PHYSICAL LAYER IMPAIRMENTS BASED OPTICAL ROUTING

A THESIS SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

In

Telematics and Signal Processing

by

Kalyan Chakravarthi P

Roll No: 209EC1113

Department of Electronics & Communication Engineering

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Under the guidance of

Prof. Santos Kumar Das

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CERTIFICATE

This is to certify that the thesis entitled, “PHYSICAL LAYER IMPAIRMENTS BASED OPTICAL ROUTING” submitted by KALYAN CHAKRAVARTHI P (209EC1113) in partial fulfilment of the requirements for the award of Master of Technology degree in Electronics and Communication Engineering with specialization in “Telematics and Signal Processing” at National Institute of Technology, Rourkela (Deemed University) and is an authentic work by her under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any Degree or Diploma.

Date:

Prof. Santos Kumar Das
Dept. of E.C.E
National Institute of Technology
Rourkela-769008
Email: dassk@nitrkl.ac.in

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Kalyan Chakravarthi P

Roll No: 209ec1113

Dept of ECE,

NIT, Rourkela

ABSTRACT

In optical networks, physical layer impairments (PLIs) incurred by non-ideal optical transmission media, accumulates along the optical path. The overall effect of PLIs determines the feasibility of the light-paths. It is important to understand the process that provide PLI information to the central manager and use this information efficiently to compute feasible routes and wavelengths. Based on the PLI impairments like fiber attenuation, chromatic dispersion ,cross talk, amplifier spontaneous noise and polarization mode dispersion, which reflects the Quality of service, factors (Q-Factor); In this project we worked about both linear and non linear physical layer impairments and calculated parameters like power loss , channel capacity and Quality factor of all possible paths. From that we proposed centralized PLI based routing algorithm is proposed for the selection of data-paths.

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ACRONYMS

PLI – Physical Layer Impairments

WDM – Wavelength Division Multiplexing

DWDM-Dense Wavelength Division Multiplexing

Q-Factor- Quality Factor

DP-Data-path

SN-Source Node

DN-Destination Node

PP-Possible paths

ASE – Amplifier Spontaneous Emission

CD-Chromatic Dispersion

OSNR- Optical Signal to Noise Ratio

PL: Power Loss

BP: Best path

AQF: Average Q-Factor required from Clients)

BPPRN: Best possible path reference number according to highest overall Q-Factor

Chapter 1

Introduction

1.1 Introduction

Day to day growth in telecommunication network requires functionalities like dynamic data-path selection with guaranteed Quality of service (QoS) [**1**] [**2**], which are essential for any optical network. Data-path selection of the WDM network depends on the physical as well as IP layer information. The degradation of data-path may happen due to Physical layer impairments (PLI).

WDM (Wavelength Division Multiplexing) technology is growing day-by-day in accordance with the requirement of clients. The basic requirement of clients is QoS (Quality of Service), which depends on various parameters in network as well as in physical layer. In order to satisfy such Requirements, it is necessary to search for a data-path in WDM network. The optical information on data-paths are generally affected or degraded by various constraints such as physical layer impairments [**1**] .

Q-Factor can be widely used as a system performance indicator for optical communication systems since it is directly related to system-bit error rate [**1**] [**2**] [**3**] [**4**] [**5**] [**6**] . This also can be used for light-path routing. There are few PLI based routing algorithms considered in [**7**] [**8**]. The advantages of Q-Factor [9] include rate transparency and in service performance monitoring in addition to fast and compete performance analysis.

1.2 **Physical layer impairments**

PLIs are broadly classified in to two categories: linear and non-linear impairments [**3**] [**4**] [**5**] [**6**]. The terms linear and non-linear in fiber optics mean intensity-independent and intensity-dependent, respectively. The linear impairments are static in nature and non-linear impairments are dynamic in nature [**9**]. The non-linear impairments strongly depend on the current allocation of route and wavelength, i.e., on the current status of allocated light paths. Linear impairments are independent of the signal power and affect each of the wavelengths (optical channels) individually, whereas nonlinear impairments affect not only each optical channel individually but they also cause disturbance and interference between them [**10**].

1.2.1 Linear impairments

The important linear impairments are: fiber attenuation, component insertion loss, amplifier spontaneous emission (ASE) noise, chromatic dispersion (CD) (or group velocity dispersion (GVD)), polarization mode dispersion (PMD), polarization dependent losses (PDL), crosstalk (XT) (both inter- and intra-channel), and filter concatenation (FC). Optical amplification in the form of EDFAs always degrades the optical signal to noise ratio (OSNR). The amplifier noise is quantified by noise figure (NF) value, which is the ratio of the optical signal to noise ratio (OSNR) before the amplification to the same ratio after the amplification and is expressed in dB [**10**].

Chromatic dispersion causes pulse broadening, which affects the receiver performance by: (1) reducing the pulse energy within the bit slot and (2) spreading the pulse energy beyond the allocated bit slot leading to inter-symbol interference (ISI). CD can be adequately (but not optimally) compensated for on a per link, and/or at transmission line design time [**10**]

PMD is not an issue for most type of fibers at 10 Gbps, however it become an issue at 40 Gbps or higher rates [**11**], [**12**] [**13**] [**14**] In general, in combination with PMD there is also polarization dependent loss (PDL). It can cause optical power variation, waveform distortion and signal-to-noise ratio fading.

Imperfect optical components (e.g. filters, de-multiplexers, and switched) inevitably introduce some signal leakage either as inter-channel (also incoherent or out-of-band) or intra-channel [**15**] (or intra-band) crosstalk in WDM transmission systems.

Filter concatenation is the last physical impairment that we consider and define in this category. As more and more filtering components are concatenated along the light-path, the effective pass band of the filters becomes narrower [**16**]. This concatenation also makes the transmission system susceptible to filter pass band misalignment due to device imperfections, temperature variations and aging.

A. *Power Losses:* Power loss can be defined as the optical loss that is accumulated from source to destination along fiber links and is normally made up of intrinsic fiber losses and extrinsic bending losses [**1**] . Intrinsic fiber losses are due to attenuation, absorption, reflections, refractions, Rayleigh scattering, optical component insertion losses, etc. Let *Pin* be the power launched at the input of a fiber of length L; then the output power *Pout* is given by $Pout = Pin \cdot e^{-\alpha L,}$ where α is the fiber attenuation coefficient. The loss introduced by the insertion of optical components, such as couplers, filters, multiplexers/ de multiplexers, and switches, into the optical communications system is called insertion loss and is usually independent of wavelength.

The extrinsic losses are due to micro and macro bending losses. Additional losses occur due to the combined effects of dispersion resulting from inter symbol interference (ISI), mode-partition noise, and laser chirp as discussed later in this section.

B. *Chromatic Dispersion (CD):* The degradation of an optical signal caused by the various spectral components traveling at their own different velocities is called *dispersion*. CD causes an optical pulse to broaden such that it spreads into the time slots of the other pulses. It is considered as the most serious linear impairment for systems operating at bit-rates higher than *2.5 Gb/s*. CD depends on bit-rate, modulation format, type of fiber, and the use of dispersion compensation fiber (DCF) modules.

The total dispersion at the end of a light-path is the sum of dispersions on each fiber-link of the considered light-path, where the dispersion on a fiber-link is the sum of dispersions on the fiber-spans that compose the link. Most commonly deployed compensation techniques are based on DCF. Dispersion compensation techniques are useful in long-haul as well as metro networks. A fiber of length L_f and dispersion D_f can be compensated by using a spool of DCF of length L_c and dispersion parameter D_c such that the dispersion at the end of the fiber is close to zero and satisfies $D_fL_f + D_cL_c = 0$. Due to imperfect matching between the dispersion slopes of CD and DCF, some wavelengths may be over-compensated and some others may be undercompensated.

Moreover DCF modules may only be available in fixed lengths of compensating fiber. Hence, sometimes it may be difficult to find a DCF chat exactly compensates the CD introduced by the fiber, leading to residual CD. A typical value of dispersion compensation tolerance in commercial receivers is around ±800 *ps/nm* for non-return-to-zero (NRZ) *10 Gb/s*, while it is ±160 *ps/nm* for optical duo binary (ODB) *40 Gb/s* [**7**].

C. *Polarization Mode Dispersion (PMD):* Anywhere along a fiber-span, fiber could be non-circular, contain impurities, or be subject to environmental stress such as local heating or movement. These irregularities present obstacles to an optical pulse along its path. These obstacles cause different polarizations of the optical signal to travel with different group velocities resulting in pulse spread in the frequency domain, known as PMD. The differential group delay (DGD) is proportional to the square root of fiber length L, i.e., $\Delta\tau = D_{PMD} \cdot\sqrt{L}$, where D_{PMD} is the PMD parameter of the fiber and typically measured in $ps/\sqrt{km}$. Because of the $\sqrt{L}$ dependence, the PMD-induced pulse broadening is relatively small compared to CD. The PMD on a fiber link is a function of PMD on each fiber-span and is given by $PMD_{fiber-link} = \sqrt{(\sum_{fiber-spans} PMD(f)^2)}$.

The PMD at __ the end of a light-path is $PMD_{light\ path} = \sqrt{(\sum_{fiber\ links\ along\ the\ route} PMD(f)^2)}$. The PMD values vary from fiber to fiber in the range of *0.01-10* $ps/\sqrt{km}$ [**7**]. PMD becomes a major limiting factor for WDM systems designed for longer distances at higher bit-rates. The effect of second and higher order PMD becomes prominent at high-bit rates exceeding

40 Gb/s. PMD induced problems can be reduced by shortening the optical transmission distance by placing OEO regenerators between two optical nodes.

However, as most long-haul DWDM systems are multi-wavelength, the transmission link must first be de-multiplexed, then regenerated, and then multiplexed again, which is a very expensive operation. Another alternative is to use dispersion compensation modules (DCM) at optical add/drop multiplexers (OADMs), optical cross-connects (OXCs), or amplifier sites to compensate for accumulated PMD on an optical path. Because PMD effects are random and time-dependent, this requires an adaptive/active PMD compensator that responds to feedback over time. Hence, the most reliable and efficient PMD compensation technology is the use of adaptive optics to realign and correct the pulses of dispersed optical bits.

D. *Polarization Dependent Loss (PDL):* The two polarization components along the two axes of a circular fiber suffer different rates of loss due to irregularities in the fiber, thereby degrading signal quality in an uncontrolled and unpredictable manner and introducing fluctuations in optical signal to noise ratio (OSNR). The combined effect of PMD and PDL can further degrade the optical signal quality.

PDL is a measure of the peak-to-peak difference in transmission of an optical component/system w.r.t. all possible states of polarization and is given by $PDL_{dB} = 10 \cdot log\ (P_{Max}/P_{Min})$, where P_{Max} and P_{Min} are the maximum and minimum output power, respectively. PDL mainly occurs in passive optical components. The most common passive optical components that exhibit PDL include couplers, isolators, multiplexers/de-multiplexers, and photo detectors. The polarization scanning technique (PST) and the Mueller matrix method (MMM) are suitable methods for measuring the PDL [**8**]. While the PST is preferable for determining PDL at a specific wavelength, the MMM has clear advantages when PDL must be characterized at numerous wavelength points with equal spacing.

The worries that plagued optical fiber communication in the early days were fiber attenuation and, sometimes, fiber dispersion; however, these issues are dealt with using a variety of dispersion compensation techniques. However, fiber nonlinearities present a new realm of obstacles that must be overcome. Effects of non-linear impairments become crucial as data transmission rates, transmission lengths, number of wavelengths, and optical power levels increase in addition to reduction in channel spacing. Network designers must be aware of these limitations and of the steps that can be taken to minimize the detrimental effects of these fiber non-linearities. The response of any dielectric medium to light becomes non-linear under intense electromagnetic field, and optical fibers are no exception.

Due to an harmonic motion of bound electrons the total polarization P induced by electric dipoles is not linear in the electric field E, but satisfies a more general relation as

$P = \varepsilon 0(\chi(1).E1 + \chi(2).E2 + \chi(3).E3 + ...)$,

where $\varepsilon 0$ is the permittivity of vacuum and $\chi(k)$ is the k^{th} order susceptibility. The predominant contribution to P is from linear susceptibility $\chi(1)$. For a medium like fiber with symmetric molecules, $\chi(2)$ vanishes. Therefore optical fibers do not exhibits second order non-linear refractive effects. Hence, the third order susceptibility $\chi(3)$ is responsible for the lowest order non-linear effects such as non-linear refraction, third order harmonic generation, and four-wave mixing as discussed later. The non-linear effects in optical fiber occur either due to change in the refractive index of the medium with optical intensity (power) or due to inelastic-scattering phenomenon.

A general classification of non-linear effects in fiber medium [**2**] are the dependence of refractive index on power is responsible for Kerr effect which produces three different kinds of effects—self-phase modulation (SPM), cross phase modulation (XPM), and four-wave mixing (FWM),depending on the type of input signal. At high power levels, the light waves (optical signals) interact with the phonons of the fiber medium resulting in scattering phenomenon. The intensity of scattered light grows exponentially if the incident power exceeds a certain threshold value.

The inelastic scattering phenomenon can induce stimulated effects such as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). The Brillouin generated phonons (acoustic) are coherent and give rise to a macroscopic acoustic wave in the fiber, whereas, in Raman scattering, the phonons (optical) are incoherent and no macroscopic wave is generated. All nonlinear effects, except SPM and XPM, provide gains to some channel at the expense of depleting power from other channels. SPM and XPM affect only the phase of the optical signal and can cause spectral broadening, which leads to increased dispersion. A comparison of various non-linear effects in fiber medium is presented in Table I [**6**]

The importance of non-linear effects is growing due to

- Increase in optical power levels to increase the optical reach,
- Recent developments in optical components such as EDFA and DWDM systems to build more flexible networks

- Increase in channel bit-rate to increase the traffic carrying capacity of wavelengths
- Decrease in channel spacing to increase the number of wavelengths and overall network capacity.

