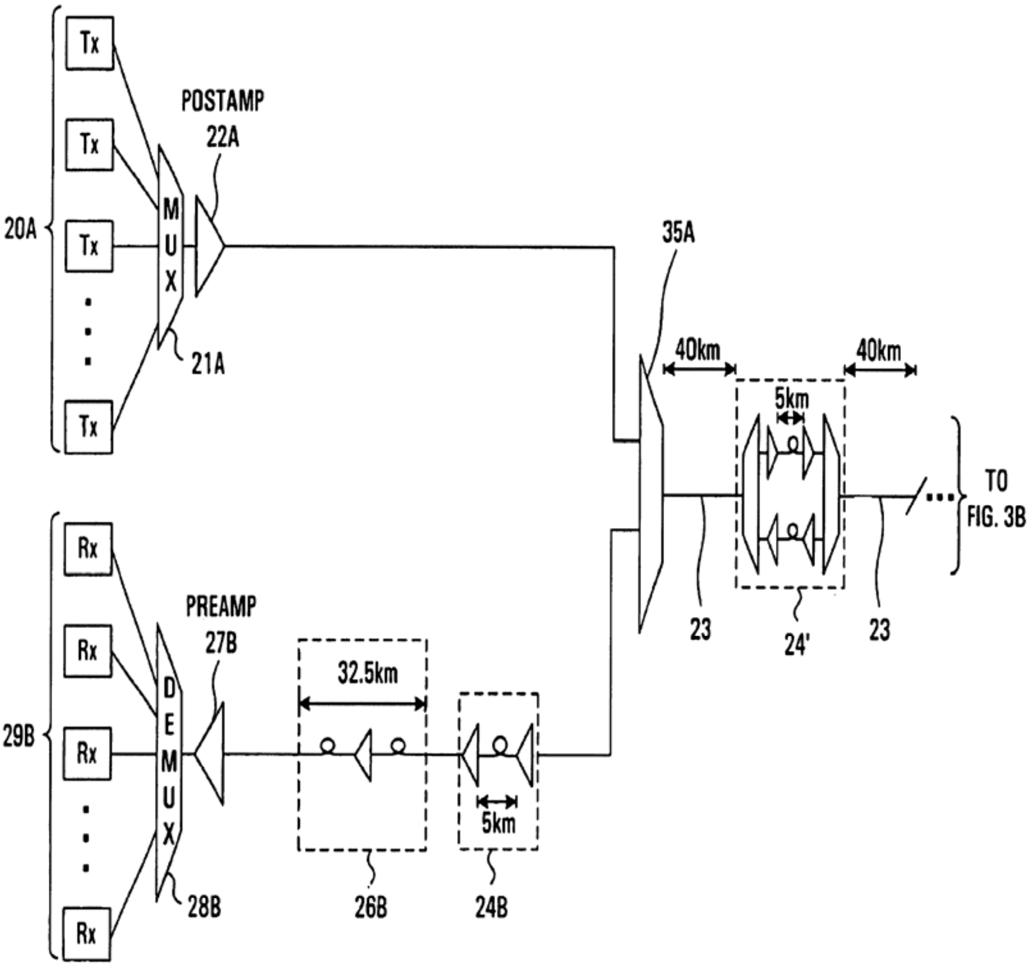


Figure2.2: Dispersion in DWDM System

The invention, then, is the intentional design and use of a particular distribution of dispersion compensating modules in a wavelength-division multiplexed optical transport system in order to achieve a reduction or suppression of four-wave mixing. An important practical point is that its use does not preclude efficient optimization of the net system dispersion as determined by the effects of fiber dispersion, other non-linear effects and transmitter chirp.

As the invention only requires the use of dispersion compensating modules (some realizations of which are currently commercially available and some being in development), an obvious advantage of the invention is that the cost of implementing such a scheme should not make much difference to the overall system cost. Therefore this invention is likely to be very important to the high capacity transport market.

Other aspects and features of the present invention will become apparent to those ordinarily skilled in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying drawings.

2.2.2 Cross-phase modulation (XPM)

Cross-phase modulation (XPM) is a nonlinear optical effect where one wavelength of light can affect the phase of another wavelength of light through the optical kerr effect.

The optical Kerr effect or AC Kerr effect is the case in which the electric field is due to the light itself. This causes a variation in index of refraction which is proportional to the local irradiance of the light. This refractive index variation is responsible for the nonlinear optical effects of self-focusing, self-phase modulation and modulation instability, and is the basis for Kerr-lens mode locking. This effect only becomes significant with very intense beams such as those from lasers.

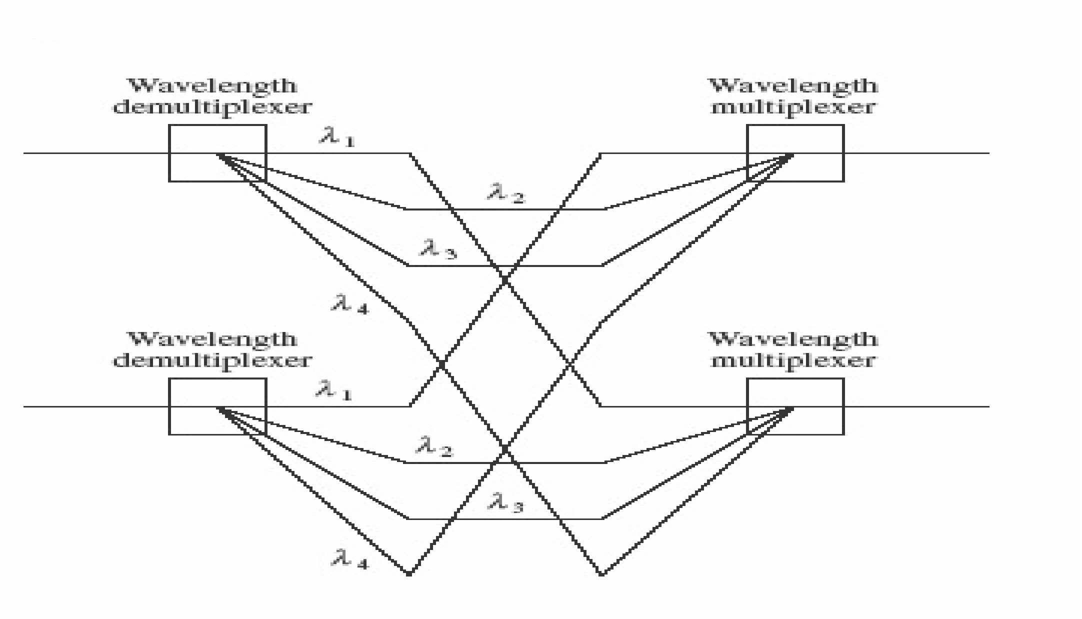


Figure2.3: Cross-phase modulation (XPM) in DWDM System

Cross-phase modulation can be used as a technique for adding information to a light stream by modifying the phase of a coherent optical beam with another beam through interactions in an appropriate non-linear medium. This technique is applied to fiber optic communications.

In DWDM applications with intensity modulation and direct detection (IM-DD) the effect of XPM is a two step process: First the signal is phase modulated by the co propagating second signal. In a second step dispersion leads to a transformation of the phase modulation into a power variation. Additionally the dispersion results in a walk-off between the channels and thereby reduces the XPM-effect.

Effect of XPM:

- XPM limits the maximum allowable power into the fiber.
- XPM limits the maximum allowable bit rate through the fiber
- XPM limits the maximum allowable transmission length of a DWDM link

2.3 What is crosstalk?

The term crosstalk refers to any phenomenon by which a signal transmitted on one circuit or channel of a transmission system creates an undesired effect in another circuit or channel. Crosstalk is usually caused by undesired capacitive, inductive or conductive coupling from one circuit, part of a circuit or channel to another.

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.

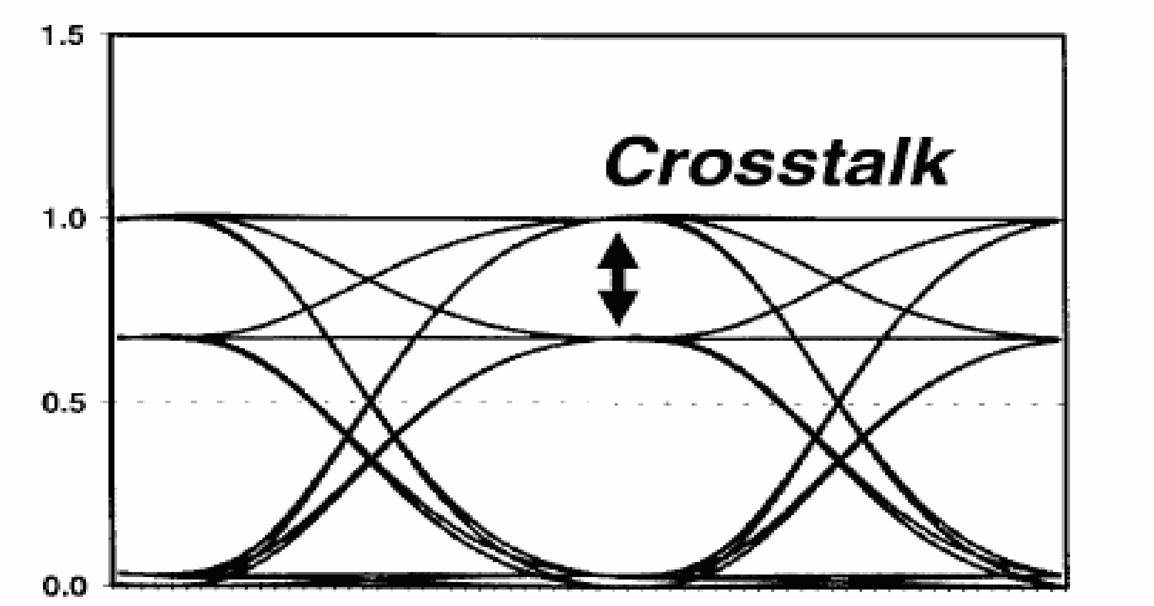


Figure2.4: Crosstalk in DWDM System

Sources of crosstalk:

- Coherent crosstalk
- Non Coherent crosstalk
- Crosstalk due to filtering
- Linear crosstalk
- Non-linear crosstalk

2.3.1 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.

2.3.2 Non Coherent Crosstalk

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

2.3.3 Crosstalk due to Filtering

Crosstalk element superimposed on the signal as a random power adding process. However, no significant beating element. A narrow band optical filter would largely reduce the electrical impairment.

2.3.4 Linear Crosstalk

- Space switches crosstalk
- Homowavelength crosstalk
- Heterowavelength crosstalk

Both arises due to non-ideal wavelength filtering, occurring in multiplexer, demultiplexer, filter and space switches.

2.3.5 Non-linear Crosstalk

- Four wave mixing: Wave mixing gives rise of new frequency.
- Cross phase modulation: Intensity dependent refractive index.
- Scattering: Transfer of power between propagation modes.

2.3.5.1 Space switches crosstalk

In a N x N switch, there are N^2 combination of cross points which will introduce crosstalk

- Intra-band crosstalk
- Inter-band crosstalk

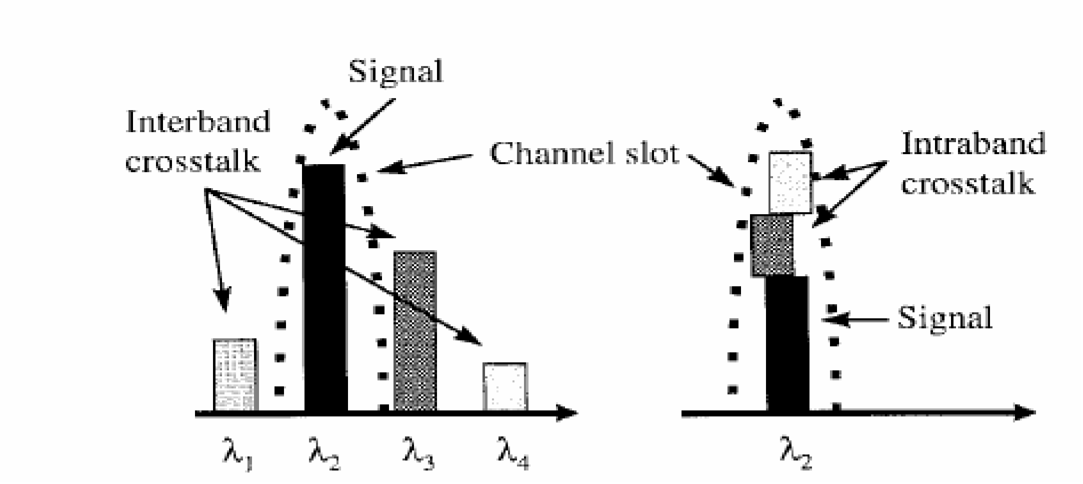


Figure2.5: Interband Crosstalk and Intraband Crosstalk

Crosstalk point of the path will introduce crosstalk since it involve the same wavelength transverse of path may occur randomly. Blocking may occur if two wavelengths transverse to the same destination receiver

2.3.5.2 Homowavelength Crosstalk

Different fiber route and each channel occupy the same wavelength as the desired signal. Crosstalk element occupy the same frequency as the desired signal, thus can not be removed once coupled and accumulate through the network. Crosstalk element will beat with signal and results in complex impairment.

- A serious limitation to the system performance

2.3.5.3 Heterowavelength Crosstalk

Same fiber route but each channel operating at different wavelength

- Note that secondary crosstalk element is negated

2.4 Optical Cross-connect (OXC)

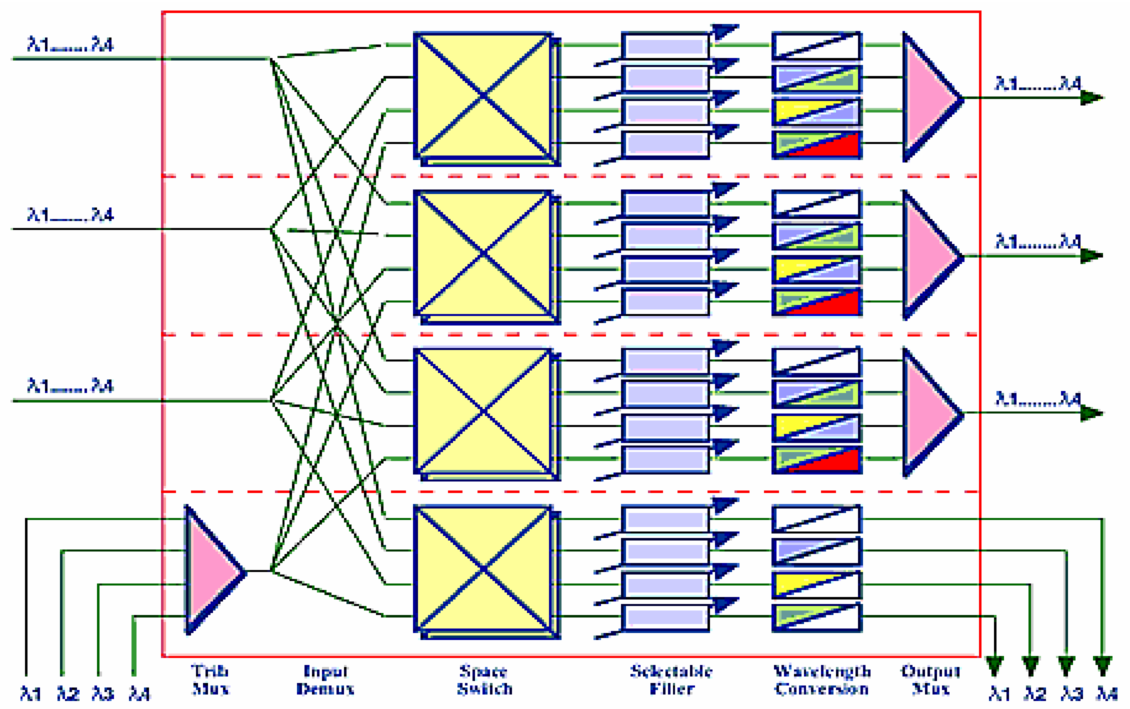


Figure2.5: OXC Block Diagram

An optical cross-connect (OXC) is a device used to switch high-speed optical signals. There are several ways to realize an OXC.