Although the individual power in each channel may be below the one needed to produce non-linearities, the total power summed over all channels in a multi-wavelength WDM system can become significant. The combination of high total optical power and a large number of channels at closely spaced wavelengths is ideal for many kinds of non-linear effects. For all these reasons it is important to understand and be able to accurately measure fiber non- linearities. In the following, we briefly explain the reasons behind each of these non-linear effects and discuss some possible solutions to overcome these effects.

1.1.2 Non-Linear Impairments:

The important non-linear impairments are Self phase modulation (SPM), Cross Phase Modulation (CPM), Four wave mixing (FWM) , Stimulated Brilloin Scatter and Stimulated Raman Scattering . The following sections describe the all non linear impairments in detail.

A. Self-Phase Modulation (SPM): The non-linear phase modulation of an optical pulse caused by its own intensity in an optical medium is called SPM. An ultra-short optical pulse, when travelling in a medium, will induce a time varying refractive index of the medium, i.e., the higher intensity portions of an optical pulse encounter a higher refractive index of the fiber compared with the lower intensity portions.

This results in a positive refractive index gradient (dn/dt) at the leading edge of the pulse and a negative refractive index gradient (−dn/dt) at its trailing edge. This temporally varying refractive index change results in a temporally varying phase change leading to frequency chirping, i.e., the leading edge of the pulse finds frequency shift towards the higher side whereas the trailing edge experiences shift towards the lower side.

Hence, the primary effect of SPM is to broaden the pulse in the frequency domain, keeping the temporal shape unaltered. As the chirping effect is proportional to the transmitted signal power, the SPM effects are more pronounced in systems with high transmitted power. SPM is the strongest among the Kerr effects for DWDM systems workingat100GHz spacing. The chirp also depends on the input pulse shape. The appropriate chirping of input signals using chirped RZ (CRZ) modulation can reduce the SPM effects [**11**].The effects produced by nonlinear SPM and linear dispersion are opposite in nature. By proper choice of pulse shape and input power, one effect will compensate for another, leading to undistorted pulse in both time and frequency domains. Such a pulse is called a soliton pulse and is useful in high-bandwidth optical communication systems.

B. Cross-Phase Modulation (XPM): The non-linear refractive index seen by an optical pulse depends not only on the intensity of the pulse but also on the intensity of the other co-propagating optical pulses, i.e., the non-linear phase modulation of an optical pulse caused by fluctuations in intensity of other optical pulses is called XPM. The result of XPM may be asymmetric spectral broadening and distortion of the pulse shape. XPM hinders the system performance through the same mechanism as SPM: chirping frequency and chromatic dispersion. XPM damages the system performance even more than SPM and influences it severely when the number of channels is large. The XPM-induced phase shift can occur only when two pulses overlap in time.

Due to this overlap, the intensity-dependent phase shift and consequent chirping is enhanced, leading to enhanced pulse broadening. The effects of XPM can be reduced by increasing the wavelength spacing between individual channels. Another way to reduce XPM effects is by careful selection of bit-rates for adjacent channels that are not equal to the present channels. For increased wavelength spacing, the pulses overlap for such a short time that XPM effects are virtually negligible. XPM is more important at50 (or less) GHz spacing compared to 100GHz spacing.

C. Four Wave Mixing (FWM): FWM originates from third order non-linear susceptibility (χ (3)) in optical links. If three optical signals with carrier frequenciesω1,ω2 andω3, co-propagate inside a fiber simultaneously, (χ(3)) generates a fourth signal with frequencyω4, which is related to the other frequencies by $\omega 4 = \omega 1 \pm \omega 2 \pm \omega 3$. In general for W wavelengths launched into a fiber, the number of FWM channels produced is M=W2 (W−1)/2).

The FWM effect is independent of the bit-rate and is critically dependent on the channel spacing and fiber dispersion. Decreasing the channel spacing increases the four-wave mixing effect. FWM has severe effects in a WDM system, which uses dispersion-shifted fiber. If there is some dispersion in the fiber, then the effect of FWM is reduced. This is why non-zero dispersion-shifted fibers are normally used in WDM systems. Another way to reduce FWM effect is to employ unequal channel spacing in such a way that the generated signals do not interfere with the original signals.

D. Stimulated Brillouin Scattering (SBS): SBS occurs when an optical signal in fiber interacts with the density variations such as acoustic phonons and changes its path. In SBS, the scattering process is stimulated by photons with a wavelength higher than the wavelength of the incident signal.SBS is recognized as the most dominant fiber non-linear scattering effect. SBS sets an upper limit on the amount of optical power that can be launched into an optical-fiber [**4**] .

When input optical power exceeds the SBS threshold, a significant amount of the transmitted light is redirected back to the transmitter leading to saturation of optical power in the receiver, and introducing noise that degrades the BER performance.

The SBS threshold depends on the line-width of the optical source, with narrow line-width sources having considerably lower SBS thresholds. The back-scattered signals can be measured using a Fabry-Perot interferometer or pump probe or self-heterodyne techniques. Externally modulating the transmitter provides one way to broaden the line-width of the optical source. Hence, it is particularly important to control SBS in high-speed transmission systems that use external modulators and continuous wave (CW) laser sources.

E. Stimulated Raman Scattering (SRS): In WDM systems, if two or more optical signals at different wavelengths are injected into a fiber, the SRS effect causes optical signal power from lower wavelength optical channels to be transferred to the higher wavelength optical channels. This can skew the power distribution among the WDM channels— reducing the signal-to-noise ratio of the lower wavelength channels and introducing crosstalk on the higher wavelength channels.

Both of these effects can lower the information carrying capacity of the optical transmission system. SRS occurs at significantly higher optical powers than SBS, with threshold powers of the order of watts for SRS compared to milli watts for SBS. Unlike SBS, SRS scatters in both forward and reverse directions.

The effect of SRS, i.e., Raman gain co-efficient, can be measured using relative cross-section method or pulse-scanning technique or Raman amplification method. Several optical filtering techniques are proposed to suppress SRS interactions in optical fiber systems [**17**].

The filters, when inserted appropriately into the transmission link, can effectively suppress the SRS power flow from the WDM channels to lower frequency noise. Furthermore, usage of a high-pass filter can enhance the SRS threshold in an optical fiber.

1.2.3 Classification of physical impairments

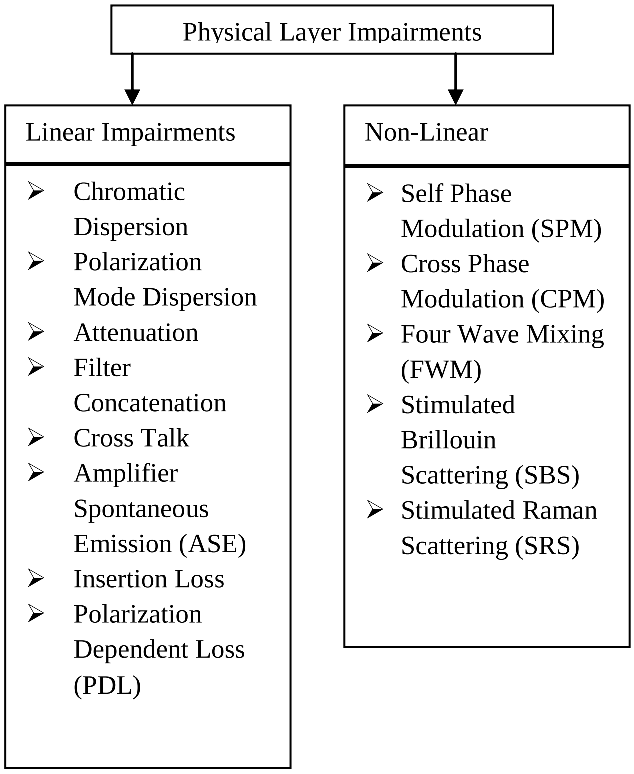

Figure 1: Classification of Physical impairments

1.3 **Proposed Work**

In this project, we focus on PLI Impairments, which are defined as the parameter effect in the physical layer while establishing the connection between source nodes to destination node. The main objectives of this paper is to when and how to select a data-path. In this project we proposed a centralized network. Then the Data-path selection is based on client requirement. Here we focused on the improvements in Data-path selection for WDM and DWDM networks.

1.4 **Organization of rest of report**

In the next Chapter, PLI Based Quality of Service Analysis for WDM introduced. In that chapter we discussed about introduction to WDM networks, and Calculation of PLI parameters for WDM network, in the 3rd Chapter, PLI Based Quality of Service Analysis for DWDM introduced. In that chapter we discussed about introduction to DWDM networks, and Calculation of PLI parameters for DWDM network. In 4th chapter we discussed about the result and discussion. Finally some conclusions are drawn.

Chapter 2

WDM Network

2.1 Introduction to WDM

Wavelength Division Multiplexing (WDM) is a promising technology for future all-optical networks. In WDM several optical signals using different wavelengths share the same fiber. The capacity of such fiber links can be huge, even terabits per second. So, essentially the optical spectrum is used more efficiently. Routing in the network nodes is based on wavelengths of incoming signals [**18**] [**19**]. Currently the WDM technology is used to increase the capacity of optical links where at the end of each link the signal is converted back to electrical domain. But the technology is progressing towards transparent all-optical networks where the signal is routed through the network in the optical domain.

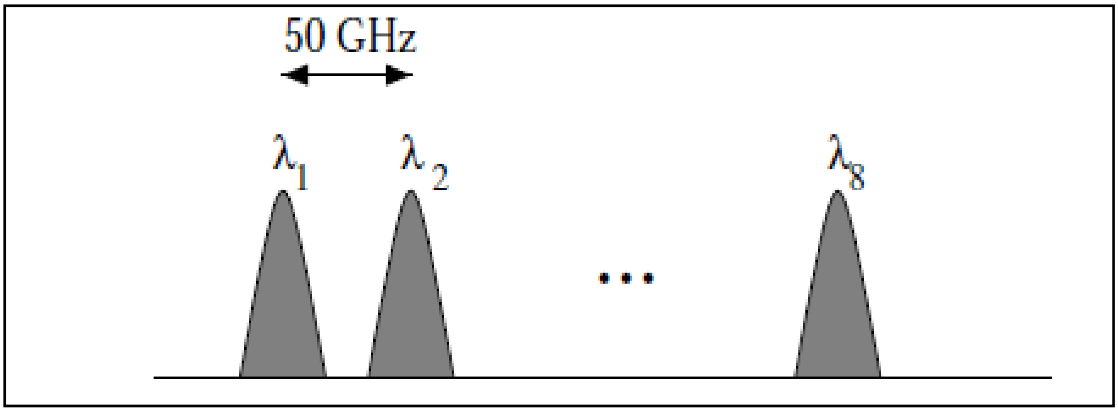

Figure 2 : The optical spectrum and 8 wavelength channels.

The International Telecommunication Union (ITU) has standardized the use of the wave-length channels in a WDM link in standard G.692 (see [**20**]). The channel spacing is proposed to be 50 GHz or 100 GHz around the reference frequency of 193.10 THz, as depicted in Fig. 2. 193.10 THz corresponds to about 1550 nm, hence the proposal is meant for the 1540 nm - 1560 nm pass band of the optical fiber.

2.2 Components of WDM-Network

During recent years lots of effort has been put into the development of better optical components to enable all-optical WDM-networks (AON) . The most important components are light sources, tunable optical filters, optical switches and of course the fiber. Different components are briefly presented in the following sections.

a) Light Sources

One important element of an optical system is the light source. For communication purposes a good light source should be quickly tunable with a wide range of wavelengths. To make a component also commercially attractive low power consumption and low price are vital parameters [**21**]. The time scale of tuning depends on case, with the optical packet switching the requirements are somewhere between microseconds and nanoseconds while with circuit switched WDM-networks the time scale is slower. Here is a list of several candidates:

- Mechanically tuned lasers
- Acousto-optically and electro-optically tuned lasers
- Injection current tuned lasers
- Switched sources
- Array sources (using arrayed waveguide gratings (AWG) or distributed feedback (DFB) lasers)

Mechanically tuned lasers, for example, have a tuning time of the order of milliseconds and are thus too slow for packet switched optical networks. Generally the choice between different light source types depends on the application and the two most important parameters for light sources are the tuning time and the tuning range.

b) Tunable Filters

A tunable optical filter is also an important part of the optical network. Many promising approaches have been studied including Fabry-Perot, acousto-optic, electro-optic and liquid crystal Fabry-Perot filters. The filters have two important parameters dealing with the performance: tuning range and tuning time. The tuning ranges are from around 10 nm up to 500 nm, while the tuning time is from nanoseconds up to 10 milliseconds.

c) Optical Switches

The optical switch, or optical cross-connect (OXC), is a device which can be dynamically configured to connect given input ports to any of the output ports.

The optical switches can be classified according to how flexible they are :

- A non-blocking switch means any connection pattern can be realized by re-connection of some or all of the current connections.
- Wide-sense non-blocking switch is a switch which can, with careful configuration, add any new connection without interrupting previously configured connections through the switch.
- Strict-sense non-blocking switch, on the other hand, means that a simple configuration strategy allows adding new connections to the switch any time without interrupting any of the current connections.
- Clearly the number of elements and device complexity grows at the same time as the flexibility. This means a trade-off between hardware complexity and management complexity.

d) Wavelength channels

In WDM-networks each fiber contains W wavelength channels, and thus the optical switches should be capable to treat channels individually. The optical cross-connects used in WDM-networks can be divided into two categories. A wavelength selective cross-connect (WSXC) is a device capable to configure any given input λ-channel from arbitrary input port to a given output port (using the same wavelength).

Wavelength translation (conversion) is an operation where an incoming signal using λ_1 channel is converted to another channel λ_2 at the output port. Wavelength interchange cross-connect (WIXC), depicted in Figure 3, is a more advanced device than WSXC which can manipulate wavelengths of the signals as well, i.e. an incoming signal can emerge from the switch using another wavelength.

Hence, such a device can configure any λ_1 channel from any input port to any output port using λ_2 channel, i.e. it is capable of doing wavelength translations as well. Clearly a WIXC device is more complex than WSXC, but it also gives more flexibility in the configuration of the network, and hence leads to more efficient use of the network resources. Note that both WSXC and WIXC are devices where every input channel is connected to no more than one output-channel (permutation switch).

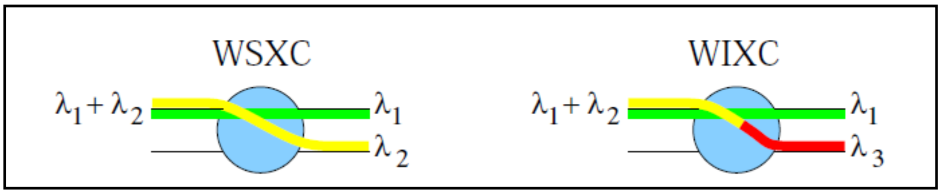

Figure 3 : The basic components of the wavelength routed network. Wavelength selective cross-connect (WSXC) routes incoming signals per wavelength basis, while wavelength interchange cross-connect (WIXC) has also capability to perform wavelength

e) Wavelength Conversion

Wavelength conversion, as noted in the previous section, allows more efficient use of the network resources. The reason is that without it so called wavelength-continuity constraint has to be satisfied, i.e. the light-path reserves the same wavelength all the way along the route. Hence, even if there are free channels available in every link of the network, some connections may not be configured unless wavelength conversion is possible in some of the nodes.

Again, an easy solution is to do the opto-electronic wavelength conversion where the optical signal is first converted to the electric domain and then reproduced in the optical domain at a different wavelength. The drawback with this approach is the limited bit rate of electronics.

Another approach is to do the conversion in the optical domain. Suggested solutions include using the four-wave mixing and fiber nonlinearities, and cross modulation with active semiconductor devices. An up-to-date survey on wavelength conversion can be found in [**22**]

f) Optical Amplifiers

The attenuation of optical signals is low in comparison with electrical signals. Still long-distance links may need amplifiers in order to operate properly. The traditional way to solve the problem is to convert the signal back to electrical domain for amplification and retransmit it optically. This approach, however, requires knowledge of the used bit rate and modulation. A new solution is to use amplifiers operating totally in the optical domain. In particular, the erbium doped fiber amplifier (EDFA) operating at 1540 nm region has proven to be an excellent choice for the WDM systems. The amplifier is transparent to used coding and bit-rate, and thus suits well to all-optical framework. Also a similar amplifier for the 1300 nm region has been built using praseodymium instead of erbium.

2.3 Evolution of WDM Technology

Telecommunication field is full of standards defining different layers for the whole infrastructure. In the past the end users were people making phone calls or using fax machines etc. But now it has become very clear that in the future almost all the traffic will be IP-based. The evolution will go towards IP-over-WDM networks, where several alternative approaches have been proposed. Each additional layer brings naturally some extra overhead to the transmission. Hence, the standard IP over ATM over SONET/SDH over WDM mapping can be considered as an inefficient solution. The other extreme is a direct IP/MPLS over WDM solution, so called λ-labelling, presented in [**23**].

2.4 Quality Of Service :

Q-Factor of a light-path is defined as the ratio of output power relative to input power. It is normalized by dividing the value of Q-Factor with maximum value of Q-Factor possible. It is expressed in percentage. So 100% Q-Factor means light-path has the highest Q-Factor and the light-path corresponding to this value of Q-Factor will be the best light-path.

To maximize the Q-Factor we need to maximize the output power for constant value of input power. We know that output power received is the attenuated version of input power due to attenuation loss, splice loss and connector loss. So we should try to minimize the losses in the optical fiber communication. Losses can be reduced by selecting the best components like connectors, splices and optical fiber which are having minimum power loss values. Out of all possible light-paths, the light-path having minimum power loss should be selected as optimal light-path. Q-Factor has benefits like it allows simplified analysis of system performance and reflects the quality of the system without using difficult algorithm. It gives the cost in terms of power loss. Higher is the value of Q-Factor, better is the light-path of optical communication. It requires less time than other performance analysis method.

Chapter 3

DWDM Network

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3.1 Introduction to DWDM

Dense wavelength division multiplexing (DWDM) is a fiber-optic transmission technique that employs light wavelengths to transmit data parallel-by-bit or serial-by-character. The emergence of DWDM is one of the most recent and important phenomena in the development of fiber optic transmission technology. In the following discussion we briefly trace the stages of fiber optic technology and the place of DWDM in that development [**24**]. We then examine the functions and components of a DWDM system, including the enabling technologies, and conclude with a high-level description of the operation of a DWDM system.

3.2 Evolution of Fiber Optic Transmission

The reality of fiber optic transmission had been experimentally proven in the nineteenth century, but the technology began to advance rapidly in the second half of the twentieth century with the invention of the fiberscope, which found applications in industry and medicine, such as in laparoscopic surgery. After the viability of transmitting light over fiber had been established, the next step in the development of fiber optics was to find a light source that would be sufficiently powerful and narrow [**25**]. The light-emitting diode (LED) and the laser diode proved capable of meeting these requirements. Lasers went through several generations in the 1960s, culminating with the semiconductor lasers that are most widely used in fiber optics today. Light has an information-carrying capacity 10,000 times greater than the highest radio frequencies. Additional advantages of fiber over copper include the ability to carry signals over long distances, low error rates, immunity to electrical interference, security, and light weight. Aware of these characteristics, researchers in the mid-1960s proposed that optical fiber might be a suitable transmission medium. There was an obstacle, however, and that was the loss of signal strength, or attenuation, seen in the glass they were working with. Finally, in 1970, Corning produced the first communication-grade fibers. With attenuation less than 20 decibels per kilometer (dB/km), this purified glass fiber exceeded the threshold for making fiber optics a viable technology. Innovation at first proceeded slowly, as private and government monopolies that ran the telephone companies were cautious. AT&T first standardized transmission at DS3 speed (45 Mbps) for multimode fibers. Soon thereafter, single-mode fibers were shown to be capable of transmission rates 10 times that of the older type, as well as spans of 32 km (20 mi). In the early 1980s, MCI, followed by Sprint, adopted single-mode fibers for its long-distance network in the U.S.

Further developments in fiber optics are closely tied to the use of the specific regions on the optical spectrum where optical attenuation is low. These regions, called windows, lie between areas of high absorption. The earliest systems were developed to operate around 850 nm, the first window in silica-based optical fiber. A second window (S band), at 1310 nm, soon proved to be superior because of its lower attenuation, followed by a third window (C band) at 1550 nm with an even lower optical loss. Today, a fourth window (L band) near 1625 nm is under development and early deployment.

3.3 Development of DWDM Technology

Early WDM began in the late 1980s using the two widely spaced wavelengths in the 1310 nm and 1550 nm (or 850 nm and 1310 nm) regions, sometimes called wideband WDM. Figure 4 shows an example of this simple form of WDM. Notice that one of the fiber pair is used to transmit and one is used to receive. This is the most efficient arrangement and the one most found in DWDM systems.

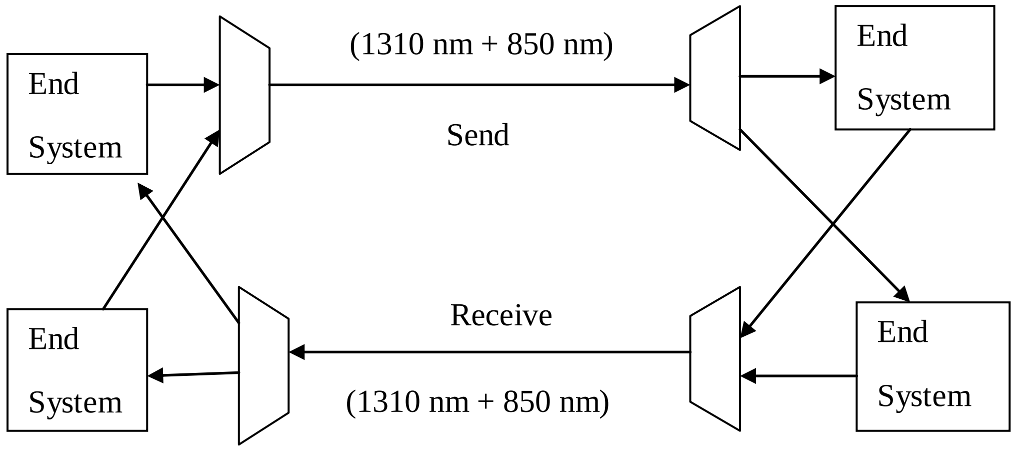

Figure 4: WDM with two channels

The early 1990s saw a second generation of WDM, sometimes called narrowband WDM, in which two to eight channels were used. These channels were now spaced at an interval of about 400 GHz in the 1550-nm window. By the mid-1990s, dense WDM (DWDM) systems were emerging with 16 to 40 channels and spacing from 100 to 200 GHz. By the late 1990s DWDM systems had evolved to the point where they were capable of 64 to 160 parallel channels, densely packed at 50 or even 25 GHz intervals. The progression of the technology can be seen as an increase in the number of wavelengths accompanied by a decrease in the spacing of the wavelengths. Along with increased density of wavelengths, systems also advanced in their flexibility of configuration, through add-drop functions, and management capabilities.

Figure 5 shows the increases in channel density resulting from DWDM technology have had a dramatic impact on the carrying capacity of fiber. In 1995, when the first 10 Gbps systems were demonstrated, the rate of increase in capacity went from a linear multiple of four every four years to four every year .

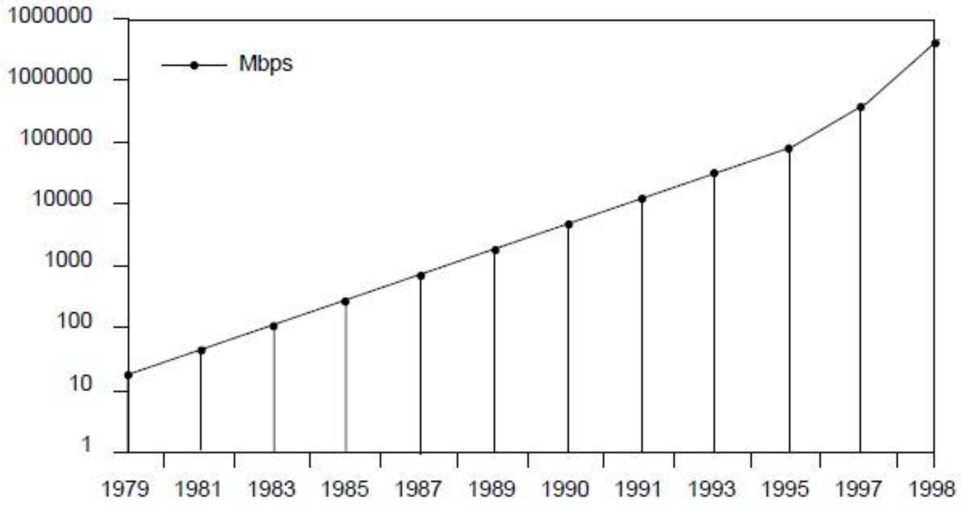

Figure 5 : Growth in Fiber Capacity

3.4 DWDM System Functions

At its core, DWDM involves a small number of physical-layer functions. These are depicted in Figure 6, which shows a DWDM schematic for four channels [**26**]. Each optical channel occupies its own wavelength.

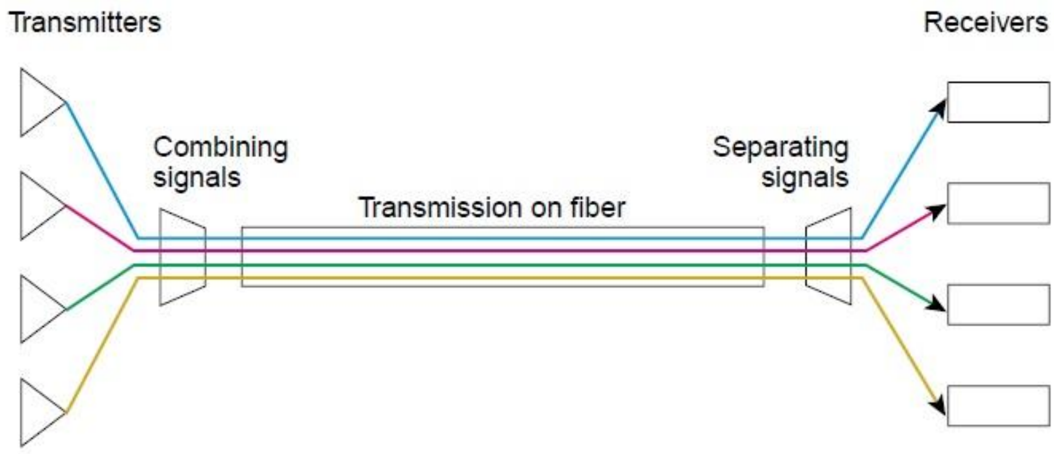

Figure 6 : DWDM schematic for four channels

The system performs the following main functions:

- Generating the signal—the source, a solid-state laser, must provide stable light within a specific, narrow bandwidth that carries the digital data, modulated as an analog signal.

- Combining the signals—Modern DWDM systems employ multiplexers to combine the signals. There is some inherent loss associated with multiplexing and de-multiplexing. This loss is dependent upon the number of channels but can be mitigated with optical amplifiers, which boost all the wavelengths at once without electrical conversion.