- One can implement an OXC in the electronic domain: all the input optical signals are converted into electronic signals after they are demultiplexed. The electronic signals then switched by an electronic signals are converted back into optical signals by using them to modulate lasers and then the resulting optical signals are multiplexed by optical multiplexers onto outlet optical fibers. This is known as an “OEO” (Optical-Electrical-Optical) design. Cross-connects based on an OEO switching process generally has a key limitation: the electronic circuits limit the maximum bandwidth of the signal. Such an architectural prevents an OXC from performing with the same speed as an all-optical cross-connect and is not transparent to the network protocols used. On the other hand, it is easy to monitor signal quality in an OEO device, since everything is converted back to the electronic format at the switch node. An additional advantage is that the optical signals are regenerated, so they leave the node free of dispersion and attenuation. An electronic OXC is also called an opaque OXC.

- Switching optical signals in al-optical device is the second approach to realize an OXC. Such a switch is often called a transparent OXC or photonic cross-connect (PXC). Specially, optical signals are demultiplexed and then the demultiplexed wavelengths are switched by optical switch modules. After switching, the optical signals are multiplexed onto output fibers by optical multiplexers. Such switch architecture keeps the features of data rate and protocol transparency. However, because the signals are kept in the optical format, the transparent OXC architecture does not allow easy optical signal quality monitoring.

As a compromise between opaque and transparent OXC’s, there is a type of OXC called a translucent OXC. In such switch architecture, there is a switch stage which consists of an optical switch module and an electronic switch module. Optical signals passing through the switch stage can be switched either by the optical switch module or the electronic switch module. In most cases, the optical switch module is preferred for the purpose of transparency. When the optical switch module’s switching interfaces are all busy or an optical signal needs signal regeneration through an OEO conversion process, the electronic module is used. Translucent OXC nodes provide a compromise of full optical signal transparency and comprehensive optical signal monitoring. It also provides the possibility of signal regeneration at each node.

2.4.1 Cross-talk Reduction Schemes

- Using Frequency Shift Keying (FSK): Constant amplitude of FSK signal provides less effect of input intensity fluctuation.
- Electronic Compensation: A part of input power is tapped off and photo-detected.
- The detected signal is then used to control the bias current of the amplifier so as to produce a constant amplifier gain and remove the effect input power fluctuation and crosstalk. However, average power saturation effect will remain.

2.4.2 Co-channel interference (CCI)

CCI is crosstalk from different radio transmitter using the same frequency. There can be several causes of co-channel radio interference – three examples are listed here:

- Adverse weather conditions
- Poor frequency planning
- Overly-crowded radio spectrum

2.4.3 Adjacent channel interference (ACI)

Adjacent-channel interference (ACI) is distinguished from crosstalk. It is the interference caused by extraneous power from a signal in an adjacent channel. Adjacent channel interference may be caused by inadequate filtering, such as incomplete filtering of unwanted modulation products in frequency modulation (FM) systems, improper tuning, or poor frequency control, in either the reference channel or the interfering channel or both.

CHAPTER 3

Analysis of Crosstalk in Optical Cross Connects (OXC)

3.1 Introduction

This paper treats the performance analysis of a dense WDM optical transport network with crosstalk, where four optical wavelength division multiplexed (WDM) cross-connects (OXC) topologies are taken in concern. Crosstalk is defined as the power leakage from other channel is one of the major impairments in the optical networks.

Crosstalk occurs due to introducing of fibers, wavelength multiplexers and de-multiplexers, switches, optical amplifiers, and the fiber itself in a WDM link.
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 source of crosstalk exist, which makes it difficult to optimize the components parameters for minimum total crosstalk.

In this paper, the crosstalk of four different OXC topologies are calculated and compared with each other and the influence of the component crosstalk on the total crosstalk is identified with the help of analytical approximation for the total crosstalk level of four different OXC topologies, which makes the component parameter optimization considerably easier.
In here, firstly the different OXC topologies are presented and explained.

Secondly, the different crosstalk sources in the OXC are identified regarding SNR and BER.

Finally the power penalty due to crosstalk is determined.

3.2 System Block Designs

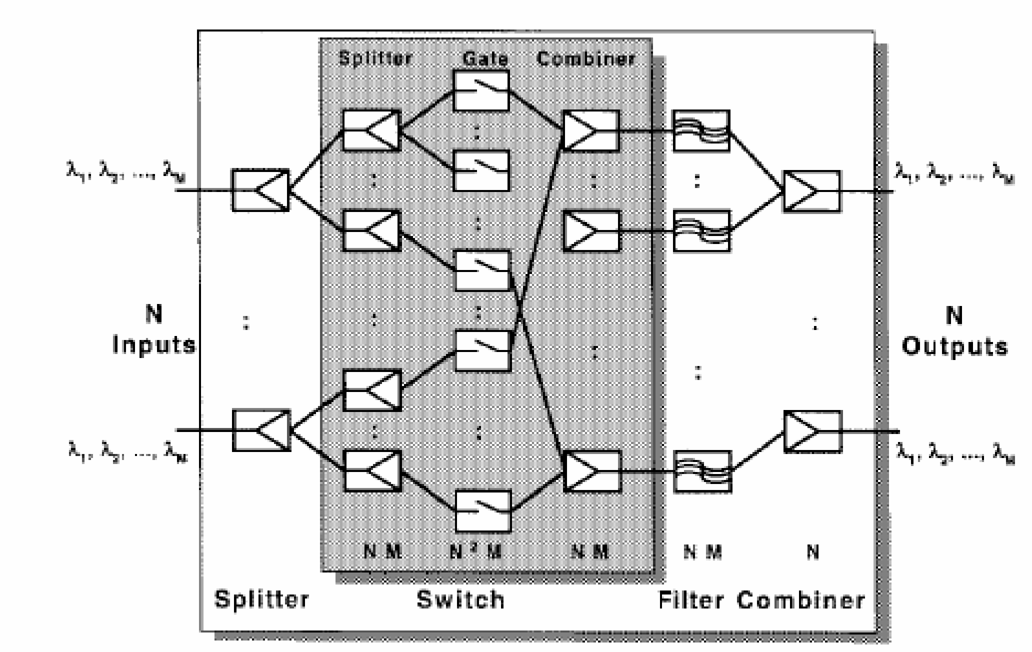


Figure 3.1: Topology 1: OXC switch based on gates

The first OXC topology includes switching matrix to route the different wavelength channel based on an array of gates. Splitters and combiners are placed in front of and behind the switch matrix and filters are used to select the wavelength channels. The wavelength channels are first routed to the desired output fiber before being selected by a filter. The N input fiber s are routed to the desired N output fibers, each carrying M wavelength channels. After the switching part, the correct wavelength is selected by a filter with a fixed center frequency.

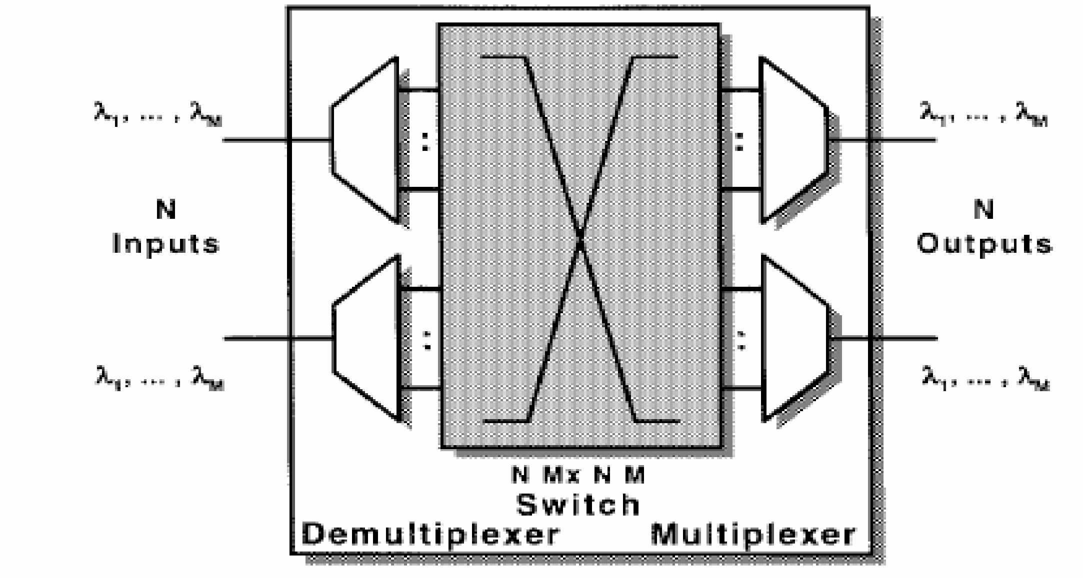


Figure 3.2: Topology 2: OXC switch based on space switch

This OXC topology is based on a mechano-optical space switch, which makes use of multiplexers and de-multiplexers to select the wavelength channels. In this second topology the N input fibers are de-multiplexed by N de-multiplexers. A NM x NM space switch routes the channel to the out put fibers. The multiplexers and de-multiplexers can be implemented for example as phased arrays.

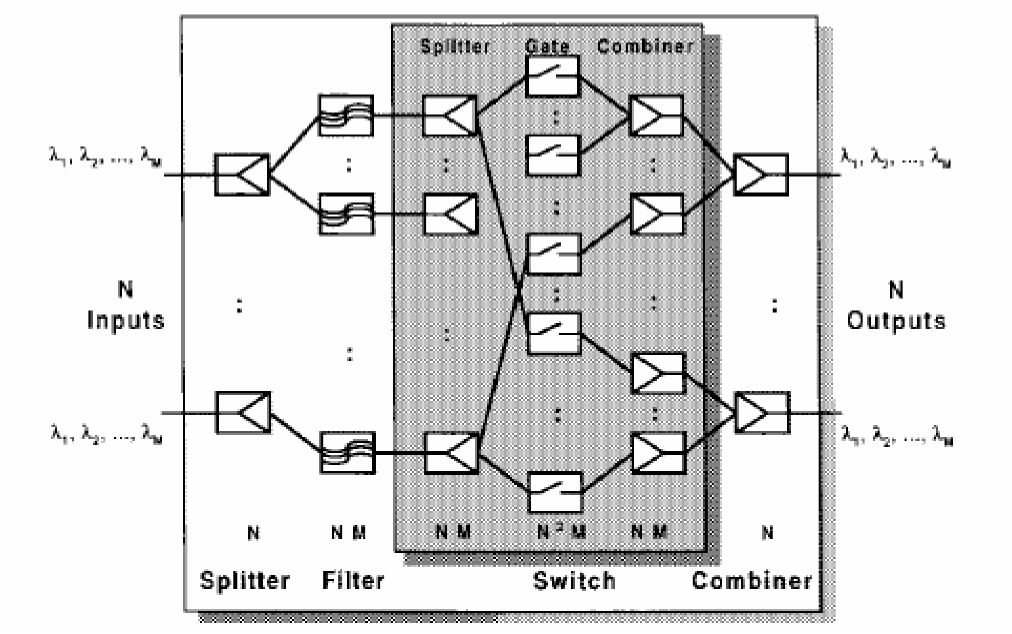


Figure 3.3: Topology 3: OXC switch based on gates, the wavelength channel is selected before switched.

To analyze the impact when swapping the order between switching and selecting of the wavelength channels, A third OXC topology has been defined (fig. 3). This topology is the mirror image of the first topology. The switching matrix of topology 1 is used but the wavelength channels are selected by the filters, before being routed to the desired output fiber. The third topology acts more or less the same as the first one. The difference is that the desired wavelength channel is selected by the filter (with a fixed center frequency) before the channel is routed to the output fiber.

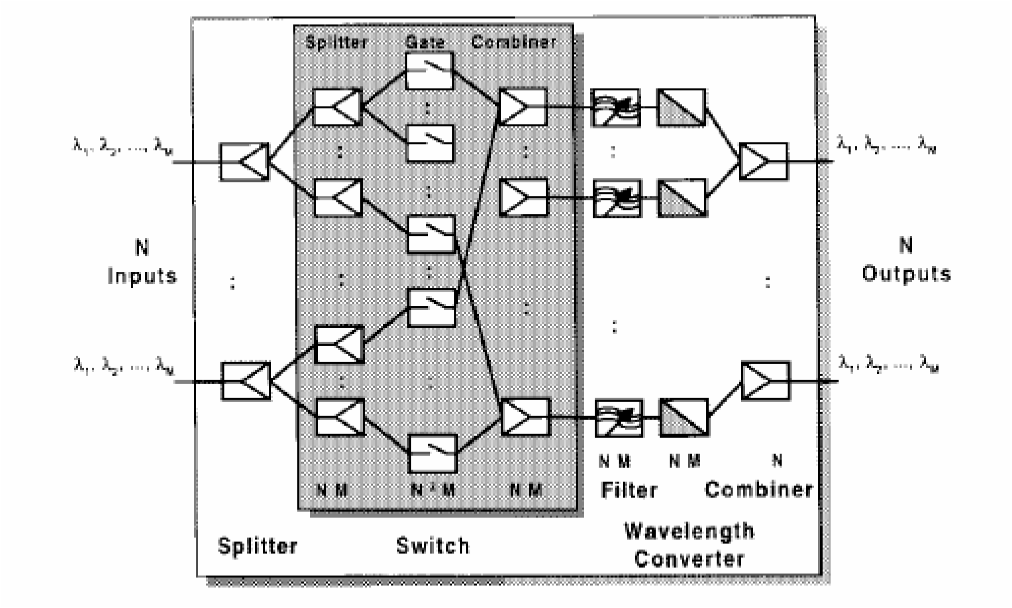


Figure 3.4: Topology 4: OXC switch based on gates, wavelength converters are included after the switch.