- Transmitting the signals—the effects of crosstalk and optical signal degradation or loss must be reckoned with in fiber optic transmission. These effects can be minimized by controlling variables such as channel spacing's, wavelength tolerance, and laser power levels. Over a transmission link, the signal may need to be optically amplified.

- Separating the received signals—at the receiving end, the multiplexed signals must be separated out. Although this task would appear to be simply the opposite of combining the signals, it is actually more technically difficult.

- Receiving the signals—the de-multiplexed signal is received by a photo-detector

In addition to these functions, a DWDM system must also be equipped with client-side interfaces to receive the input signal. This function is performed by transponders On the DWDM side are interfaces to the optical fiber that links DWDM systems.

Optical networking, unlike SONET/SDH, does not rely on electrical data processing. As such, its development is more closely tied to optics than to electronics. In its early form, as described previously, WDM was capable of carrying signals over two widely spaced wavelengths, and for a relatively short distance. To move beyond this initial state, WDM needed both improvements in existing technologies and invention of new technologies. Improvements in optical filters and narrowband lasers enabled DWDM to combine more than two signal wavelengths on a fiber. The invention of the flat-gain optical amplifier, coupled in line with the transmitting fiber to boost the optical signal, dramatically increased the viability of DWDM systems by greatly extending the transmission distance. Other technologies that have been important in the development of DWDM include improved optical fiber with lower loss and better optical transmission characteristics, EDFAs, and devices such as fiber Bragg gratings used in optical add/drop multiplexers.

Components and Operation

DWDM is a core technology in an optical transport network. The essential components of DWDM can be classified by their place in the system as follows:

• On the transmit side, lasers with precise, stable wavelengths

• On the link, optical fiber that exhibits low loss and transmission performance in the relevant wavelength spectra, in addition to flat-gain optical amplifiers to boost the signal on longer spans

• On the receive side, photo-detectors and optical de-multiplexers using thin film filters or diffractive elements and Optical add/drop multiplexers and optical cross-connect components.

3.5 Quality of Service :

Q-Factor of a light-path is defined as the ratio of output power relative to input power. It is normalized by dividing the value of Q-Factor with maximum value of Q-Factor possible. It is expressed in percentage. So 100% Q-Factor means light-path has the highest Q-Factor and the light-path corresponding to this value of Q-Factor will be the best light-path.

To maximize the Q-Factor we need to maximize the output power for constant value of input power. We know that output power received is the attenuated version of input power due to attenuation loss, splice loss and connector loss. So we should try to minimize the losses in the optical fiber communication.

Losses can be reduced by selecting the best components like connectors, splices and optical fiber which are having minimum power loss values. Out of all possible light-paths, the light-path having minimum power loss should be selected as optimal light-path. Q-Factor has benefits like it allows simplified analysis of system performance and reflects the quality of the system without using difficult algorithm.

It gives the cost in terms of power loss. Higher is the value of Q-Factor, better is the light-path of optical communication. It requires less time than other performance analysis method.

Chapter 4

Network Model & Problem Formulation

4.1 Network Model

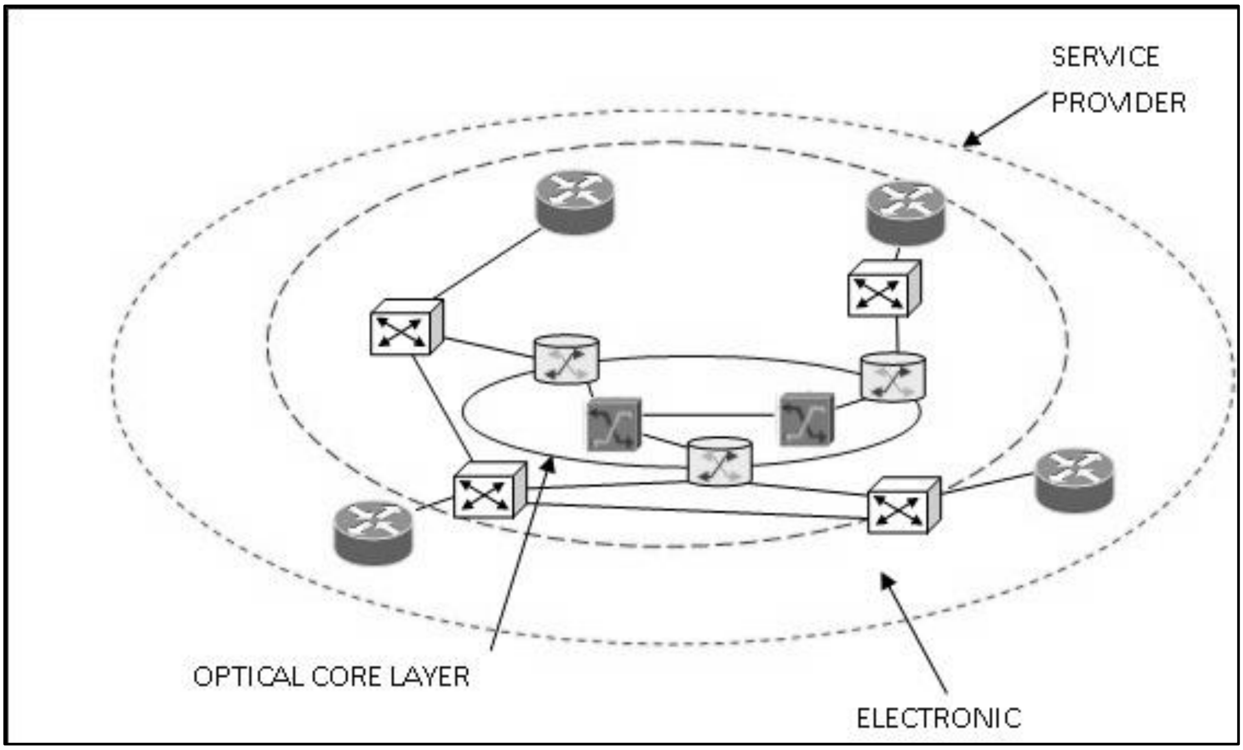

Figure 7 : Physical Topology

The model shown in Figure 7 shows the physical topology of the network, consisting of three layers, the Service provider layer shown as the outermost layer, the Optical core layer which is the innermost Optical network layer, and the Electronic intermediate layer or also known as IP layer. This is an abstraction of the combined electro-optical network which allows us to focus on that portion of the network where our innovation applies, i.e. the combined electro-optical network.

The optical layer provides point-to-point connectivity between routers in the form of fixed bandwidth circuits, which is termed as light-paths. The collection of light-paths therefore defines the topology of the virtual network interconnecting electronics/IP Routers.

In IP layer the IP routers are responsible for all the non-local management functions such as management of optical resources, configuration and capacity management, addressing, routing, topology discovery, traffic engineering, and restoration etc.

The IP router communicates with the TCM (Traffic Control Manager) of service provider network and provides the information about the status of the optical layer.

Ideally the service provider layer will include elements of the access network such as the PON (Passive Optical Network) related elements and other devices / equipment located at the premises / home. However for this invention such details are not necessary.

We assume that the service provider has access to General Purpose Routers and also optical components in the core optical network. Such an assumption is reasonable, given the fact that the prices of optical switching equipment have fallen by orders of magnitude till the point that they are being used in the premises of large corporations in order to interconnect buildings etc.

Thus it is reasonable to assume, as we have done, that the service provider has information about the GPRs and the optical equipment within its domain of control. The service provider layer controls all the traffic corresponding to both IP and optical layers. All the routers shown in the figure are controlled by the service provider (SP).

The SP maintains a traffic matrix in a Traffic Control Manager (TCM) for all the connected general purpose routers, i.e. all the Electronic Gateway Routers (EGR), Electronic Access Routers (EAR) and Optical Access Routers (OAR) within its domain of control. The Traffic Control Manager (TCM) maintains the network as well as PLI constraints such as Capacity, delay, and Q-Factor matrices for all the GPRs in the network, belonging to all the layers. In the following sections we outline our algorithms that carry out the computations necessary for the decisions that lead to provisioning/de-provisioning of data-paths.

Due to more number of possible paths, user can not select one path for data communication. To archive that information we consider quality factor is a factor to choose one best path among all possible paths.

In the following section I describe network topology and calculation of physical layer impairments like power loss, channel capacity and quality factor for WDM network, DWDM network and finally comparison of WDM and DWDM network parameters.

4.1.1 Network Topology :

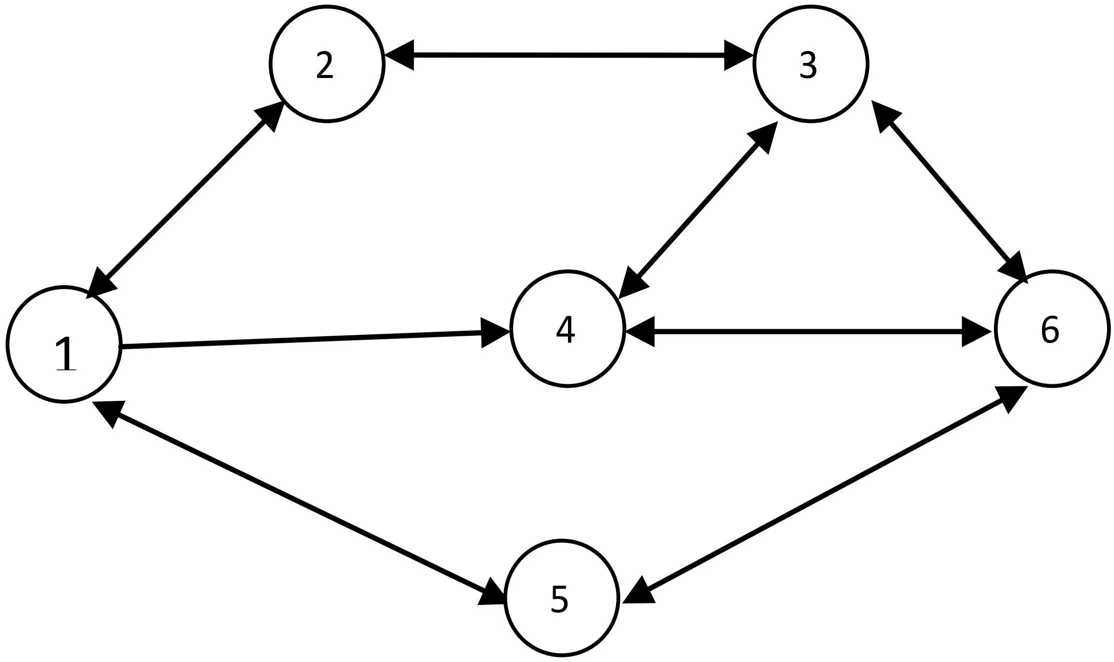

Figure 8 : Network Topology Graph

For our simulation work, we have used MATLAB. The Figure 8 shows the basic network topology with six nodes. Here we considered three pair of source and destination nodes (1, 6), (2, 5), and (1, 3). Here all nodes considers as routers.

There will be single wavelength or multiple wavelengths possible in between two routers. In my simulation I consider two cases one is WDM and another one is DWDM.

In case of WDM, we considered 8 wavelengths with center wavelength 1532nm and in case of DWDM I considered 64 channels with same center wavelength.

At final we compare both WDM and DWDM values in case of power loss, channel capacity and quality factor.

In the following section described about calculation of power loss, channel capacity and quality factor. From the values we are going to choose best path based on Data-path selection mechanism.

The next table shows the parameters used in calculation.

Table 1 Parameters Used in Simulation

Parameter	*Values*
Attenuation Constant(α)	0.15db
Chromatic dispersion (δ_{cd})	3000 ps
Wavelength of lights (λ)	1530 nm-1564 nm
Noise Figure(F)	0.4db

4.2 Problem Formulation

4.2.1 Power loss calculation

Power loss can be defined as the optical loss that is accumulated from source to destination along fiber links and is normally made up of intrinsic fiber losses and extrinsic bending losses [**1**].

Intrinsic fiber losses are due to attenuation, absorption, reflections, refractions, Rayleigh scattering, optical component insertion losses, etc. Let *Pin* be the power launched at the input of a fiber of length *L*; then the output power *Pout* is given by

$$P^{out} = P^{in} \cdot e^{-\alpha L} \tag{4.1}$$

Where α is the fiber attenuation coefficient. The loss introduced by the insertion of optical components, such as couplers, filters, multiplexers/ de multiplexers, and switches, into the optical communications system is called insertion loss and is usually independent of wavelength.

The extrinsic losses are due to micro and macro bending losses. Additional losses occur due to the combined effects of dispersion resulting from inter symbol interference (ISI), mode-partition noise, and laser chirp as discussed later in this section.

$$\text{Power loss} = P^{out} - P^{in} \tag{4.2}$$

4.2.2 Channel capacity Calculation

Suppose a flow for client *m* and *n with* data-path from source *s* to destination *d*. For every edge router, a free available capacity matrix has been considered, where *s* and *d* are the source and destination edge GPRs for a DP.

If *D (i, j)* is the dispersion of the fiber at the operating wavelength with unit's seconds per nano meter per kilometer, and *L (i, j)* is the length of fiber link pair *(i, j)* in kilometers, then the capacity matrix $C(m,n,s,d)$ can be explained [7] as follows:

$$C(i,j) = \frac{\delta}{D(i,j) \times \sqrt{L(i,j)}} \tag{4.3}$$

Here *C(i,j)* is light-path capacity .where, δ represents the pulse broadening factor should typically be less than 10% of a bit's time slot for which the polarization mode dispersion (PMD) can be tolerated [**27**]and *D (i, j)* = *L (i, j)* = ∞, when there is no link between i^{th} *and* j^{th} node. The capacity metrics $C(m,n,s,d)$ calculation is derived from a single link to a group of links in a Data-path (*P)*.

$$C(m,n,s,d) = \min(C(i,j)), \forall (i,j) \in p \tag{4.4}$$

4.2.3 Q-Factor Calculation

Assume a flow for client *m* and *n with* DP from source *s* to destination *d* has Q-Factor requirement *QFR* (*m, n, s, d*). Then the average Q-Factor $AQF(m,n,s,d)$ can be expressed as follows:

$$AQF(m,n,s,d) = \frac{\sum_{m=1}^{M_i} QFR(m,n,s,d)}{M} \tag{4.5}$$

Where, *M* is the total number of clients for sources *i* and destination *j*. M_i *is the* total possible light-paths between source and destination. The optical domain involves with variety of PLIs and their impact on the overall network performance. In order to get a possible DPs based on the link cost, we can consider either network layer QoS parameters such as bandwidth and delay or PLI constraints in terms of Q-Factors. Also we can consider both the cases. We consider the Q-Factor as the link cost corresponding to a light-path as mentioned in [**28**]. The Q-Factor (QF_i) for i^{th} link is given as below:

$$QF_i = \frac{\sum_{k=1}^{N_i} 10\log\left[Q_{i,k}^{s} / Q_{i,k}^{d}\right]}{N_k} \tag{4.6}$$

Where, N_k is the number of light-path at the i^{th} link, $Q_{i,k}^{s}$ and $Q_{i,k}^{d}$ are the quality factor measurements of the k^{th} light-path at the source (s) and destination (d) node of the i^{th} link respectively.

If $p(m,n,s,d)$ is the route between m ,n clients source(s) and destination(d) nodes containing l number of links, the overall Q-Factor $QF_{overall}(p(m,n,s,d))$ will be:

$$QF_{overall}(p(m,n,s,d)) = \sum_{i}^{l} QF_i \qquad 4.7)$$

Further according to [**29**],

$$\frac{Q_{i,k}^{s}}{Q_{i,k}^{d}} = \frac{1}{(\delta_{eye}(i,k)) \times (\delta_{noise}(i,k))} \tag{4.8}$$

Where, $\delta_{eye}(i,k)$, $\delta_{noise}(i,k)$ are the Eye penalty and Noise penalty at i^{th} and k^{th} link.

Then equation 4.6 becomes,

$$QF_i = \frac{\sum_{j=1}^{N_i} 10\log\left[1/(\delta_{eye}(i,k)) \times (\delta_{noise}(i,k))\right]}{N_i} \tag{4.9}$$

Due to amplifier spans, the channel lunch power can be relatively low without significant penalties due to noise accumulation. The eye related penalty is due to the effect of linear physical impairments such as polarization mode dispersion (PMD) and chromatic dispersion

(CD), while the noise related penalty is due to the effect of amplifier spontaneous emission (ASE) and crosstalk.

$$\delta_{noise}(i,k) = \frac{P^d}{p^s} \times \frac{1}{\sqrt{F}} \tag{4.10}$$

Where, P^d is the outputs signal power, P^s is the input signal power and F is the noise figure and $P^d = P^s e^{-\alpha L}$, α is the attenuation constant and L is the length of the DP.

$$\delta_{eye}(i,k) = \delta_{pmd}(i,k) \times \delta_{cd}(i,k) \tag{4.11}$$

$$\delta_{eye}(i,k) = 10.2 \times C^2(i,k) \times D_p^2(i,k) \times L(i,k) \times \delta_{cd}(i,k) \tag{4.12}$$

Where, $C(i,k)$ is the capacity, $D_p(i,k)$ is the PMD parameter and $L(i,k)$ is the transmission length.

4.3 Data-path Selection Mechanism

Depending on bandwidth and PLI model explained in previous section, we have considered three different scenarios for data-path selection mechanism as follows.

4.3.1 Data-path selection based on power loss

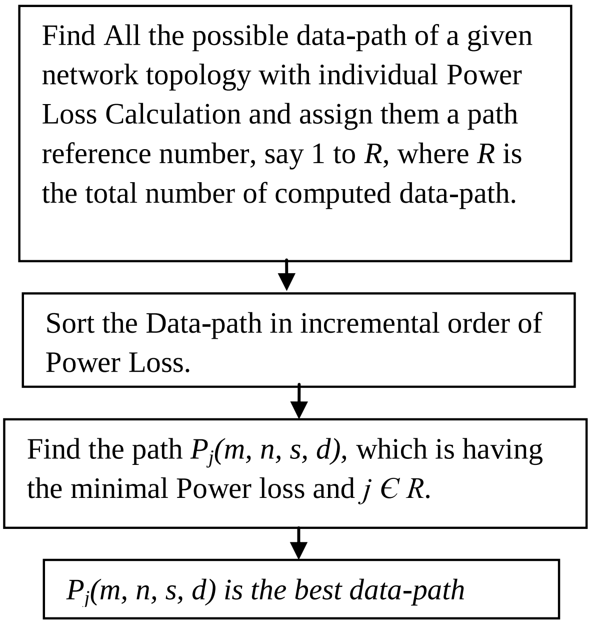

Figure 9 : Flowchart for Data-path Selection based on Power Loss

For this case we analyze the power loss for all possible paths existing in between source and destination. The data-path among the all possible paths, which is having the minimal power loss, will be selected as the best data-path.

4.3.2 Data-path selection based on Channel capacity

The capacity matrix will be analyzed using equation 1, for all possible data-paths, among all which has the highest channel capacity that can be chosen as the best path.

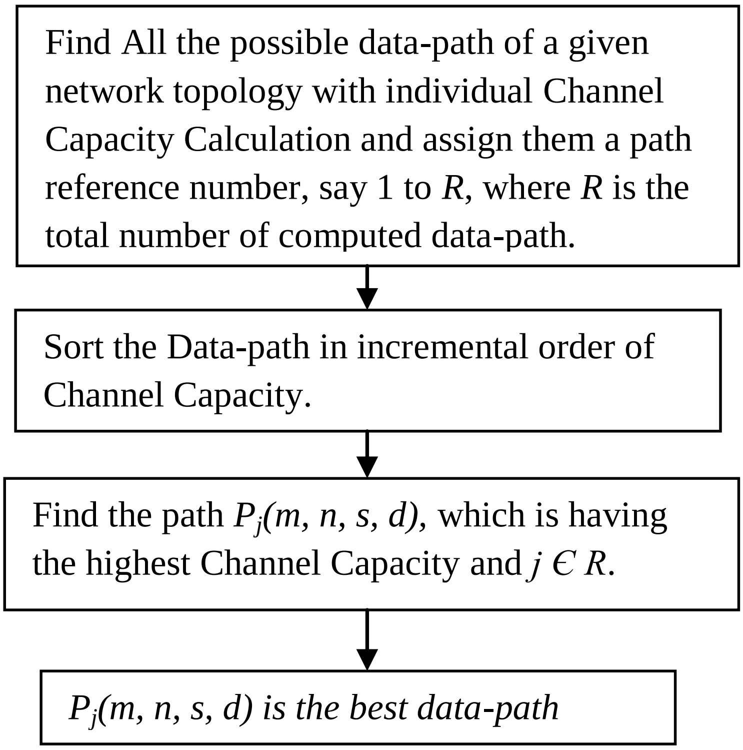

Figure 10 : Flowchart for Data-path Selection based on Channel Capacity

4.3.3 Data-path selection based on Q-Factor

This method is the combination of both the above scenarios. For this case we analyze Q-Factor for all possible data-paths with a path reference number.

Again all the data-paths are sorted in an incremental order with a new path reference number, then based on the client Q- Factor requirement one of the data-path will be selected as the best one. We expressed the above mathematically as follows.

$$AQF\left(m,n,s,d\right) \leq QF_{overall}\left(p_j\left(m,n,s,d\right)\right) \tag{4.13}$$

Where, j is the new data-path reference number and $j = 1, 2, \ldots, J$. The new path reference number will be based on the incremental order of the data-path overall Q-Factor.

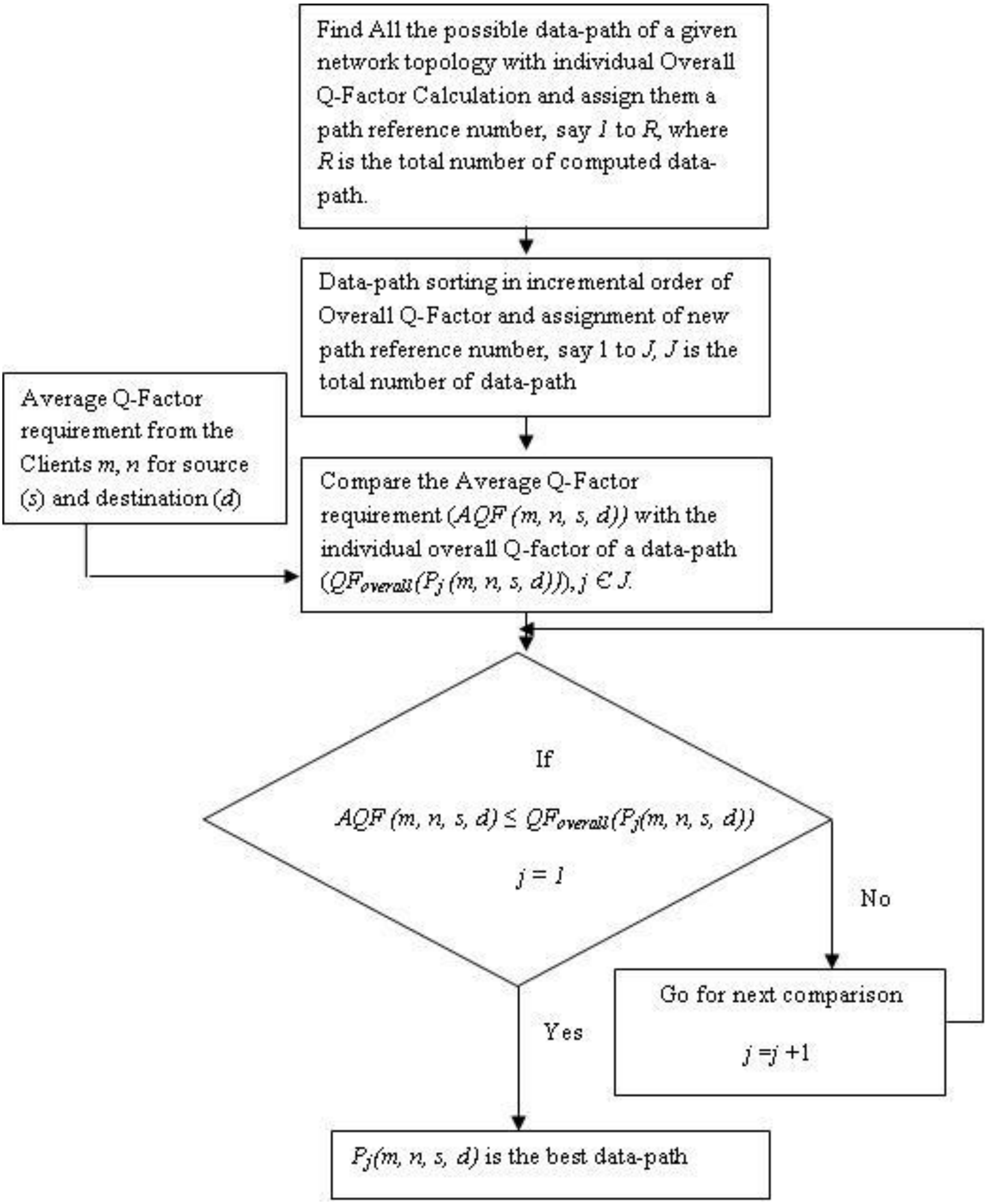

Figure 11 : Flowchart for Data-path Selection based on Q-Factor

Chapter 5

Simulation Results

5.1 Simulation of PLI Based WDM network

5.1.1 Power loss calculation

For all calculation we considered the network shown in Figure 8, for that we consider three source and destination pairs ((1, 6), (2, 5), and (1, 3)).

Table 2 Power loss calculation

SN	DN	Path	PL(db)	Ref. No	BP
1	6	1-2-3-6	96.31	1	3
		1-4-3-6	94.22	2	
		1-4-6	92.19	3	
		1-5-6	97.64	4	
2	5	2-3-6-5	98.71	1	2
		2-1-5	93.28	2	
		2-1-4-6-5	99.4	3	
		2-3-4-6-5	99.5	4	
1	3	1-2-3	89.47	1	2
		1-4-3	83.47	2	
		1-5-6-3	99.17	3	
		1-4-6-3	97.26	4	

SN: Source Node, DN: Destination Node, PL: Power Loss, BP: Best path

In Figure 12, it shows the power loss for all the possible paths for a given source-destination pair, which are referred as path reference number. We have taken three different source-destination pairs such as (1, 6), (2, 5), and (1, 3). The path reference number starts from 1, 2, 3, and 4 etc has been assigned to all possible paths. From the plot, it has shown that, the minimum power loss path's are (1-4-6), (2-1-5), and (1-4-3) for (1, 6), (2, 5), and (1, 3) source-destination pair respectively.