The effect of wavelength converters on the signal quality has been investigated by adding converters to the first topology (fig.3.4). Wavelength converters are often desired in the OXC to make the network management much easier, to reduce the blocking probability and because of their signal regeneration and noise reduction capabilities. The draw back of the wavelength converter is the price and the higher complexity of the system. In this topology tunable filters are used. In this last topology the wavelength channel is converted to another (or the same) wavelength by a wavelength converter which is assumed to be a Mach-Zender interferomatirc wavelength converter in contradict ional mode. This converter is placed behind the filter, which has to be tunable. Finally, N times M outputs with a different central wave length, are combined into the N output fibers.

3.3 Crosstalk Sources

Crosstalk will be one 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. There are two types of crosstalk. Interband and intraband crosstalk. Interband crosstalk can be classified into two types: coherent crosstalk and incoherent crosstalk. This different types of crosstalks can be illustrated as:

$$\begin{aligned} P_{\text{out}} = P_1 + P_2 + 2\sqrt{P_1 P_2}\cos[(\omega_1 - \omega_2)t + \Phi_1(t) \\ - \Phi_2(t) + \Theta_1 - \Theta_2] \end{aligned}$$

where,

P1=main signal power

P2= crosstalk signal power

We will now identify the crosstalk sources of topologies considering this paper. The output of the gate can be modeled as Pout= Pin+Pcross, if the amplification by the gate is neglected. The crosstalk power at wavelength i is then given by (by definition of Xgate)

$$P_{\text{cros},i} = X_{\text{gate}} P_{\text{in},i} \sum_{k=1}^{M} P_{\text{in},k}$$

3.4 Analytical Expression for the Crosstalk

For the first topology, the crosstalk we gate is coherent crosstalk. The first three terms are the non interfering contributions and the last three terms are the contributions due to the interference of different channels (beat terms). The crosstalk of the multiplexers and demultiplexers are given by Xmux and Xdemux and also defined as transmission factors (<1). So, the equation for the first topology we get is:

$$
\begin{aligned}
P_{i_0}^{\text{out}} &= P_{i_0}^{j_0} + P_{i_0}^{j_0}\left\{X_{\text{gate}}\left((M-1)P_{i}^{j_0} + P_{i_0}^{j_0}\right)\right\} \\
&+ P_{i_0}^{j}\left\{\begin{array}{l}(N-1)R_{\text{gate}}\left[1+X_{\text{gate}}MP_{i}^{j}\right] \\ +(M-1)T_F\left[1+X_{\text{gate}}MP_{i}^{j}\right] \\ +(M-1)(N-1)T_F R_{\text{gate}}\end{array}\right\} - 2\sqrt{P_{i_0}^{j_0}}\sqrt{P_{i_0}^{j}}\left\{\begin{array}{l}(N-1)\sqrt{R_{\text{gate}}} \\ +(M-1)\sqrt{T_F} \\ +(N-1)(M-1)\sqrt{R_{\text{gate}}}\sqrt{T_F}\end{array}\right\} \\
&- 2P_{i_0}^{j}\left\{\begin{array}{l}(N-1)(M-1)\sqrt{R_{\text{gate}}}\sqrt{T_F} \\ +(N-1)^2(M-1)R_{\text{gate}}\sqrt{T_F} \\ +(N-1)(M-1)^2\sqrt{R_{\text{gate}}}T_F\end{array}\right\} - 2P_{i_0}^{j}\left\{R_{\text{gate}}\sum_{t=1}^{N-2} t + T_F\sum_{t=1}^{M-2} t + R_{\text{gate}}T_F\sum_{t=1}^{(M-1)(N-1)-1} t\right\}
\end{aligned}
$$

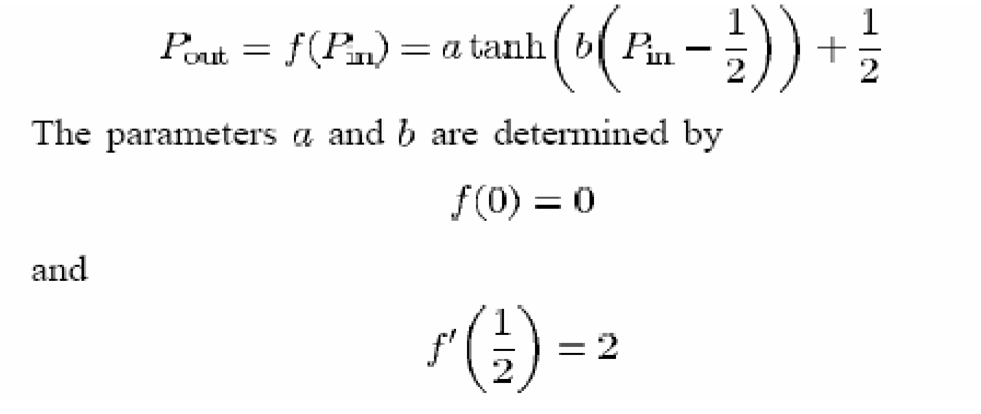
The equation for the second topology differs from the previous one because other components are used (space switch and muxs and demuxs). A simplified version of the equation is given below:

$$
\begin{aligned}
P_{i_0}^{\text{out}} &= P_{i_0}^{j_0} + P_{i_0}^{j}\left[X_{\text{sw}}(N-1)\right] - 2P_{i_0}^{j}\left[X_{\text{sw}}\sum_{t=1}^{N-2} t\right] - 2\sqrt{P_{i_0}^{j_0}}\sqrt{P_{i_0}^{j}} \\
&\times\left[\begin{array}{l}\sqrt{X_{\text{sw}}X_{\text{demux}}}N(M-1) + \sqrt{X_{\text{sw}}}(N-1) \\ +\sqrt{X_{\text{mux}}X_{\text{sw}}}(M-1)N + \sqrt{X_{\text{mux}}X_{\text{demux}}}(M-1) \\ +\sqrt{X_{\text{mux}}X_{\text{sw}}X_{\text{demux}}}(M-1)(NM-N-1)\end{array}\right] - 2P_{i_0}^{j}\left[\begin{array}{l}X_{\text{sw}}\sqrt{X_{\text{demux}}}N(N-1)(M-1) \\ +X_{\text{sw}}\sqrt{X_{\text{mux}}}N(N-1)(M-1) \\ +\sqrt{X_{\text{mux}}X_{\text{sw}}X_{\text{demux}}}(M-1)(N-1)\end{array}\right]
\end{aligned}
$$

The equation for the third topology is rather equal to the equation for the first topology. The only difference between both equations (and OXC) is that the crosstalk due to the non perfect gain clamping of the gate is less important in this topology because the other wavelength channels are filtered before the gate:

$$
\begin{aligned}
P_{i_0}^{\text{out}} &= P_{i_0}^{j_0} + P_{i_0}^{j_0}\left\{X_{\text{gate}}\left((M-1)T_F P_i^{j_0} + P_{i_0}^{j_0}\right)\right\} \\
&+ P_{i_0}^{j}\left[\begin{matrix}(N-1)R_{\text{gate}}\left[1+X_{\text{gate}}MT_F P_i^{j}\right] \\ +(M-1)T_F\left[1+X_{\text{gate}}MT_F P_i^{j}\right] \\ +(M-1)(N-1)T_F R_{\text{gate}}\end{matrix}\right\} - 2\sqrt{P_{i_0}^{j_0}}\sqrt{P_{i_0}^{j}}\left\{\begin{matrix}(N-1)\sqrt{R_{\text{gate}}} \\ +(M-1)\sqrt{T_F} \\ +(N-1)(M-1)\sqrt{R_{\text{gate}}}\sqrt{T_F}\end{matrix}\right\} \\
&- 2P_{i_0}^{j}\left\{\begin{matrix}(N-1)(M-1)\sqrt{R_{\text{gate}}}\sqrt{T_F} \\ +(N-1)^2(M-1)R_{\text{gate}}\sqrt{T_F} \\ +(N-1)(M-1)^2\sqrt{R_{\text{gate}}}T_F\end{matrix}\right\} - 2P_{i_0}^{j}\left\{R_{\text{gate}}\sum_{t=1}^{N-2} t + T_F\sum_{t=1}^{M-2} t + R_{\text{gate}}T_F\sum_{t=1}^{(M-1)(N-1)-1} t\right\}
\end{aligned}
$$

the equation of the fourth topology is more difficult due to the non linear behavior of the wavelength converter. The converter is known as Mach-Zehnder (MZI) wavelength converter. The output of converter is given by:



$$P_{\text{out}} = f(P_{\text{in}}) = a\tanh\left(b\left(P_{\text{in}} - \frac{1}{2}\right)\right) + \frac{1}{2}$$

The parameters a and b are determined by

$$f(0) = 0$$

and

$$f'\left(\frac{1}{2}\right) = 2$$

with Pin and Pout normalized between 0 and 1.

3.5 Validation of the Analytical Approach

The analytical approach has been validated by calculating the crosstalk for the first topology as a function of the input power and comparing this result with the results of a numerical simulation of the same topology.

3.6.1 Influence of Component Parameters

The influence of the component parameters and the input power on the total crosstalk is calculated. The aim of these calculations are to optimize the parameter values for the OXC and to identify the most critical components.

3.6.1.1 Input Power

This parameter is only relevant for the topologies with a switch based on gates. In here, coherent crosstalk is due to interference of channels from different input fibers and can strongly be reduced 9if the conditions for coherent crosstalk are not fulfilled,

3.6.1.2 Crosstalk Parameters of the GC-SOA

The influence of the crosstalk produced by the gate is only relevant for the topologies based on gates. The total crosstalk is calculated for topologies 1 and 3. For the first OXC the crosstalk increases if the crosstalk of the gate increases.

3.6.1.3 Filter Parameter and ON-OFF Ratio

The crosstalk is calculated in function of the filter parameter and the ON-OFF ratio of the gate for the first and third topologies. The total crosstalk in the function of the filter parameter is shown for the ON-OFF ratio between 10db and 90db in steps of 20db. An ON-OFF ratio of 50db can be obtained with present gate, so one can conclude that higher ON-OFF ratios are not required. We can conclude that the filter limits the performance of the OXC in terms of total crosstalk.

3.6.1.4 Crosstalk of the Space Switch and Demultiplexer

The total crosstalk i9s calculated in function of the space switch and multiplexers/demultiplexers for the second topology. The total crosstalk is dominated by the space switch as long as the crosstalk of the switch is smaller than twice the multiplexers/demultiplexers crosstalk. But machano–optical space switches have very good crosstalk performance so, in practice the total crosstalk will be limited by the crosstalk multiplexers/demultiplexers.

3.7 Comparison of different OXC topologies

The total crosstalk is presented in function of the number of OXC cascaded and this for the three topologies studied in the paper. As can be expected the highest crosstalk is obtained for the first and third topologies. Both topologies perform equally. The passive OXC based on the switch matrix performs much better. Best performance is obtained with the OXC included with the wavelength conversion for topology 2. The better performance of the passive topology compared to the first two topologies can be expected due to low crosstalk values of the space switch and because filtering occurs before and after the space switch. By comparing the first two topologies, we see that the first one has considerable higher crosstalk. From the calculations in the function of the component parameters we see the both topologies are limited by the filter.

CHAPTER 4

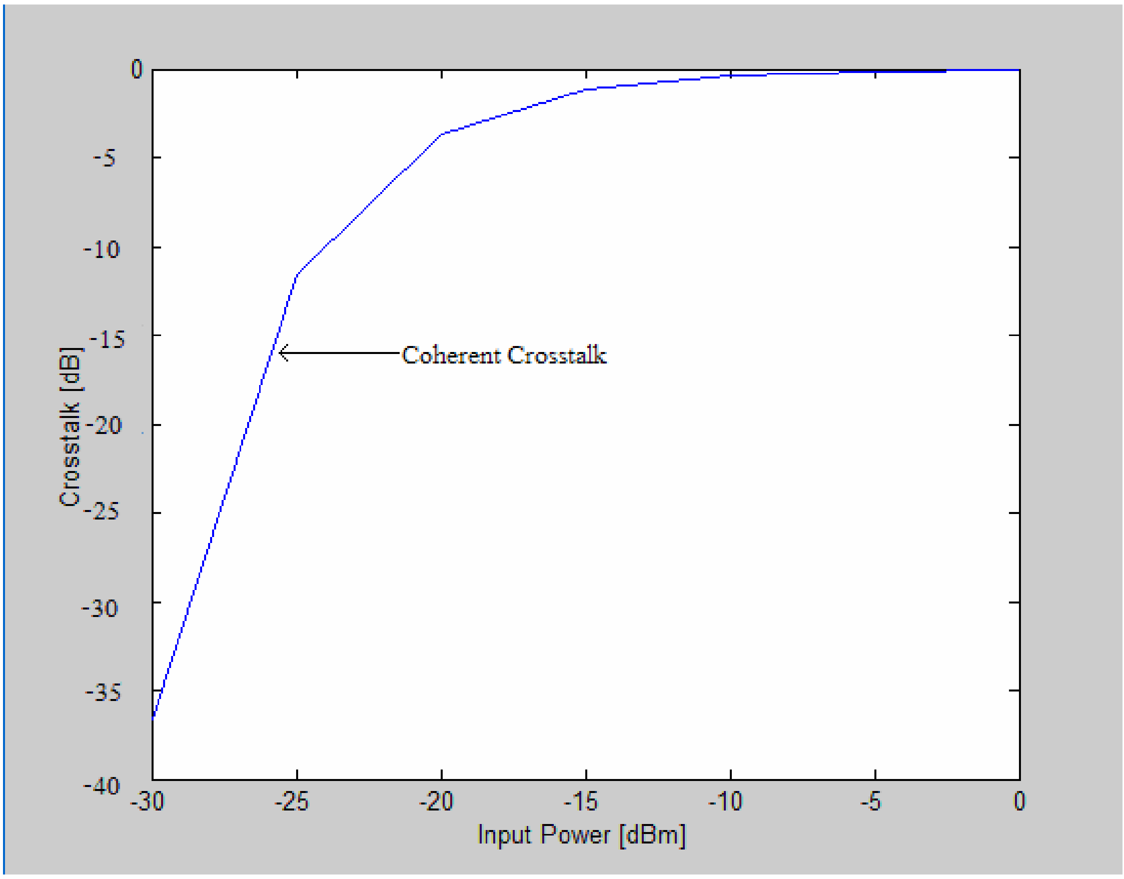


Fig: 4.1: Topology 1: Crosstalk for various input power

For this topology, we assumed -30 dB input power and increased it significantly. the graph shows us that when input power is getting greater, the crosstalk is increasing slightly.

Due to the good alignment of the laser sources in a DWDM network, it is likely that different channels interfere coherently. The higher the input power of the gate, the more crosstalk is added by this gate.