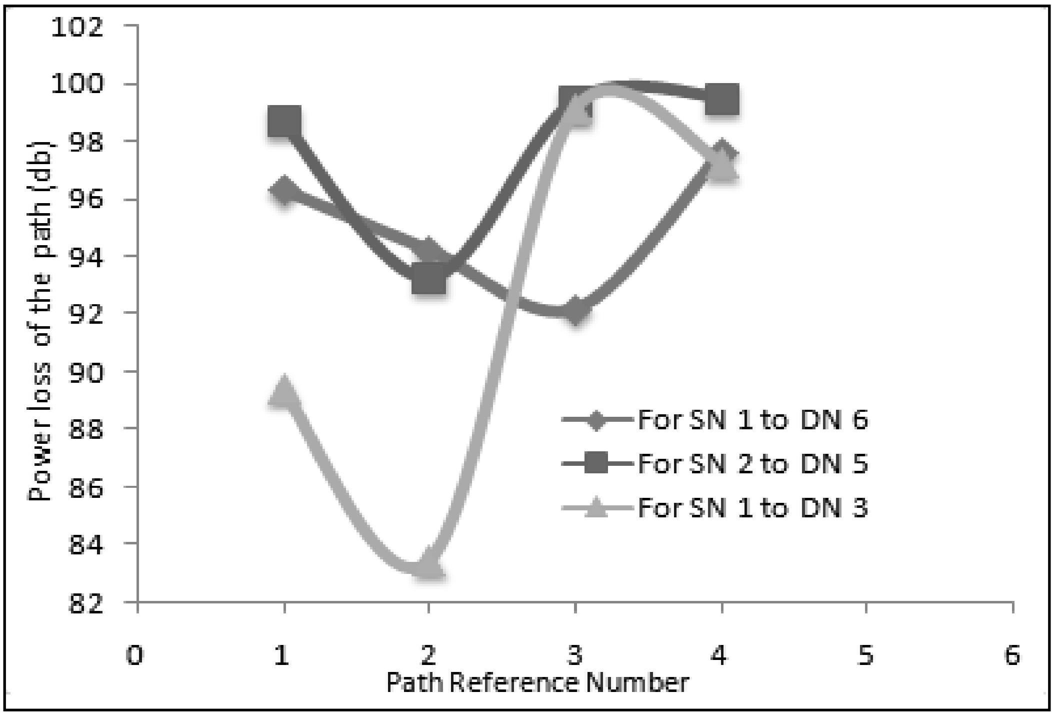

Figure 12 : Power loss calculations

5.1.2 Channel capacity calculation

For channel capacity calculation we used the network topology with three source and destination pairs shown in Figure 8.

We calculated by using equation 4.3 .Here dispersion values are taken from relation between dispersion with distance. The relation between dispersion and distance state that dispersion is proportional with distance. Here pulse broadening factors we taken as 0.187 for single mode fiber. In case of WDM we consider single mode fiber for transmission medium.

Here channel capacity is calculated for all possible paths existing between source and destination pairs. Among all paths the best path is chosen by following Data-path selection schemes described above. The following table shows the calculation of channel capacity for all possible paths existing between source and destination pairs as described above.

Table 3 Capacity Calculation

SN	DN	Path	Capacity (/ps*10^{-3})	Ref. No	BP
1	6	1-2-3-6	0.39	1	2
		1-4-3-6	0.52	2	
		1-4-6	0.41	3	
		1-5-6	0.3	4	
2	5	2-3-6-5	0.25	1	2
		2-1-5	0.6	2	
		2-1-4-6-5	0.2	3	
		2-3-4-6-5	0.22	4	
1	3	1-2-3	0.9	1	2
		1-4-3	3.3	2	
		1-5-6-3	0.21	3	
		1-4-6-3	0.32	4	

SN: Source Node, DN: Destination Node, BP: Best path

In Figure 13, it shows the channel capacities for all the possible data-paths for the same source-destination pair as mentioned above. The plot says, the corresponding best possible paths are (1-4-3-6), (2-1-5), and (1-4-3) respectively for the given source-destination pair.

All the above calculations like power loss and channel capacity are calculated for single mode fiber WDM network. By following Data-path selection mechanism best path will be chosen based on power loss and channel capacity. In case of power loss we will choose best path which has less power loss and in case of channel capacity we will choose best path which has high channel capacity. If channel capacity is very high, then bandwidth also will be high. If maximum bandwidth is available then large number of data will be transmitted.

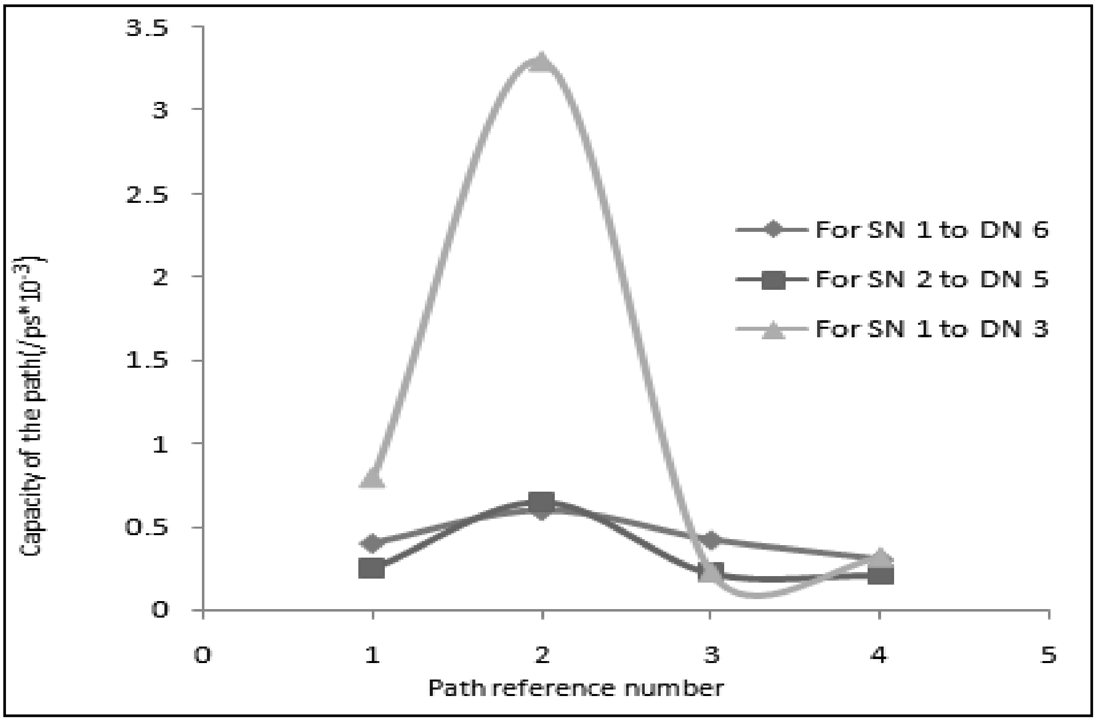

Figure 13 : Channel Capacity

5.1.3 Q-Factor Calculation:

For Q-Factor calculation we used the network topology with three source and destination pairs shown in figure 8.

We calculated by using equation 4.4 to 4.10. .Here dispersion values are taken from relation between dispersion with distance. The relation between dispersion and distance state that dispersion is proportional with distance. Here pulse broadening factor I taken as 0.187 for single mode fiber. In case of WDM we consider single mode fiber for transmission medium.

Here Q-Factor is calculated for all possible paths existing between source and destination pairs. Among all paths the best path is chosen by following Data-path selection schemes described above. The following table shows the calculation of Q-Factor for all possible paths existing between source and destination pairs as described above.

Table 4 Q-Factor calculations

SN	DN	PP	Path Ref. No	$QF_{overall}$	BP
1	6	1-2-3-6	1	10.47	4
		1-4-3-6	2	7.88	
		1-4-6	3	6.09	
		1-5-6	4	12.98	
2	5	2-3-6-5	1	16.23	3
		2-1-5	2	6.99	
		2-1-4-6-5	3	20.18	
		2-3-4-6-5	4	12.98	
1	3	1-2-3	1	4.25	3
		1-4-3	2	1.32	
		1-5-6-3	3	18.61	
		1-4-6-3	4	12.15	

PP: Possible Path; BP: Best Path; SN: Source Node; DN: Destination Node

For Q-Factor based Data-path selection has two types one is based on all possible paths Q-Factors and other one is based on client requirement. First case stated above. The figure 4.8 shows the Q-Factor based Data-path selection. In that case we consider all possible paths Q-Factor calculation and then choose maximum Q-Factor as best path. In case of client required Q-Factor we consider a default value as client requirement and compare it with all possible paths Q-Factors. By checking all possible path Q-Factors will choose nearest Q-Factor as best Data-path for communication.

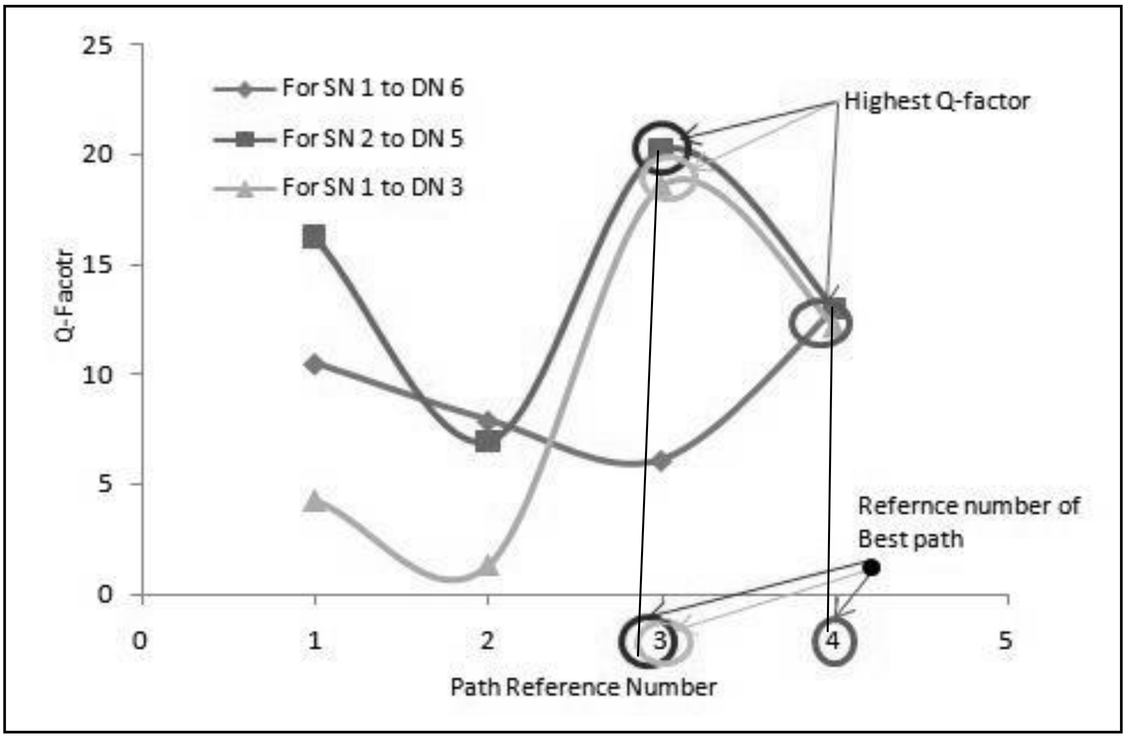

Figure 14 : Q-Factor calculation

Figure 14 shows the plot of Q-Factor with respect to path reference number for all possible paths and source and destination pairs. Corresponding to the highest Q-Factor values, the best path for (1, 6), (2, 5), and (1, 3) are (1-5-6), (2-1-4-6-5), and (1-5-6-3) respectively.

We had taken the average Q-Factor of 11 as the client requirement for all the source-destination pair and the corresponding best path (BP) is shown in the table. According to the table 4.5, Fig. 15 shows the plot of Q-Factor vs. the BPPRN i.e., the assigned new path reference number.

Here new path reference number taken by arranging the all Q-Factors in increment order for all possible Data-paths between source and destination nodes. From this plot, the best data-path can be selected for a source-destination pair of a client based on their required Q-Factor i.e., average Q-Factor.

For example, if a client has average Q-Factor requirement (AQF) of 11 for the source destination pair (1, 6), then in accordance with the proposed algorithm, $QF_{overall}$ >= AQF, i.e., 12.5 >= 11, which is approaching the new path reference number 4, which will be the best path.

Table 5 Q-Factor with client requirement

SN	DN	PP	Path Ref. No	$QF_{overall}$	BPP RN	AQF	BP
1	6	1-2-3-6	1	10.47	3	11	4
		1-4-3-6	2	7.88	2		
		1-4-6	3	6.09	1		
		1-5-6	4	12.98	4		
2	5	2-3-6-5	1	16.23	3	11	2
		2-1-5	2	6.99	1		
		2-1-4-6-5	3	20.18	4		
		2-3-4-6-5	4	12.98	2		
1	3	1-2-3	1	4.25	2	11	3
		1-4-3	2	1.32	1		
		1-5-6-3	3	18.61	4		
		1-4-6-3	4	12.15	3		

BPPRN: Best possible path reference number according to highest overall Q-Factor ($QF_{overall}$) ; AQF: Average Q-Factor required from Clients);

Here the above table shows the Q-Factor values for all individual Data-paths existing in between source and destination pairs. Here we consider 11 as the client required Q-Factor. We can calculate Q-Factor for cent percent also.

For that case we consider maximum Q-Factor as cent percent remaining cases are taken the ratio for cent percent. For example in case of 1 to 3 source and destination pair maximum Q-Factor is 18.61 so we called that path has 100% Q-Factor. Remaining results are normalized.

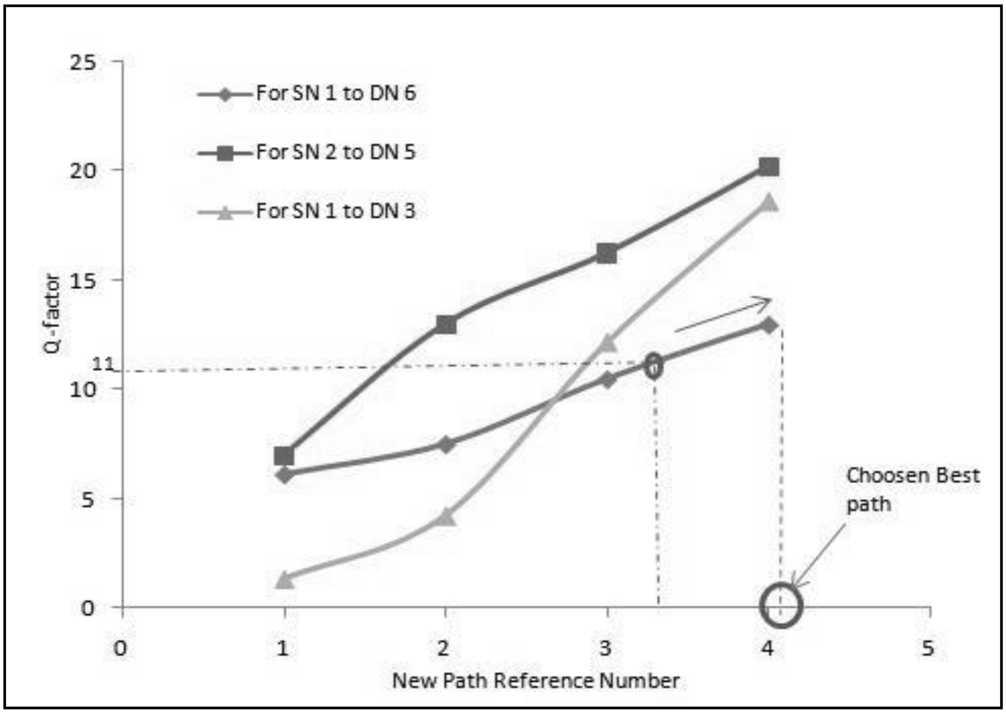

Figure 15 : Q-Factor calculation with respect to client requirement

Figure 15, shows the Q-Factor for best possible data-path reference number to Q-Factor. From this plot, based on Q-Factor value and clients Q-profile requirement, the best possible data-path can be selected. For example, the below table shows the various values for two source destination pairs 1,6 whose Q-Factor requirement is 11 , then in accordance with our algorithm,

$AQF\ (m, n, s, d) \leq QF_{overall}\ (P_j(m, n, s, d))$, i.e., a client has average Q-Factor requirement (AQF) of 11 for the source destination pair (1, 6), then in accordance with the proposed algorithm, $QF_{overall}$ >= AQF, i.e., 12.5 >= 11, which is approaching the new path reference number 4, which will be the best path. So the above figure shows path 4 is the best path for (1,6) source and destination pairs.

5.2 Simulation of PLI Based DWDM network

Here in case of DWDM we consider multiple wavelengths in multi mode fiber for DWDM transmission. The power loss is same as WDM because it does not depends on wavelengths. It depends on distance only.

5.2.1 Power loss calculation:

For all calculation we considered the network shown in Figure 8, for that we consider three source and destination pairs ((1, 6), (2, 5), and (1, 3)).

Table 6 : Power loss calculation for DWDM

SN	DN	Path	PL(db)	Ref. No	BP
1	6	1-2-3-6	96.31	1	3
		1-4-3-6	94.22	2	
		1-4-6	92.19	3	
		1-5-6	97.64	4	
2	5	2-3-6-5	98.71	1	2
		2-1-5	93.28	2	
		2-1-4-6-5	99.4	3	
		2-3-4-6-5	99.5	4	
1	3	1-2-3	89.47	1	2
		1-4-3	83.47	2	
		1-5-6-3	99.17	3	
		1-4-6-3	97.26	4	

In Figure 4.6, it shows the power loss for all the possible paths for a given source-destination pair, which are referred as path reference number. We have taken three different source-destination pairs such as (1, 6), (2, 5), and (1, 3).

The path reference number starts from 1, 2, 3, and 4 etc has been assigned to all possible paths. From the plot, it has shown that, the minimum power loss path's are (1-4-6), (2-1-5), and (1-4-3) for (1, 6), (2, 5), and (1, 3) source-destination pair respectively.

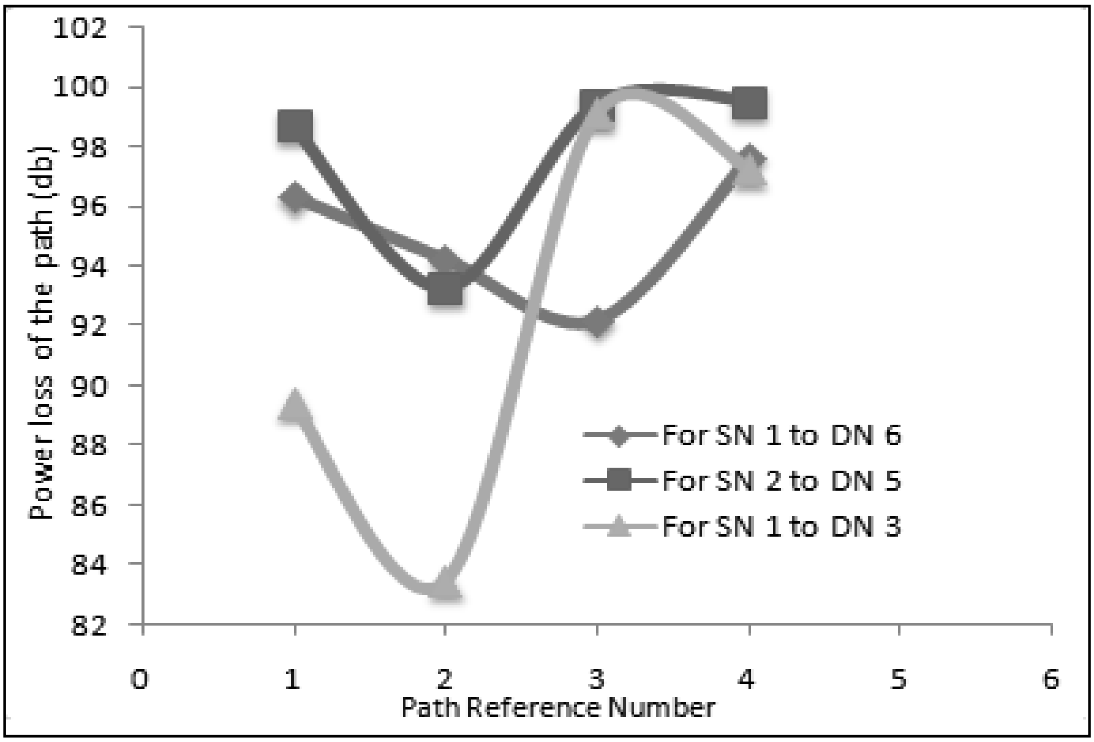

Figure 16 : Power loss calculations for DWDM

5.2.2 Channel capacity calculation

For channel capacity calculation we used the network topology with three source and destination pairs shown in figure 8.

We calculated by using equation 4.3 .Here dispersion values are taken from relation between dispersion with distance. The relation between dispersion and distance state that dispersion is proportional with distance. Here pulse broadening factors we taken as 0.187 for single mode fiber. In case of DWDM we consider multi mode fiber for transmission medium.

Here channel capacity is calculated for all possible paths existing between source and destination pairs. Among all paths the best path is chosen by following Data-path selection schemes described above.

The following table shows the calculation of channel capacity for all possible paths existing between source and destination pairs as described above.

Table 7 : Channel capacity calculation for DWDM

SN	DN	Path	Capacity (/ps*10^{-3})	Ref. No	BP
1	6	1-2-3-6	29.1263	1	1
		1-4-3-6	28.6069	2	
		1-4-6	15.57	3	
		1-5-6	5.876	4	
2	5	2-3-6-5	18.58	1	3
		2-1-5	16.42	2	
		2-1-4-6-5	32.0122	3	
		2-3-4-6-5	30.4879	4	
1	3	1-2-3	20.8804	1	4
		1-4-3	20.369	2	
		1-5-6-3	14.1219	3	
		1-4-6-3	23.82	4	

In Figure 17, it shows the channel capacities for all the possible data-paths for the same source-destination pair as mentioned above. The plot says, the corresponding best possible paths are (1-4-3-6), (2-1-5), and (1-4-3) respectively for the given source-destination pair.

All the above calculations like power loss and channel capacity are calculated for multi mode fiber DWDM network. By following Data-path selection mechanism best path will be chosen based on power loss and channel capacity.

In case of power loss we will choose best path which has less power loss and in case of channel capacity we will choose best path which has high channel capacity.

If channel capacity is very high, then bandwidth will be high. If maximum bandwidth is available then large number of data will be transmitted.

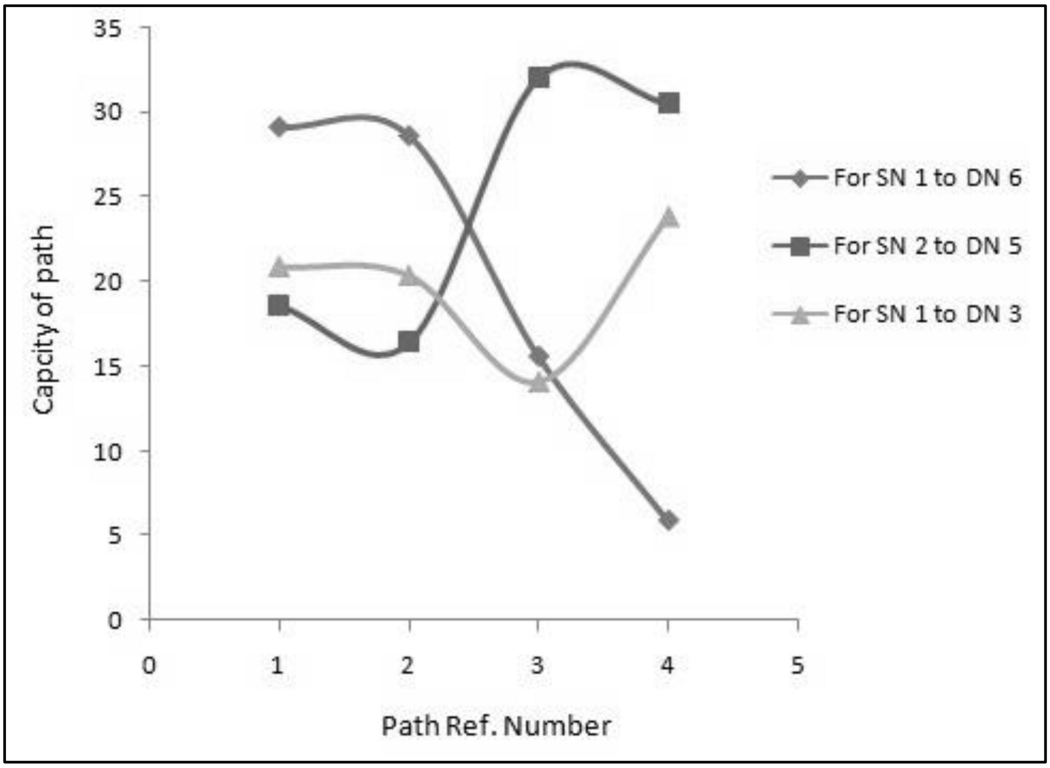

Figure 17 : Channel Capacity for DWDM

5.2.3 Q-Factor Calculation:

For Q-Factor calculation we used the network topology with three source and destination pairs shown in figure 8. We calculated by using equation 4.4 to 4.10. .Here dispersion values are taken from relation between dispersion with distance.

The relation between dispersion and distance state that dispersion is proportional with distance. Here pulse broadening factor w taken as 0.187 for single mode fiber. In case of DWDM we consider multi mode fiber for transmission medium.

Here Q-Factor is calculated for all possible paths existing between source and destination pairs. Among all paths the best path is chosen by following Data-path selection schemes described above. The following table shows the calculation of Q-

Factor for all possible paths existing between source and destination pairs as described above.

Table 8 : Q-Factor calculation for DWDM

SN	DN	PP	Path Ref. No	$QF_{overall}$	BP
1	6	1-2-3-6	1	87.07	1
		1-4-3-6	2	85.99	
		1-4-6	3	86.05	
		1-5-6	4	72.56	
2	5	2-3-6-5	1	79.8	4
		2-1-5	2	81.59	
		2-1-4-6-5	3	82.72	
		2-3-4-6-5	4	86.86	
1	3	1-2-3	1	82.64	4
		1-4-3	2	74.98	
		1-5-6-3	3	76.28	
		1-4-6-3	4	83.7	

PP: Possible Path; BP: Best path; SN: Source Node; DN: Destination Node

For Q-Factor based Data-path selection has two types one is based on all possible paths Q-Factors and other one is based on client requirement. First case stated above. The figure 18 shows the Q-Factor based Data-path selection. In that case we consider all possible paths Q-Factor calculation and then choose maximum Q-Factor as best path.

In case of client required Q-Factor we consider a default value as client requirement and compare it with all possible paths Q-Factors. By checking all possible path Q-Factors will choose nearest Q-Factor as best Data-path for communication.