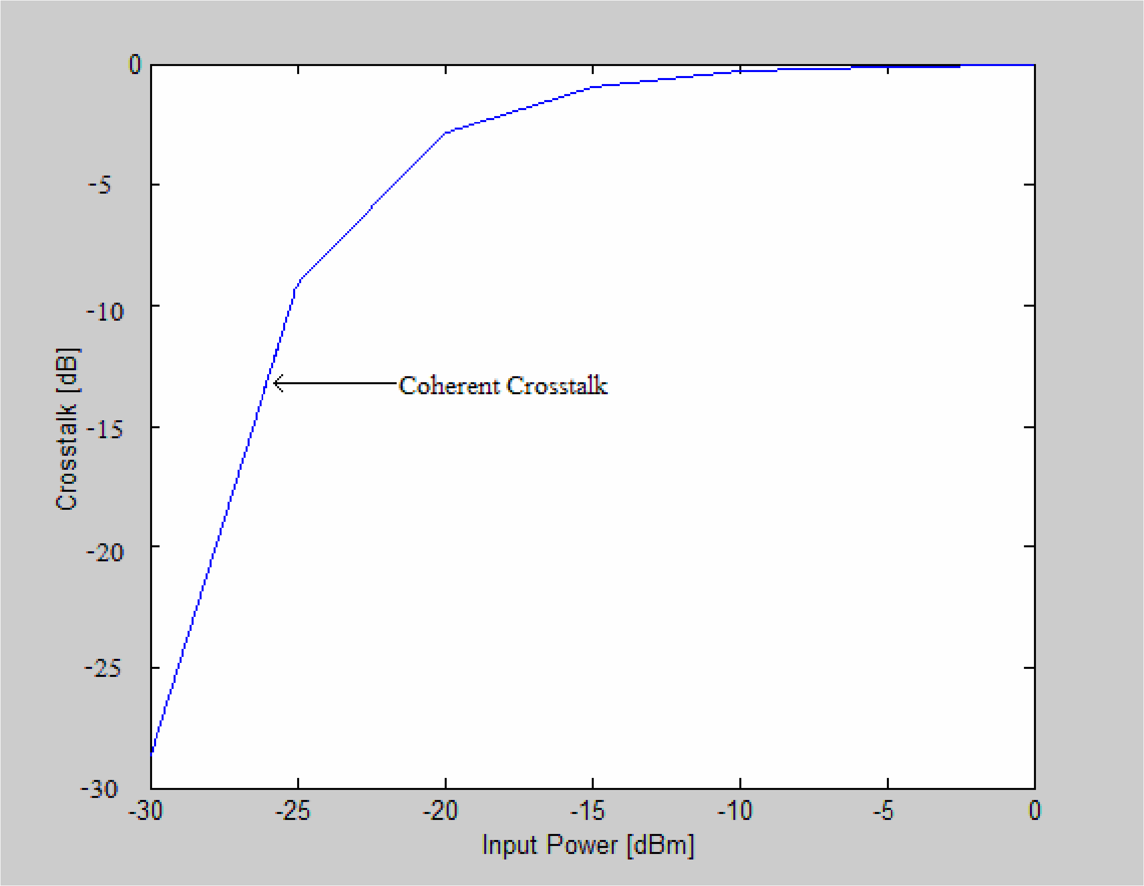


Fig: 4.2: Topology 2: Crosstalk for various input power

For this topology, we assumed -30 dB input power and increased it significantly. the graph shows us that when input power is getting greater, the crosstalk is increasing slightly.

Due to the good alignment of the laser sources in a DWDM network, it is likely that different channels interfere coherently. The higher the input power of the gate, the more crosstalk is added by this gate.

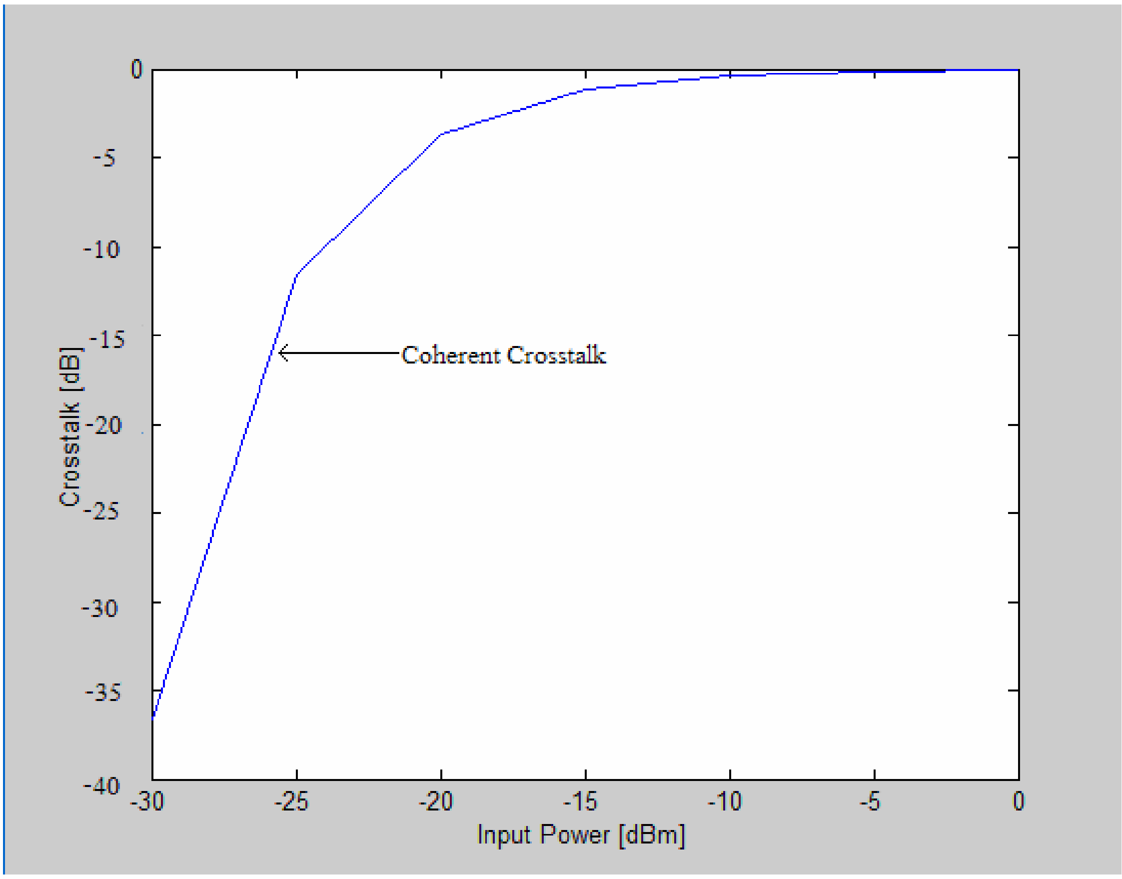


Fig: 4.3: Topology 3: Crosstalk for various input power

For this topology, we assumed -30 dB input power and increased it significantly. The graph shows us that when input power is getting greater, the crosstalk is increasing slightly.

Due to the good alignment of the laser sources in a DWDM network, it is likely that different channels interfere coherently. The higher the input power of the gate, the more crosstalk is added by this gate.

The first and the third topologies are almost the same. The difference is the alignment of the gate before and after the OXC. The crosstalk due to the non perfect gain clamping of the gate is less important because the wavelength channels are filtered before the gate.

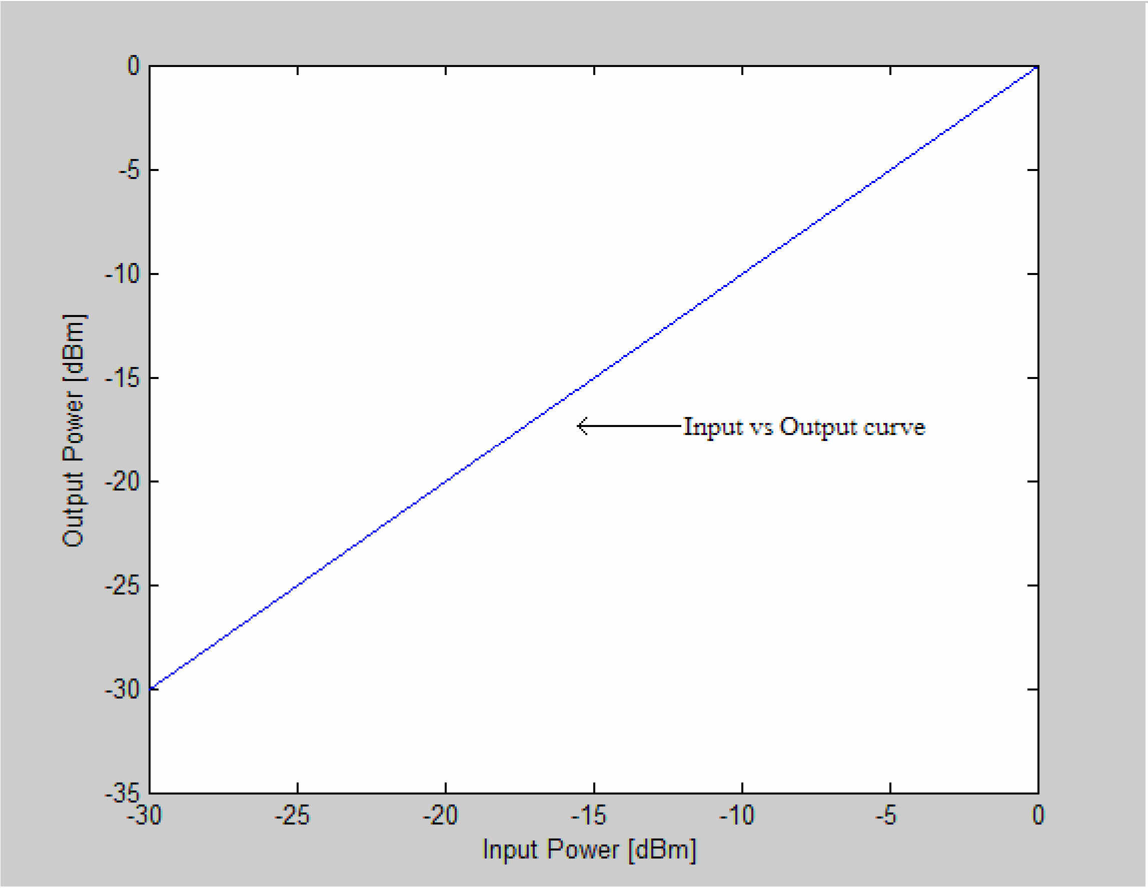


Fig: 4. 4: Topology 2: Input power versus output power

For topology 2, the input versus output power graph is linear. There is some noise at start. The input power is chosen very low because power levels at the input of the gate are taken reference. A power value of -20 dBm is a normal input value for a gate.

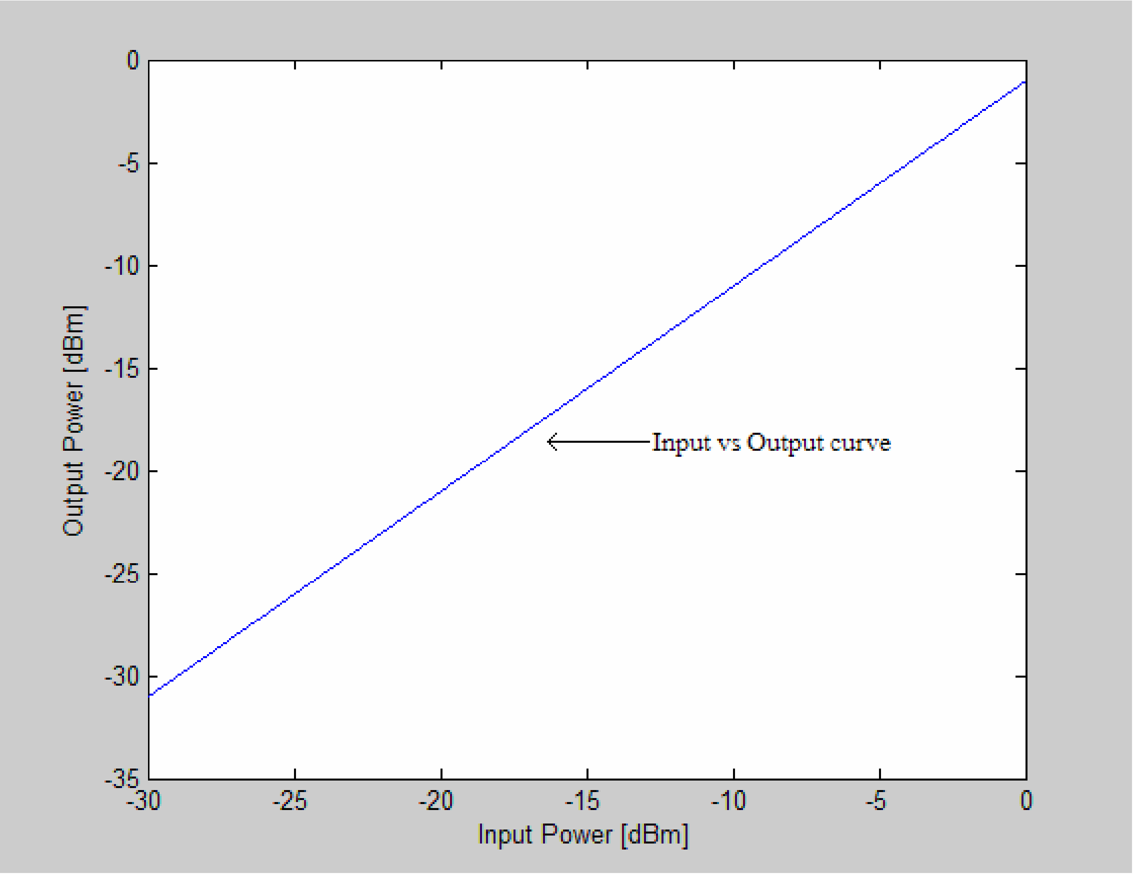


Fig: 4.5: Topology 1 & 3: Input power versus output power

For topology 1 and 3, the input versus output power graph is linear. There is some noise at start. The input power is chosen very low because power levels at the input of the gate are taken reference. A power value of -20 dBm is a normal input value for a gate. In comparison with topology 2, there is less difference at the output power.