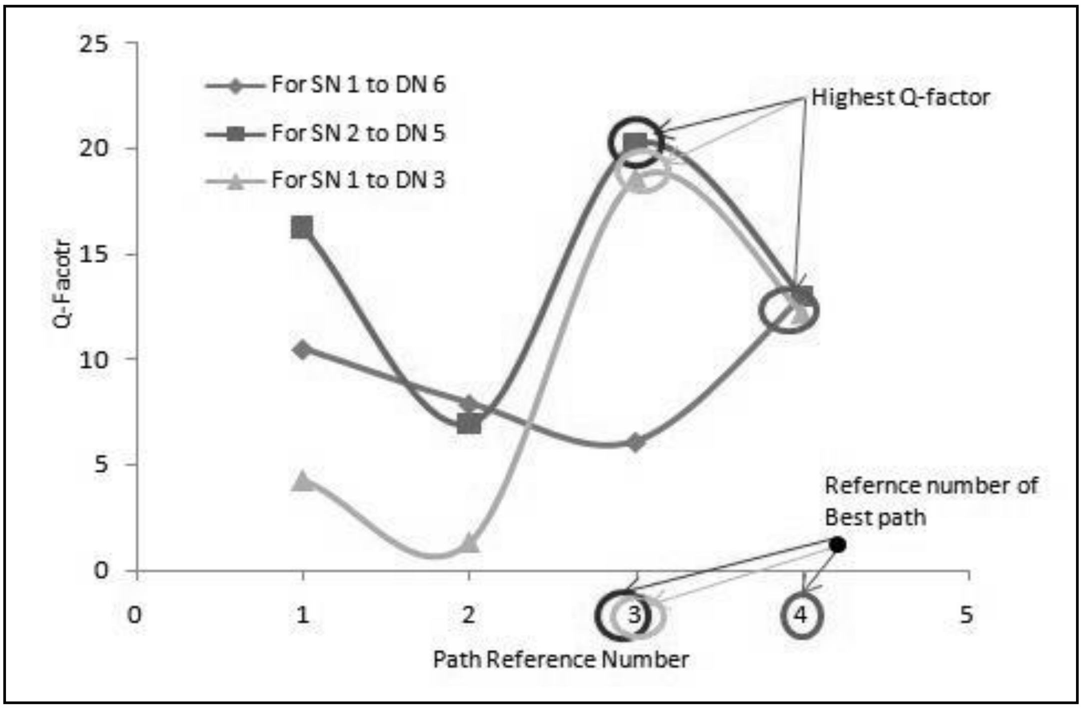

Figure 18 : Q-Factor calculation

Figure 18 shows the plot of Q-Factor with respect to path reference number for all possible paths and source and destination pairs. Corresponding to the highest Q-Factor values, the best path for (1, 6), (2, 5), and (1, 3) are (1-2-3-6), (2-3-4-6-5), and (1-4-6-3) respectively.

We had taken the average Q-Factor of 11 as the client requirement for all the source-destination pair and the corresponding best path (BP) is shown in the table. According to the table 9, Fig. 19 shows the plot of Q-Factor vs. the BPPRN i.e., the assigned new path reference number.

Here new path reference number taken by arranging the all Q-Factors in increment order for all possible Data-paths between source and destination nodes and assigned new path reference numbers to each Data-path.

After getting new path reference numbers plotted the graph between Q-Factor and new path ref number. From this plot, the best data-path can be selected for a source-destination pair of a client based on their required Q-Factor i.e., average Q-Factor.

For example, if a client has average Q-Factor requirement (AQF) of 82 for the source destination pair (1, 6), then in accordance with the proposed algorithm, $QF_{overall}$ >= AQF, i.e., 85.99 >= 82, which is approaching the new path reference number 2, which will be the best path.

Table 9 Q-Factor with client requirement

SN	DN	PP	Path Ref. No	$QF_{overall}$	BPP RN	AQF	BP
1	6	1-2-3-6	1	87.07	4	82	2
		1-4-3-6	2	85.99	2		
		1-4-6	3	86.05	3		
		1-5-6	4	72.56	1		
2	5	2-3-6-5	1	79.8	1	82	3
		2-1-5	2	81.59	2		
		2-1-4-6-5	3	82.72	3		
		2-3-4-6-5	4	86.86	4		
1	3	1-2-3	1	82.64	3	82	3
		1-4-3	2	74.98	1		
		1-5-6-3	3	76.28	2		
		1-4-6-3	4	83.7	4		

Here the above table shows the Q-Factor values for all individual Data-paths existing in between source and destination pairs. Here we consider 82 as the client required Q-Factor. We can calculate Q-Factor for cent percent also.

For that case we consider maximum Q-Factor as cent percent remaining cases are taken the ratio for cent percent. For example in case of 1 to 3 source destination pair maximum Q-Factor is 83.7 so we called that path has 100% Q-Factor. Remaining are taken with the ratio with respect to 83.7 Q-Factor.

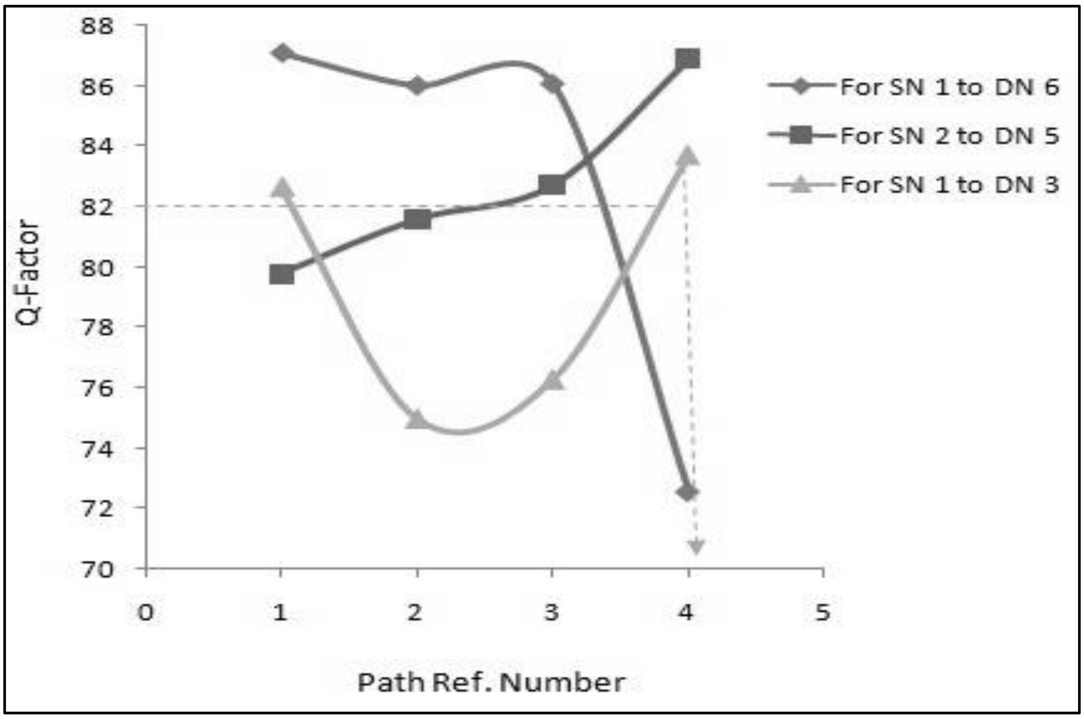

Figure 19 : Q-Factor calculation with respect to client requirement for DWDM

Figure 19, shows the Q-Factor for best possible data-path reference number to Q-Factor. $AQF\ (m,\ n,\ s,\ d) \leq QF_{overall}\ (P_j(m,\ n,\ s,\ d))$, i.e., a client has average Q-Factor requirement (AQF) of 82 for the source destination pair (1, 3), then in accordance with the proposed algorithm, $QF_{overall}$ >= AQF, i.e., 82.64 >= 82, which is approaching the new path reference number 1, which will be the best path.

5.3 Comparison of PLI based WDM/DWDM Network.

5.3.1 Power loss

Due to the individuality of wavelength power loss wont varied.

5.3.2 Channel capacity

Channel capacity is rapidly change for DWDM with multi mode fiber compare with single mode WDM network. Due to the use of multiple wavelengths the capacity of the path will increase because the dispersion values depend on wavelengths of the channel.

Table 10 comparison of Channel capacity for single wavelength and multi wavelength

SN	DN	Path	Capacity For single λ	Capacity For multiple λ
1	6	1-2-3-6	0.39	29.1263
		1-4-3-6	0.52	28.6069
		1-4-6	0.41	15.57
		1-5-6	0.3	5.876
2	5	2-3-6-5	0.25	18.58
		2-1-5	0.6	16.42
		2-1-4-6-5	0.2	32.0122
		2-3-4-6-5	0.22	30.4879
1	3	1-2-3	0.9	20.8804
		1-4-3	3.3	20.369
		1-5-6-3	0.21	14.1219
		1-4-6-3	0.32	23.82

The following figure shows graphical representation of comparison for source node 2 to destination node 5 pair.

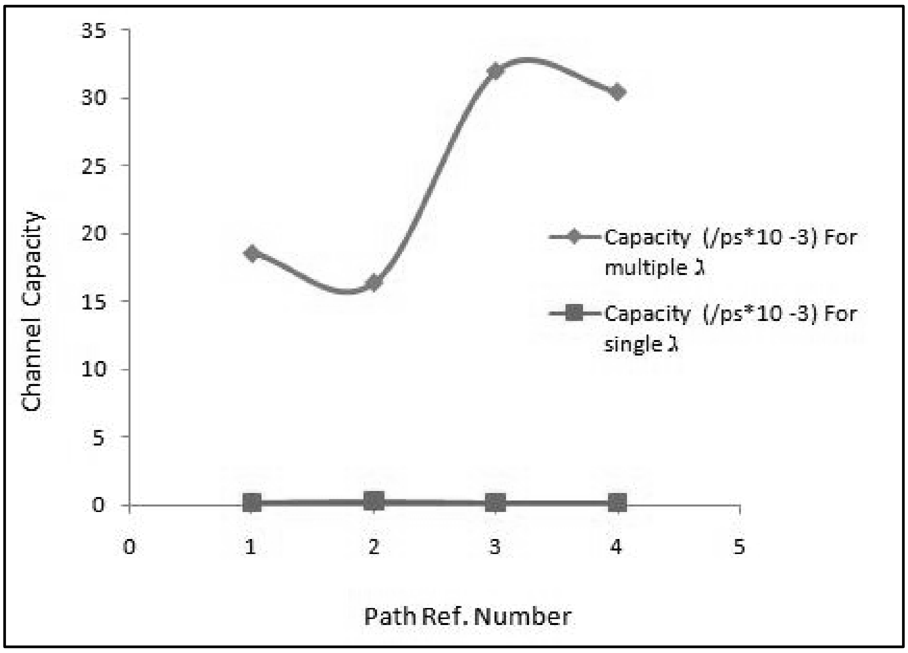

Figure 20: Comparison of Channel capacity for single and multiple wavelengths

5.3.3 Quality Factor

Quality factor also changed for single wavelength and multiple wavelengths due to the increase of channel capacity because quality factor is related to channel capacity.
Table 11 comparison of Q-Factor for single λ and multiple λ

SN	DN	Path	Q-F actor for Multiple λ	Q-F actor for Single wavelength
1	6	1-2-3-6	87.07	22.95
		1-4-3-6	85.99	24.9
		1-4-6	86.05	26.2
		1-5-6	72.56	20.99

Here for Q-Factor case we consider only one source and destination pair if we compare remaining pairs also we will get same type of results.

So in this case we consider only (1,6) source and destination pair. The following figure shows the graphical representation.

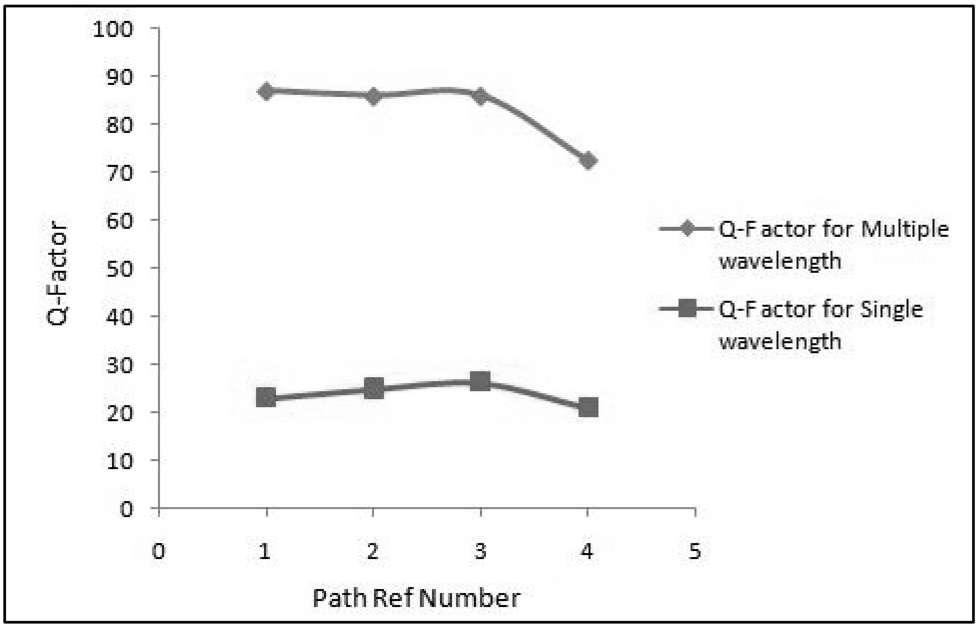

Figure 21: Comparison of Q-Factor

Chapter 6

Conclusion &

Scope of Future work

6.1 Conclusion

In our simulation, we have considered three scenarios based on power loss, channel capacity and Q-Factor for a given source-destination pair. Our proposed algorithm helps to analyze those constraints and determines the best possible data-path in between source-destination pair. The result shows the variations of power losses, channel capacity and quality factor for all possible data-paths for the clients. Among those three scenarios, we more focus on data-path selection based on Q-Factor, which is very effective due to the combination of other two scenarios data-path selection based on power loss and channel capacity. The Q-Factor is calculated in percentage, which is to be notified to the client through the traffic control manager. The Q-Factor requirement from the client again will be in the range of 1 to 100 %. Finally the best data-path has been selected based on Q-Factor requirements of the client in percentage. The reason, we provide the Q-Factor of all possible paths is to have an option for any client to choose the best suitable path based on their requirements only. It helps to utilize the resources among the clients in an efficient way.

6.2 Scope of Future work

Our proposed work is an centralized algorithm so we can give an user interface through .net or java to the user to choose best path with respect to their requirements.

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