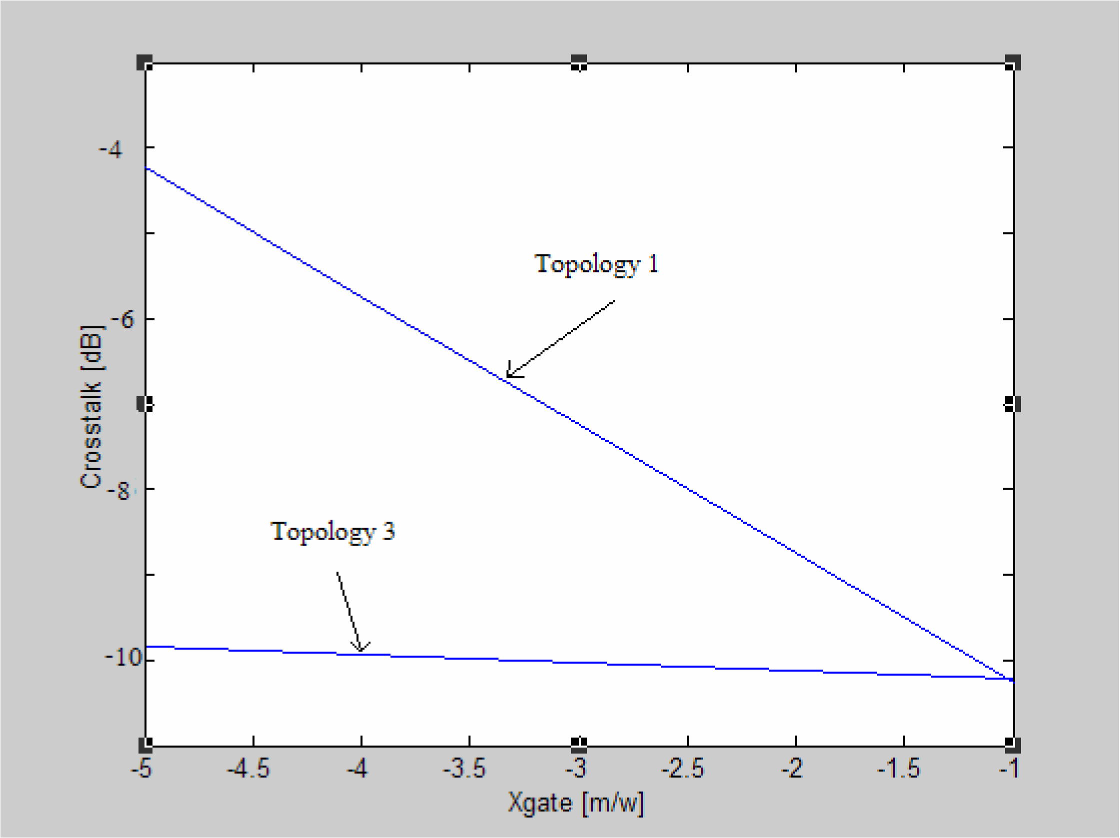


Fig: 4.6: Topology 1 and 3: Crosstalk (coherent) versus the crosstalk parameter of the GC-SOA.

The results are different for two topologies. The third topology is much static rather than the first topology. For the first topology, if the crosstalk of the gate increases, the crosstalk increases. the third topology is much more robust against crosstalk, because the channels are filtered before being passed through the gates. The crosstalk is more or less independent of the crosstalk parameter of the gate.

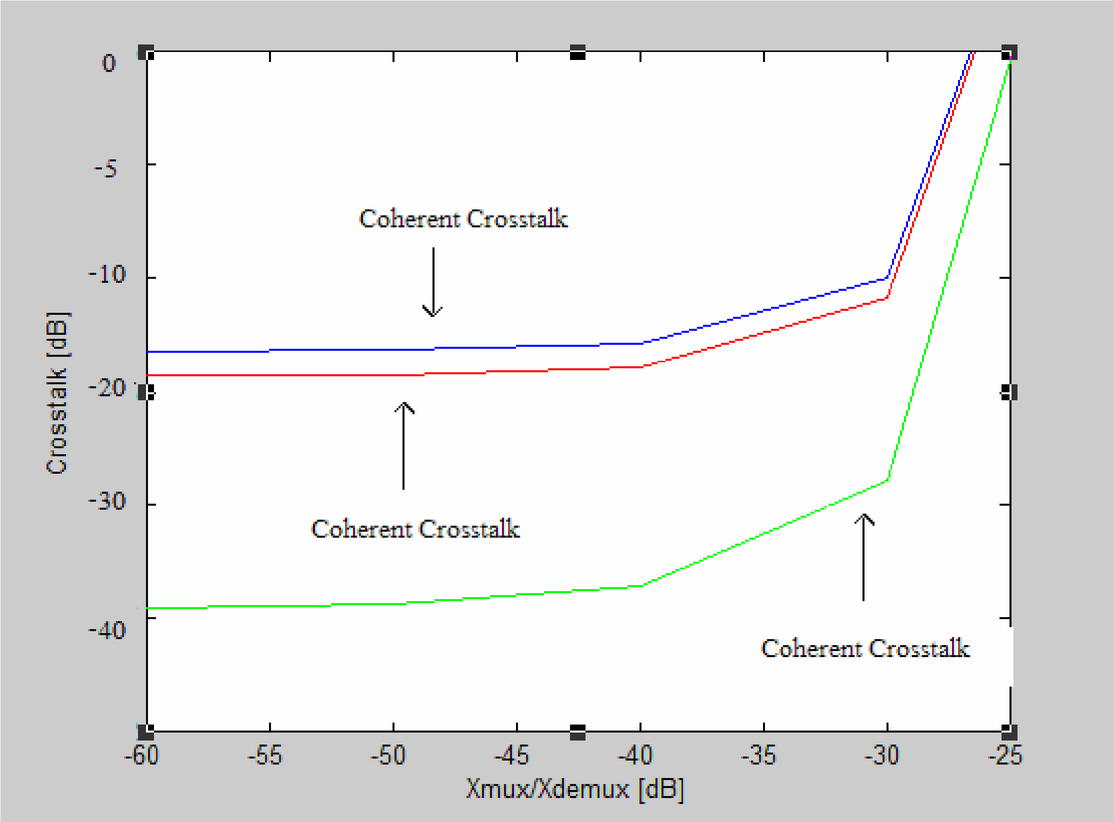


Fig: 4.7: Topology 2: Crosstalk (coherent) in function of the crosstalk of the demultiplexer for different values of Space Switch (Xsw= -40 -60 -80 -100 dB)

The total crosstalk is calculated in function of the space switch and multiplexer and demultiplexer. The total crosstalk is dominated by the space switch as long as the crosstalk of the switch is smaller than twice the multiplexer/demultiplexer crosstalk.

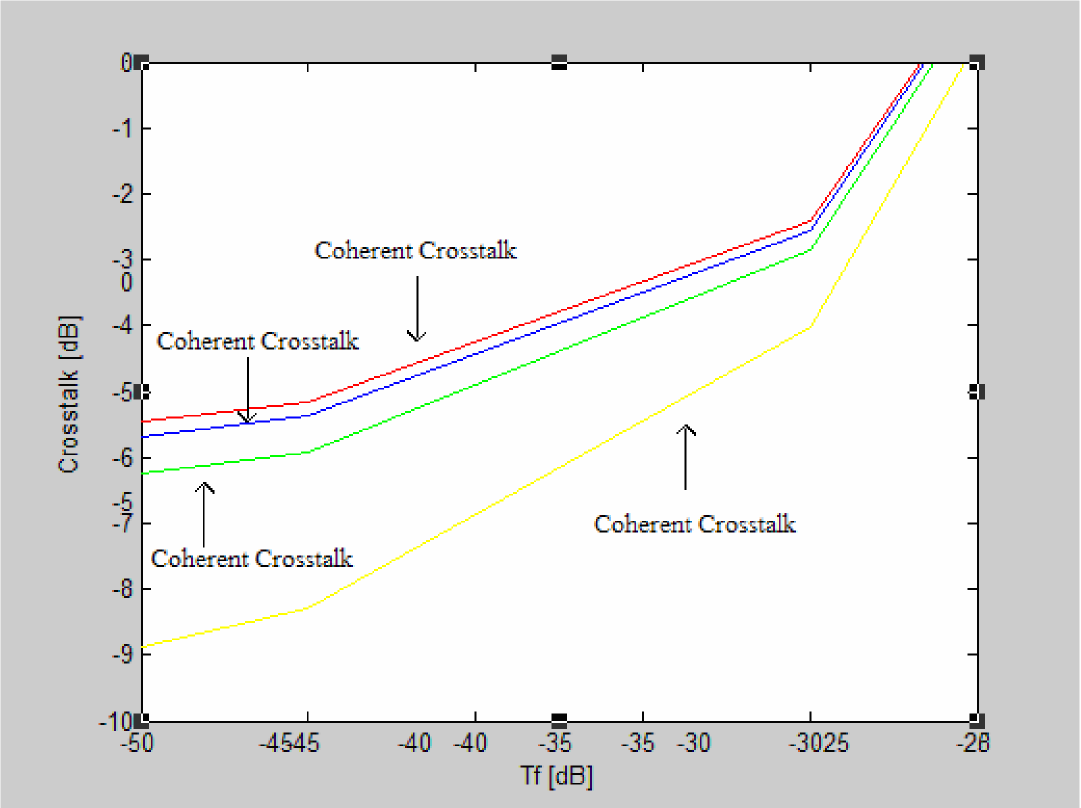


Fig: 4.8: Fig 6: Topology 1 and 3: Crosstalk (coherent) in function of the filter parameter for different on/off ratios (R= -10 -30 -50 -70 and -90dB)

The crosstalk is calculated in function of the filter parameter and the on/off ratio of the gate. The results are same for both topologies. The total crosstalk is dominated by the filter. Higher on/off ratios are not required.

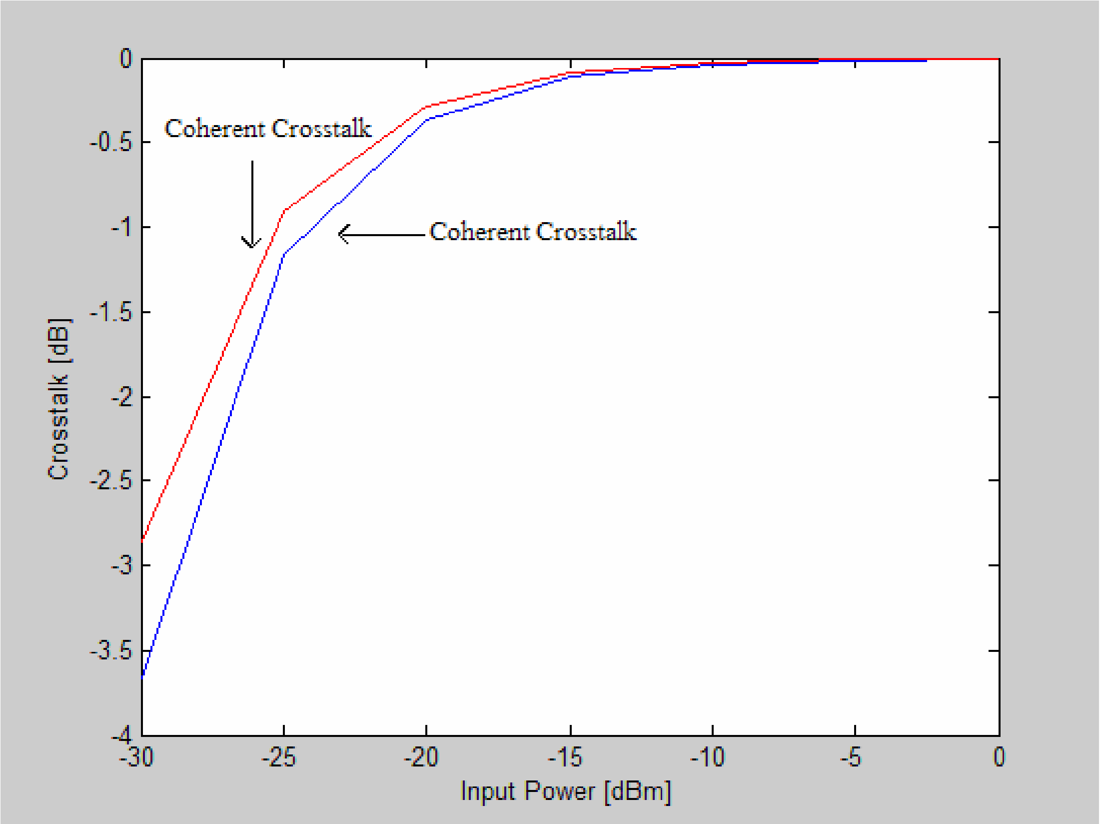


Fig: 4.9: Crosstalk (coherent) in function of the number of OXC's cascaded for three topologies. Red is for Topology 1 and 3, Blue is for topology 2.

The highest crosstalk is obtained for the first and second topologies. Both topologies perform equally. The better performance is shown by the second topology. Due to the low crosstalk values of the space switch.

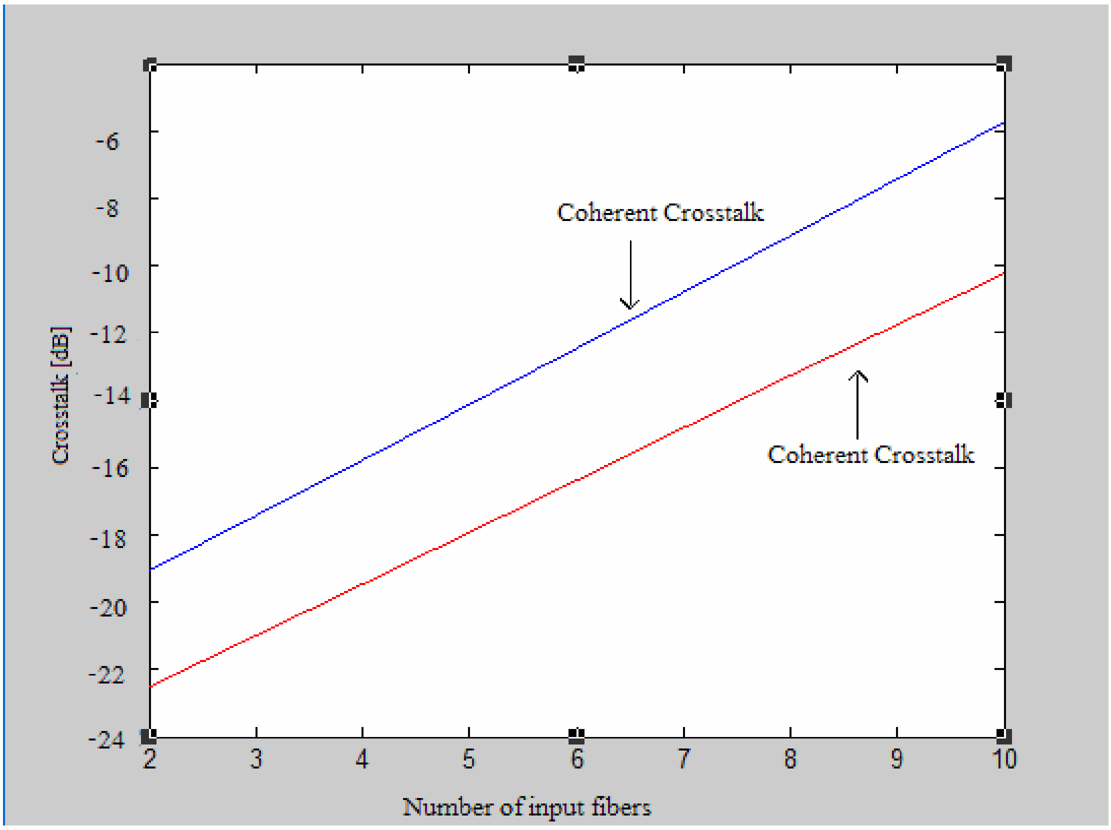


Fig: 4.10: Topology 2: Crosstalk (coherent) in function of the number of input fibers for different number of wavelength channels in a fiber (M= 2 4 6 and 8)

In the figure above, we can see that total crosstalk increases with higher number of input fibers and wavelength channels. Topology two is based on Number of input fibers which multiplies with number of wavelength channels.

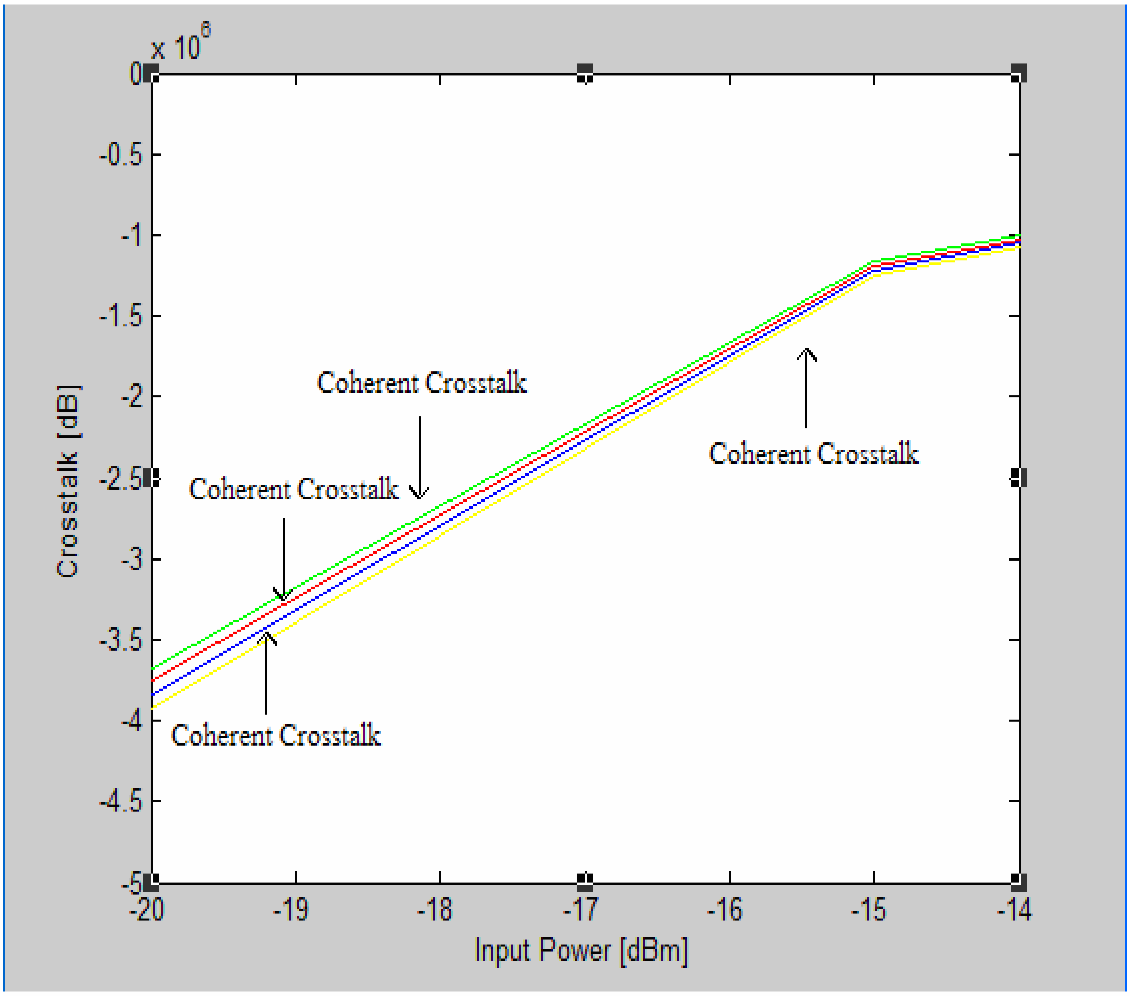


Fig: 4.11: Topology 1 and 3: Crosstalk (coherent) in function of the number of input fibers for different number of wavelength channels in a fiber (M= 2 4 6 and 8)

With certain throughput lowest crosstalk is obtained with large N and small M.

The on/off ratio has to be changed to keep the crosstalk constant.

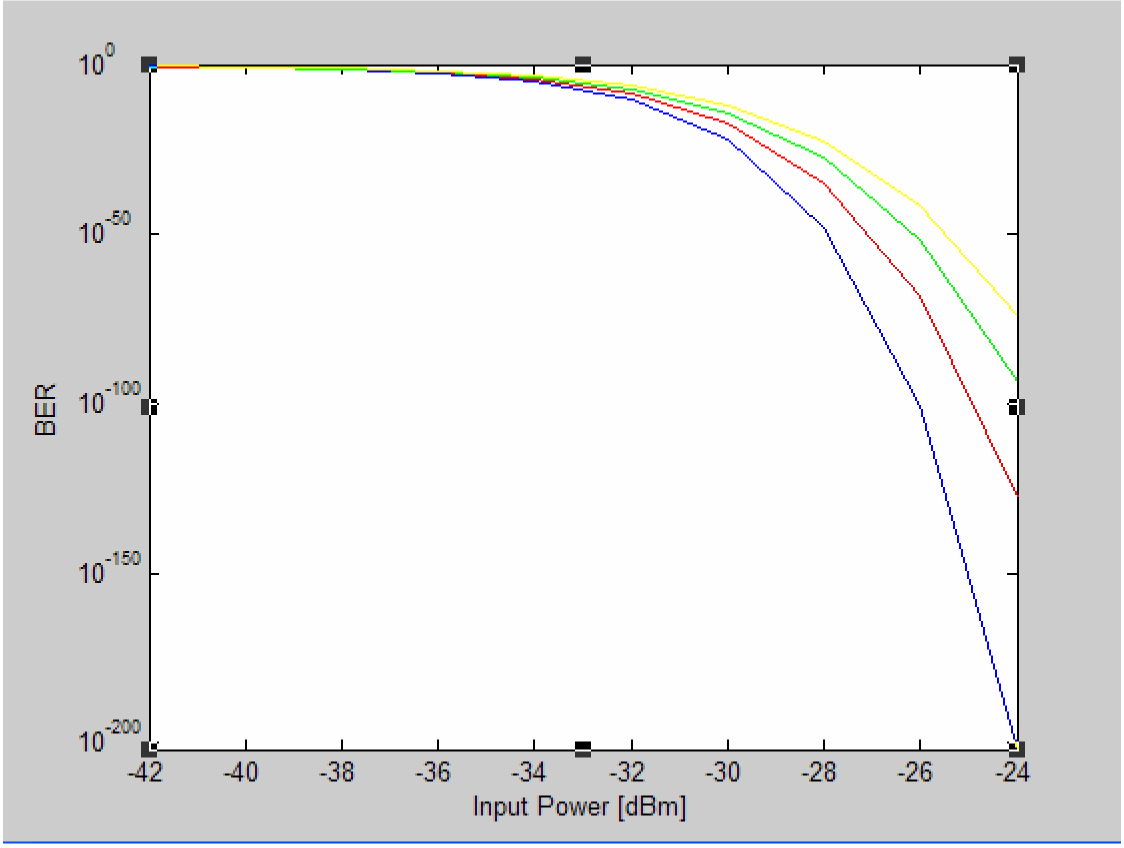


Fig: 4.12: Plots of BER of a 4-channel system with crosstalk for different channel spacing at a bit-rate of 4.5 Gbps.

Fig 4.12 shows the plotting of BER with crosstalk. For getting the specific BER our channel spacing is 9 GHz, 18 GHz, 27 GHz, 36 GHz, 45 GHz. We can say that to get a specific BER we need more input power for a large channel spacing

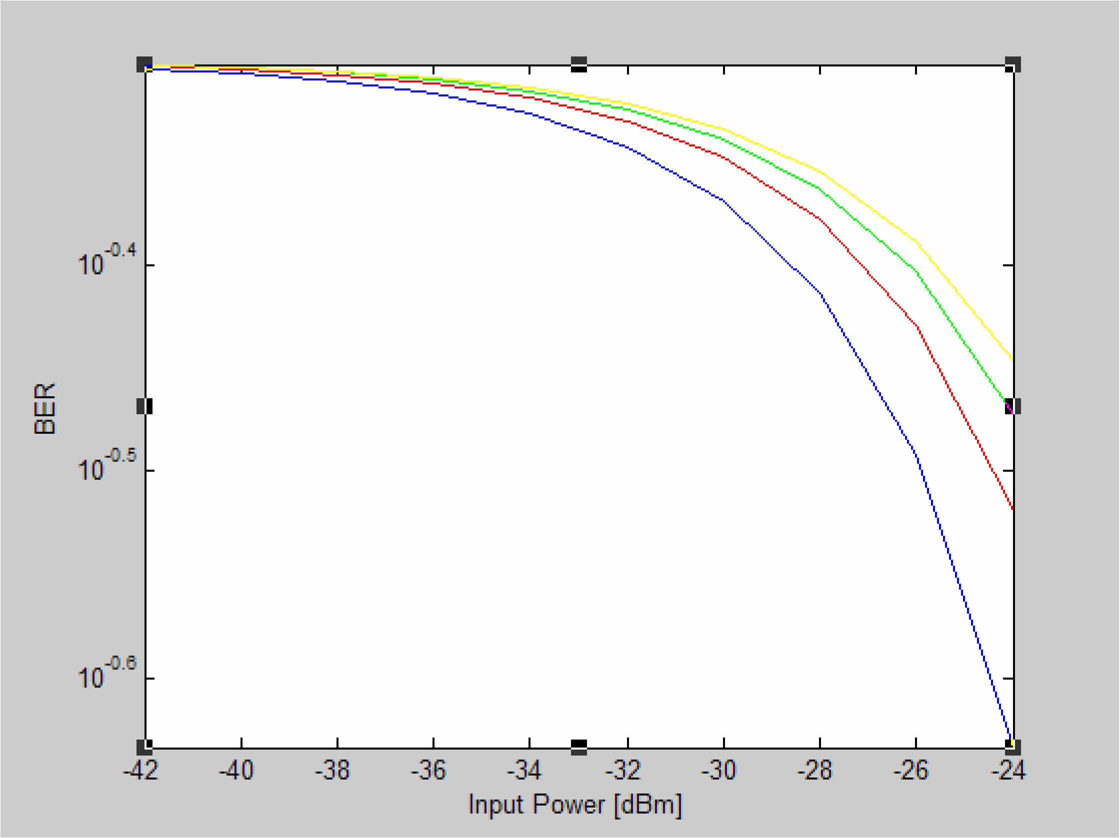


Fig:4.13: Plots of BER of a 4-channel system without crosstalk for different channel spacing at a bit-rate of 4.5 Gbps

Fig 4.13 shows the plotting of BER. For getting the specific BER our channel spacing is 9 GHz, 18 GHz, 27 GHz, 36 GHz, 45 GHz. We can say that to get a specific BER we need more input power for a large channel spacing.

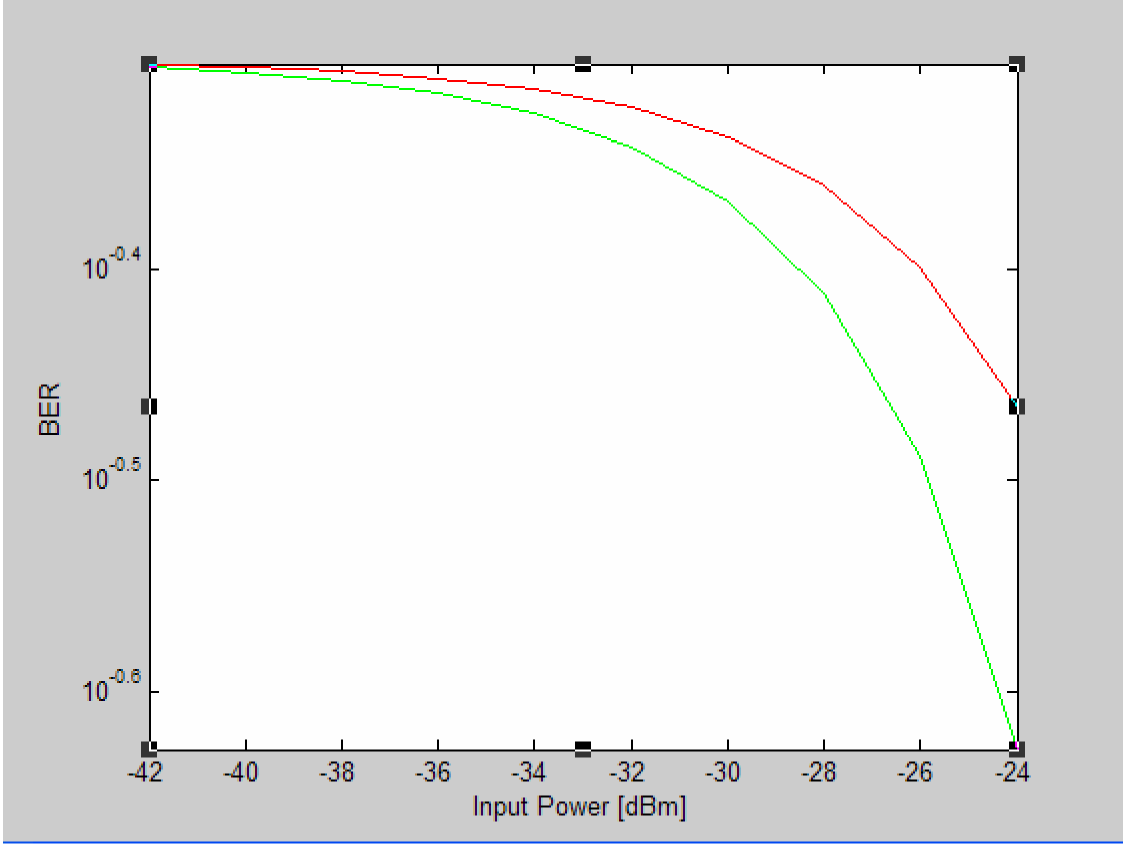


Fig: 4.14: BER comparison for with crosstalk and without crosstalk. The green curve is for with out cross talk and red curve is for with crosstalk.

Fig 4.14 shows the plotting of the BER corresponding to the BER with crosstalk and without crosstalk. The graph shows that BER is minimum when there is no cross talk.

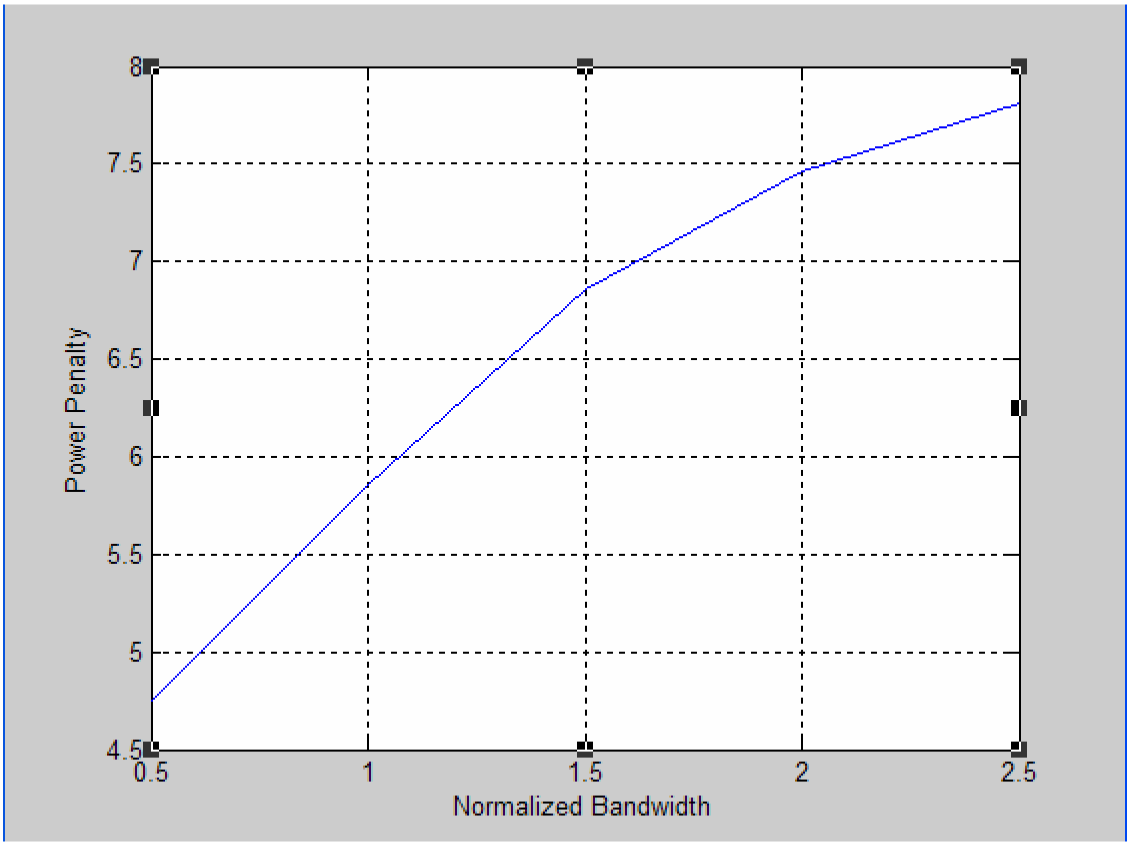


Fig: 4.15: Power penalty (at BER=10^-12) versus channel spacing with crosstalk for a bit rate of 4.5 Gbps.

Each impairment results in a power penalty to the system. In the presence of impairment, a higher signal power will be required at the receiver in order to maintain a desired bit error rate. Therefore, power penalty can be defined as the increase in signal power required (in dB) to maintain the same BER in the presence of impairments.

This curve is calculated from the BER curve with crosstalk. The difference between BER with crosstalk and BER without crosstalk at the BER of 10^-12. The result shows that the power penalty increases with decreasing channel spacing.

CHAPTER 5

Conclusion and Future work on DWDM

5.1 Conclusion

We have studied three topologies in this paper. Their crosstalk sources have been identified and their crosstalk is calculated based on analytical equations. From the comparisons between the OXCs we can conclude that the performance is limited by the filters. Both switch matrixes fulfill the demand. A high input power of the gates will result in an extra penalty. The mechano-optical space switch performs better than the switch based on gates, but in both cases the total crosstalk is limited by other components. If gates are used in the switch matrix, the total input power should be sufficiently low. Optimal results are obtained if filters are used in front of and behind the switch.

5.2 Future Works

In this paper, three different OXC topologies have been studied. The comparisons are found by analyzing performance of the different OXC, considering the level of crosstalk. The effective results are found and the best suggestion for the optimum result is given in conclusion. So we are looking forward to do further work on OXC, considering different components such as FBG, AWG and wavelength converter to reduce the level of crosstalk. The probable list of future works are given below-

- Future work can be carried out to find the crosstalk performance of the OXC, including optical wavelength converter at different locations, which is the fourth topology that is mentioned in this thesis paper.
- Further works can be carried out for OXC based on Fiber-Bragg grating (FBG) and Arrayed-waveguide grating (AWG) based switching and multiplexers. And comparison can be carried out with the OXC configuration considering this thesis.
- Further works can be done with bidirectional OXC using OA gate switch and FBG & AWG based multiplexer / Demultiplexer.

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APPENDIX

Fig: 4.1: Topology 1: Crosstalk for various input power

```
clear all
R_gate=10^-5.0;
```

```
X_gate=-0.1*10^-3;
Tf=10^-3.0;
Xmx=10^-3.0;
Xdmx=10^-3.0;
Xsw=10^-6.0;
M=4;
N=2;
Tn=0;
Tm=3;
Tmn=2;
z=0;
P_in=[-30 -25 -20 -15 -10 -5 0];
for i=1:7
Pin(i)=10^-3*10^(P_in(i)/10);
end
for i=1:7
a(i)=Pin(i)*(X_gate*((M-1)*Pin(i)+Pin(i)));
b(i)=Pin(i)*((N-1)*R_gate*(1+X_gate*M*Pin(i))+(M-1)*Tf*(1+X_gate*M*Pin(i))+(M-1)*(N-1)*Tf*R_gate);
c(i)=2*sqrt(Pin(i))*sqrt(Pin(i))*((N-1)*sqrt(R_gate)+(M-1)*sqrt(Tf)+(N-1)*(M-1)*sqrt(R_gate)*sqrt(Tf));
d(i)=2*Pin(i)*((N-1)*(M-1)*sqrt(R_gate)*sqrt(Tf)+(N-1)^2*(M-1)*R_gate*sqrt(Tf)+(N-1)*(M-1)^2*sqrt(R_gate)*Tf);
e(i)=2*Pin(i)*((R_gate*Tn)+(Tf*Tm)+(R_gate*Tf*Tmn));
P_output(i)=Pin(i)+a(i)+b(i)-c(i)-d(i)-e(i);
z=z+P_output(i);

end
cross=10*log10(z-P_output)./P_output;
plot(P_in,cross,'b')
```

Fig: 4.2: Topology 2: Crosstalk for various input power

```
clear all;
R_gate=10^-5.0;
```

```
X_gate=-0.1*10^-3;
Tf=10^-3.0;
Tn=1;
Xmx=10^-3.0;
Xdmx=10^-3.0;
Xsw=10^-6.0;
M=4;
N=2;
z=0;
P_in=[-30 -25 -20 -15 -10 -5 0];
for i=1:7
Pin(i)=10^-3*10^(P_in(i)/10);
end
for i=1:7
a(i)=Pin(i)*(Xsw*(N-1));
b(i)=2*Pin(i)*(Xsw*Tn);
c(i)=2*sqrt(Pin(i))*sqrt(Pin(i))*((sqrt(Xsw*Xdmx)*N*(M-1)+sqrt(Xmx*Xdmx)*(M-1)+sqrt(Xsw)*(N-1)+sqrt(Xmx*Xsw*Xdmx)*(M-1)*(N*M-N-1)));
d(i)=2*Pin(i)*(Xsw*sqrt(Xdmx)*N*(N-1)*(M-1)+Xsw*sqrt(Xmx)*N*(N-1)*(M-1)+sqrt(Xmx*Xsw*Xdmx)*(M-1)*(N-1));


P_output(i)=Pin(i)+a(i)-b(i)-c(i)-d(i)
z=z+P_output(i);

end
cross=10*log10(z-P_output)./P_output;
plot(P_in,cross,'b')
```

Fig: 4.3: Topology 3: Crosstalk for various input power

```
clear all
R_gate=10^-5.0;
X_gate=-0.1*10^-3;
```

```
Tf=10^-3.0;
Xmx=10^-3.0;
Xdmx=10^-3.0;
Xsw=10^-6.0;
M=4;
N=2;
Tn=0;
Tm=3;
Tmn=2;
z=0;
P_in=[-30 -25 -20 -15 -10 -5 0];
for i=1:7
Pin(i)=10^-3*10^(P_in(i)/10);
end
for i=1:7
a(i)=Pin(i)*(X_gate*((M-1)*Pin(i)+Pin(i)));
b(i)=Pin(i)*((N-1)*R_gate*(1+X_gate*M*Pin(i))+(M-
1)*Tf*(1+X_gate*M*Pin(i))+(M-1)*(N-1)*Tf*R_gate);
c(i)=2*sqrt(Pin(i))*sqrt(Pin(i))*((N-1)*sqrt(R_gate)+(M-1)*sqrt(Tf)+(N-1)*(M-
1)*sqrt(R_gate)*sqrt(Tf));
d(i)=2*Pin(i)*((N-1)*(M-1)*sqrt(R_gate)*sqrt(Tf)+(N-1)^2*(M-
1)*R_gate*sqrt(Tf)+(N-1)*(M-1)^2*sqrt(R_gate)*Tf);
e(i)=2*Pin(i)*((R_gate*Tn)+(Tf*Tm)+(R_gate*Tf*Tmn));
P_output(i)=Pin(i)+a(i)+b(i)-c(i)-d(i)-e(i);
z=z+P_output(i);

end
cross=10*log10(z-P_output)./P_output;
plot(P_in,cross,'b')
```

Fig: 4. 4: Topology 2: Input power versus output power

```
clear all;
R_gate=10^-5.0;
X_gate=-0.1*10^-3;
Tf=10^-3.0;
```

```
Tn=1;
Xmx=10^-3.0;
Xdmx=10^-3.0;
Xsw=10^-6.0;
M=4;
N=2;
z=0;
P_in=[-30 -25 -20 -15 -10 -5 0];
for i=1:7
Pin(i)=10^-3*10^(P_in(i)/10);
end
for i=1:7
a(i)=Pin(i)*(Xsw*(N-1));
b(i)=2*Pin(i)*(Xsw*Tn);
c(i)=2*sqrt(Pin(i))*sqrt(Pin(i))*((sqrt(Xsw*Xdmx)*N*(M-1)+sqrt(Xmx*Xdmx)*(M-1)+sqrt(Xsw)*(N-1)+sqrt(Xmx*Xsw*Xdmx)*(M-1)*(N*M-N-1)));
d(i)=2*Pin(i)*(Xsw*sqrt(Xdmx)*N*(N-1)*(M-1)+Xsw*sqrt(Xmx)*N*(N-1)*(M-1)+sqrt(Xmx*Xsw*Xdmx)*(M-1)*(N-1));


P_output(i)=Pin(i)+a(i)-b(i)-c(i)-d(i)
z=z+P_output(i);

end
cross=10*log10(z-P_output)./P_output;
plot(P_in, P_output,'b')
```

Fig: 4.5: Topology 1 & 3: Input power versus output power

```
clear all
R_gate=10^-5.0;
X_gate=-0.1*10^-3;
Tf=10^-3.0;
Xmx=10^-3.0;
```

```
Xdmx=10^-3.0;
Xsw=10^-6.0;
M=4;
N=2;
Tn=0;
Tm=3;
Tmn=2;
z=0;
P_in=[-30 -25 -20 -15 -10 -5 0];
for i=1:7
Pin(i)=10^-3*10^(P_in(i)/10);
end
for i=1:7
a(i)=Pin(i)*(X_gate*((M-1)*Pin(i)+Pin(i)));
b(i)=Pin(i)*((N-1)*R_gate*(1+X_gate*M*Pin(i))+(M-
1)*Tf*(1+X_gate*M*Pin(i))+(M-1)*(N-1)*Tf*R_gate);
c(i)=2*sqrt(Pin(i))*sqrt(Pin(i))*((N-1)*sqrt(R_gate)+(M-1)*sqrt(Tf)+(N-1)*(M-
1)*sqrt(R_gate)*sqrt(Tf));
d(i)=2*Pin(i)*((N-1)*(M-1)*sqrt(R_gate)*sqrt(Tf)+(N-1)^2*(M-
1)*R_gate*sqrt(Tf)+(N-1)*(M-1)^2*sqrt(R_gate)*Tf);
e(i)=2*Pin(i)*((R_gate*Tn)+(Tf*Tm)+(R_gate*Tf*Tmn));
P_output(i)=Pin(i)+a(i)+b(i)-c(i)-d(i)-e(i);
z=z+P_output(i);

end
cross=10*log10(z-P_output)./P_output;
plot(P_in, P_output,'b')
```

Fig: 4.6: Topology 1 and 3: Crosstalk (coherent) versus the crosstalk parameter of the GC-SOA.

```
clear all
R_gate=10^-5.0;
Xgate=[-5 -4 -3 -2 -1 0];
Tf=10^-3.0;
Xmx=10^-3.0;
Xdmx=10^-3.0;
Xsw=10^-6.0;
```

```
M=4;
N=2;
Tn=0;
Tm=3;
Tmn=2;
z=0;
Pin=10^-3*10^(-20/10);
for i=1:6
X_gate(i)=10^-3*Xgate(i)
end
for i=1:6
a(i)=Pin*(X_gate(i)*((M-1)*Pin+Pin));
b(i)=Pin*((N-1)*R_gate*(1+X_gate(i)*M*Pin)+(M-1)*Tf*(1+X_gate(i)*M*Pin)+(M-1)*(N-1)*Tf*R_gate);
c(i)=2*sqrt(Pin)*sqrt(Pin)*((N-1)*sqrt(R_gate)+(M-1)*sqrt(Tf)+(N-1)*(M-1)*sqrt(R_gate)*sqrt(Tf));
d(i)=2*Pin*((N-1)*(M-1)*sqrt(R_gate)*sqrt(Tf)+(N-1)^2*(M-1)*R_gate*sqrt(Tf)+(N-1)*(M-1)^2*sqrt(R_gate)*Tf);
e(i)=2*Pin*((R_gate*Tn)+(Tf*Tm)+(R_gate*Tf*Tmn));

P_output(i)=Pin+a(i)+b(i)-c(i)-d(i)-e(i)
z=z+P_output(i)
end
cross=10*log10(z-P_output)./P_output
plot(Xgate,cross,'b')
```

Fig: 4.7: Topology 2: Crosstalk (coherent) in function of the crosstalk of the demultiplexer for different values of Space Switch (Xsw= -40 -60 -80 -100 dB)

```
clear all
R_gate=10^-5.0;
X_gate=-0.1*10^-3;
Tf=10^-5.0;
Tn=2;
X_mx=[-60 -50 -40 -30 -20 -10];
```

```
X_dmx=[-60 -50 -40 -30 -20 -10];
Xsw=10^-4.0;
M=4;
N=4;
z=0;
Pin=10^-3*10^(-20/10);
for i=1:6
Xdmx(i)=10^(X_dmx(i)/10)
Xmx(i)=10^(X_mx(i)/10)
end
for i=1:6
a=Pin*(Xsw*(N-1));
b=2*Pin*(Xsw*Tn);
c(i)=2*sqrt(Pin)*sqrt(Pin)*((sqrt(Xsw*Xdmx(i))*N*(M-1)+sqrt(Xmx(i)*Xdmx(i))*(M-1)+sqrt(Xsw)*(N-1)+sqrt(Xmx(i)*Xsw*Xdmx(i))*(M-1)*(N*M-N-1)));
d(i)=2*Pin*(Xsw*sqrt(Xdmx(i))*N*(N-1)*(M-1)+Xsw*sqrt(Xmx(i))*N*(N-1)*(M-1)+sqrt(Xmx(i)*Xsw*Xdmx(i))*(M-1)*(N-1));


P_output(i)=Pin+a-b-c(i)-d(i);
z=z+P_output(i);

end
cross=10*log10(z-P_output)./P_output;
plot(X_dmx,cross,'b')
```

Fig: 4.8: Fig 6: Topology 1 and 3: Crosstalk (coherent) in function of the filter parameter for different on/off ratios (R= -10 -30 -50 -70 and -90dB

```
clear all
R_gate=10^-5.0;
X_gate=-0.1*10^-3;
Tf=10^-3.0;
Xmx=10^-3.0;
Xdmx=10^-3.0;
Xsw=10^-6.0;
```

```
M=2;
N_in=[2 4 6 8 10];
T_n=[0 3 10 21 46];
T_mn=[0 3 10 21 46];
Tm=0;
z=0;
Pin=10^-3*10^(-50/10)
for i=1:5
N(i)=1*N_in(i);
Tn(i)=1*T_n(i);
Tmn(i)=1*T_mn(i);
end
for i=1:5
a=Pin*(X_gate*((M-1)*Pin+Pin));
b(i)=Pin*((N(i)-1)*R_gate*(1+X_gate*M*Pin)+(M-1)*Tf*(1+X_gate*M*Pin)+(M-
1)*(N(i)-1)*Tf*R_gate);
c(i)=2*sqrt(Pin)*sqrt(Pin)*((N(i)-1)*sqrt(R_gate)+(M-1)*sqrt(Tf)+(N(i)-1)*(M-
1)*sqrt(R_gate)*sqrt(Tf));
d(i)=2*Pin*((N(i)-1)*(M-1)*sqrt(R_gate)*sqrt(Tf)+(N(i)-1)^2*(M-
1)*R_gate*sqrt(Tf)+(N(i)-1)*(M-1)^2*sqrt(R_gate)*Tf);
e(i)=2*Pin*((R_gate*Tn(i))+(Tf*Tm)+(R_gate*Tf*Tmn(i)));

P_output(i)=Pin+a+b(i)-c(i)-d(i)-e(i);
z=z+P_output(i);

end
cross=10*log10(z-P_output)./P_output;
plot(N_in,cross,'r')
```

Fig: 4.9: Crosstalk (coherent) in function of the number of OXC's cascaded for three topologies.

```
clear all
R_gate=10^-5.0;
X_gate=-0.1*10^-3;
Tf=10^-3.0;
Xmx=10^-3.0;
Xdmx=10^-3.0;
Xsw=10^-6.0;
M=4;
N=2;
```

```
Tn=0;
Tm=3;
Tmn=2;
z=0;
P_in=[-30 -25 -20 -15 -10 -5 0];
for i=1:7
Pin(i)=10^-3*10^(P_in(i)/10);
end
for i=1:7
a(i)=Pin(i)*(X_gate*((M-1)*Pin(i)+Pin(i)));
b(i)=Pin(i)*((N-1)*R_gate*(1+X_gate*M*Pin(i))+(M-
1)*Tf*(1+X_gate*M*Pin(i))+(M-1)*(N-1)*Tf*R_gate);
c(i)=2*sqrt(Pin(i))*sqrt(Pin(i))*((N-1)*sqrt(R_gate)+(M-1)*sqrt(Tf)+(N-1)*(M-
1)*sqrt(R_gate)*sqrt(Tf));
d(i)=2*Pin(i)*((N-1)*(M-1)*sqrt(R_gate)*sqrt(Tf)+(N-1)^2*(M-
1)*R_gate*sqrt(Tf)+(N-1)*(M-1)^2*sqrt(R_gate)*Tf);
e(i)=2*Pin(i)*((R_gate*Tn)+(Tf*Tm)+(R_gate*Tf*Tmn));
P_output(i)=Pin(i)+a(i)+b(i)-c(i)-d(i)-e(i);
z=z+P_output(i);
end
cross=10*log10(z-P_output)./P_output;
plot(P_in,cross,'r')
hold on
R_gate=10^-5.0;
X_gate=-0.1*10^-3;
Tf=10^-3.0;
Tn=1;
Xmx=10^-3.0;
Xdmx=10^-3.0;
Xsw=10^-6.0;
M=4;
N=2;
z=0;
P_in=[-30 -25 -20 -15 -10 -5 0];
for i=1:7
Pin(i)=10^-3*10^(P_in(i)/10);
end
for i=1:7
a(i)=Pin(i)*(Xsw*(N-1));
b(i)=2*Pin(i)*(Xsw*Tn);
c(i)=2*sqrt(Pin(i))*sqrt(Pin(i))*((sqrt(Xsw*Xdmx)*N*(M-1)+sqrt(Xmx*Xdmx)*(M-
1)+sqrt(Xsw)*(N-1)+sqrt(Xmx*Xsw*Xdmx)*(M-1)*(N*M-N-1)));
d(i)=2*Pin(i)*(Xsw*sqrt(Xdmx)*N*(N-1)*(M-1)+Xsw*sqrt(Xmx)*N*(N-1)*(M-
1)+sqrt(Xmx*Xsw*Xdmx)*(M-1)*(N-1));


P_output(i)=Pin(i)+a(i)-b(i)-c(i)-d(i)
z=z+P_output(i);

end
```

```
cross=10*log10(z-P_output)./P_output;
plot(P_in,cross,'b')
```

Fig: 4.10: Topology 2: Crosstalk (coherent) in function of the number of input fibers for different number of wavelength channels in a fiber (M= 2 4 6 and 8)

```
clear all;
R_gate=10^-5.0;
X_gate=-0.1*10^-3;
Tf=10^-3.0;
Tn=1;
Xmx=10^-3.0;
Xdmx=10^-3.0;
Xsw=10^-6.0;
M=4;
N=2;
```

```
z=0;
P_in=[-30 -25 -20 -15 -10 -5 0];
for i=1:7
Pin(i)=10^-3*10^(P_in(i)/10);
end
for i=1:7
a(i)=Pin(i)*(Xsw*(N-1));
b(i)=2*Pin(i)*(Xsw*Tn);
c(i)=2*sqrt(Pin(i))*sqrt(Pin(i))*((sqrt(Xsw*Xdmx)*N*(M-1)+sqrt(Xmx*Xdmx)*(M-
1)+sqrt(Xsw)*(N-1)+sqrt(Xmx*Xsw*Xdmx)*(M-1)*(N*M-N-1)));
d(i)=2*Pin(i)*(Xsw*sqrt(Xdmx)*N*(N-1)*(M-1)+Xsw*sqrt(Xmx)*N*(N-1)*(M-
1)+sqrt(Xmx*Xsw*Xdmx)*(M-1)*(N-1));


P_output(i)=Pin(i)+a(i)-b(i)-c(i)-d(i)
z=z+P_output(i);

end
cross=10*log10(z-P_output)./P_output;
plot(P_in,cross,'b')
```

Fig: 4.11: Topology 1 and 3: Crosstalk (coherent) in function of the number of input fibers for different number of wavelength channels in a fiber (M= 2 4 6 and 8)

```
clear all
R_gate=10^-5.0;
X_gate=-0.1*10^-3;
Tf=10^-3.0;
Xmx=10^-3.0;
Xdmx=10^-3.0;
Xsw=10^-6.0;
M=4;
N=2;
Tn=0;
Tm=3;
```

```
Tmn=2;
z=0;
P_in=[-30 -25 -20 -15 -10 -5 0];
for i=1:7
Pin(i)=10^-3*10^(P_in(i)/10);
end
for i=1:7
a(i)=Pin(i)*(X_gate*((M-1)*Pin(i)+Pin(i)));
b(i)=Pin(i)*((N-1)*R_gate*(1+X_gate*M*Pin(i))+(M-
1)*Tf*(1+X_gate*M*Pin(i))+(M-1)*(N-1)*Tf*R_gate);
c(i)=2*sqrt(Pin(i))*sqrt(Pin(i))*((N-1)*sqrt(R_gate)+(M-1)*sqrt(Tf)+(N-1)*(M-
1)*sqrt(R_gate)*sqrt(Tf));
d(i)=2*Pin(i)*((N-1)*(M-1)*sqrt(R_gate)*sqrt(Tf)+(N-1)^2*(M-
1)*R_gate*sqrt(Tf)+(N-1)*(M-1)^2*sqrt(R_gate)*Tf);
e(i)=2*Pin(i)*((R_gate*Tn)+(Tf*Tm)+(R_gate*Tf*Tmn));
P_output(i)=Pin(i)+a(i)+b(i)-c(i)-d(i)-e(i);
z=z+P_output(i);

end
cross=10*log10(z-P_output)./P_output;
plot(P_in,cross,'b')
```

Fig: 4.12: Plots of BER of a 4-channel system with crosstalk for different channel spacing at a bit-rate of 4.5 Gbps.

```
clear all
Br=0.1*10^9;
Rl=100*10^3;
B=10*Br;
K=1.38*10^-23;
T=300;
lamda=1550*10^-9;
f=3*10^8/lamda;
h=6.626*10^-34;
ita=1;
e=1.6*10^-19;
Rd=(ita*e)/(h*f);
Id=2*10^-15;
```

```
Ib=5*10^-14;
Pc=1.1*10^-14;
P_in=[-42 -40 -38 -36 -34 -32 -30 -28 -26 -24];
for i=1:10
Pin(i)=10^(-3)*10^(P_in(i)/10)
end
for i=1:10
 Is(i)=Rd*Pin(i);
Psig(i)=Is(i)^2;
vthermal=4*K*T*B/Rl;
vshot(i)=2*e*Is(i)*B;
vdark=2*e*Id*B;
varbackground=2*e*Ib*B;
var(i)=vthermal+vshot(i)+vdark+varbackground+Pc;
SNR(i)=Psig(i)/var(i);
BER(i)=0.5*erfc(sqrt(SNR(i))/2*sqrt(2));
end

semilogy(P_in,BER,'r')
```

Fig:4.13: Plots of BER of a 4-channel system without crosstalk for different channel spacing at a bit-rate of 4.5 Gbps

```
clear all
Br=0.9*10^9;
Rl=100;
B=Br;
K=1.38*10^-23;
T=300;
lamda=1550*10^-9;
f=3*10^8/lamda;
h=6.626*10^-34;
ita=1;
e=1.6*10^-19;
```

```
G_db=5;
G=10^(G_db/10);
nsp=1.85;
var_amp=nsp*(G-1)*h*f*B;
Rd=(ita*e)/(h*f);
Id=2*10^-15;
Ib=5*10^-14;
P_in=[-42 -40 -38 -36 -34 -32 -30 -28 -26 -24];
for i=1:10
Pin(i)=10^(-3)*10^(P_in(i)/10)
end
for i=1:10
 Is(i)=G*Rd*Pin(i);
Psig(i)=Is(i)^2;
vthermal=4*K*T*B/Rl;
vshot(i)=2*e*Is(i)*B;
vdark=2*e*Id*B;
varbackground=2*e*Ib*B;
var(i)=vthermal+vshot(i)+vdark+varbackground;
SNR(i)=Psig(i)/(var(i)+var_amp);
BER(i)=0.5*erfc(sqrt(SNR(i))/2*sqrt(2));
end

semilogy(P_in,BER,'b')
```

Fig: 4.14: BER comparison for with crosstalk and without crosstalk.

```
Br=0.9*10^9;
Rl=100*10^3;
B=10*Br;
K=1.38*10^-23;
T=300;
lamda=1550*10^-9;
f=3*10^8/lamda;
h=6.626*10^-34;
ita=1;
e=1.6*10^-19;
Rd=(ita*e)/(h*f);
Id=2*10^-15;
Ib=5*10^-14;
Pc=1.1*10^-14;
```

```
P_in=[-42 -40 -38 -36 -34 -32 -30 -28 -26 -24];
for i=1:10
Pin(i)=10^(-3)*10^(P_in(i)/10)
end
for i=1:10
 Is(i)=Rd*Pin(i);
Psig(i)=Is(i)^2;
vthermal=4*K*T*B/Rl;
vshot(i)=2*e*Is(i)*B;
vdark=2*e*Id*B;
varbackground=2*e*Ib*B;
var(i)=vthermal+vshot(i)+vdark+varbackground+Pc;
SNR(i)=Psig(i)/var(i);
BER(i)=0.5*erfc(sqrt(SNR(i))/2*sqrt(2));
end
semilogy(P_in,BER,'r')
hold on
Br=0.9*10^9;
Rl=1;
B=Br;
K=1.38*10^-23;
T=300;
lamda=1550*10^-9;
f=3*10^8/lamda;
h=6.626*10^-34;
ita=1;
e=1.6*10^-19;
G_db=5;
G=10^(G_db/10);
nsp=1.85;
var_amp=nsp*(G-1)*h*f*B;
Rd=(ita*e)/(h*f);
Id=2*10^-15;
Ib=5*10^-14;
P_in=[-42 -40 -38 -36 -34 -32 -30 -28 -26 -24];
for i=1:10
Pin(i)=10^(-3)*10^(P_in(i)/10)
end
for i=1:10
 Is(i)=G*Rd*Pin(i);
Psig(i)=Is(i)^2;
vthermal=4*K*T*B/Rl;
vshot(i)=2*e*Is(i)*B;
vdark=2*e*Id*B;
varbackground=2*e*Ib*B;
var(i)=vthermal+vshot(i)+vdark+varbackground;
SNR(i)=Psig(i)/(var(i)+var_amp);
BER(i)=0.5*erfc(sqrt(SNR(i))/2*sqrt(2));
end
```

```
semilogy(P_in,BER,'r')
```

Fig: 4.15: Power penalty (at BER=10^-12) versus channel spacing with crosstalk for a bit rate of 4.5 Gbps.

```
clear all
n=[0.5 1.0 1.5 2.0 2.5];
Pw=-37.48 %power without crosstalk%
Px=[(-32.73)-Pw (-31.68)-Pw (-30.62)-Pw (-30.02)-Pw (-29.67)-Pw];
plot(n,Px)
grid on
```