Impact of In-band Crosstalk & Crosstalk Aware Datapath Selection in WDM/DWDM Networks

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Abstract— **In this paper, the impact of in-band crosstalk on transmission performance of a transparent WDM/DWDM network incorporating optical add drop multiplexer & space switches is studied. Error probabilities and power penalties produced by crosstalk are investigated. A traditional RWA scheme pays a little regard to the physical layer impairments and cannot provide optimized network performance in practical networks. Here we proposed a novel RWA algorithm considering BER constraints due to non-ideal wavelength de-multiplexing and space switching at each node of an optical WDM/DWDM network.**

Keyword- Bit error rate, In-band crosstalk, routing and wavelength assignment (RWA), OADM/OXC, power penalty (pp), WDM/DWDM.

I. INTRODUCTION

Transparent WDM/DWDM networks have been proposed as promising solution to satisfy our dramatically increasing network throughput demands. In today's transport optical network electronic switches requiring OEO conversion have become complex and costly. Hence we move towards all optical transparent networks where no electrical conversion is used. Deploying such a network utilizing all-optical switches is promising but yet also challenging as many problems has to be anticipated. One of the difficulties is how to assign light paths (LPs) to a call request such that the impacts of physical layer impairments are minimum [9, 10, 11]. Component crosstalk is one of the major physical layer impairment that arises due to non-ideal nature of optical add-drop multiplexer & cross switches used in modern optical networks. Linear crosstalk in optical components can be classified as in-band or inter-band crosstalk [7] depending on whether it has the same nominal wavelength as the desired signal or not.

The effect of inter band crosstalk can be reduced by concatenating narrow-bandwidth optical filters. In-band crosstalk however cannot be removed as the signal and the crosstalk operates at same wavelength. The deteriorating effect of in-band crosstalk is further intensified in cascaded optical node due to its accumulative behavior [1, 2, 7]. These interferences limits system performance as network expands and wavelength density increases. In-band crosstalk causes the quality of optical signal to degrade and become so poor that its BER is unacceptably high. Conventional studies on routing and wavelength assignment has proposed many algorithms for establishing LPs without considering any physical layer impairments [15]. In last few years, RWA techniques that consider quality of transmission (QoT), as measured by BER, have been the subject of intense research [3, 10, 12]. Here we proposed a QoT guaranteed algorithm that perform conventional RWA and allow the selected LPs to be established if the BER requirement is met.

BER at the receiver is evaluated by calculating the noise in the photodetector output due to crosstalk and the noise of the detector itself. In many cases the probability density function of the overall noise is assumed to be Gaussian due to its simplicity. However, the Gaussian model, despite of its simplicity, cannot accurately describe the signal crosstalk noise, especially when the no of interfering channels is not very large. Though central limit theorem is a good reason to use Gaussian approximation for reasonable large number of crosstalk [1, 2], but for a small size mesh or ring network where no of crosstalk element are small this approximation gives inaccurate results. Therefore several non-Gaussian models are developed for better estimate of system performance. The pdf of non-Gaussian models developed for finite interference uses different techniques, such as saddle point approximation[7],moment generating function[6],Gram-Charlier series [5] and modified chernoff bound [4].However these are often computationally complex and take more time to evaluate BER during data path selection. Here we have followed a simplified approach for BER calculation based on Taylor series expansions as given in [1, 2].

The rest of the paper is organized as follows. In sec II, crosstalk and its mathematical model are discussed. Its impact on BER and power penalty is given in sec. III. In sec.

IV, BER constrained RWA algorithm is proposed. Finally in sec V simulation results are given.

II. IN-BAND CROSSTALK

In WDM/DWDM network a message is sent from one node to another node using a wavelength continuous route called lightpaths (LPs) without requiring any O-E-O conversion and buffering at the routing node. Multiplexing, de-multiplexing and switching are done in the optical domain using prisms and diffraction gratings. Non-ideal nature of these component results in-band crosstalk, which has the same wavelength as the signal and degrades the transmission performance of the network. In-band crosstalk can be divided into coherent crosstalk, whose phase is correlated with the desired signal considered, and incoherent crosstalk whose phase is not correlated with the signal considered [7]. Coherent crosstalk is believed not to cause noise but causes small fluctuation of signal power. In this paper, we considered in-coherent crosstalk which has the more adverse effect than coherent crosstalk. Fig.1 shows how crosstalk accumulates in optical networks. In ideal case there will be no crosstalk as two signals are routed to different output ports. However any leaking or in sufficient isolation may induced homodyne crosstalk.

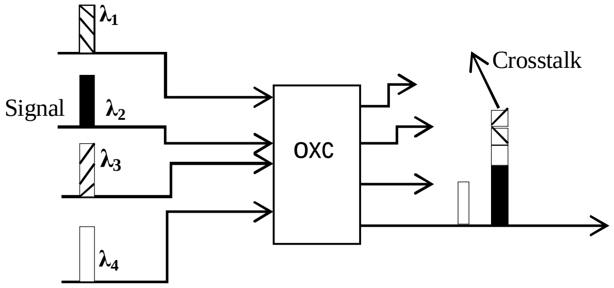

Fig. 1. Example showing how in-band crosstalk is induced in optical network

Incoherent crosstalk is often analyzed using the *pdf* of the noise in the received photocurrent. The *pdf* can be derived from the fields of the wanted signal and of each interfering signal. Desired optical signal and each interfering signal is assumed to be

$$E_S(t) = \overrightarrow{r_s}\, b_s(t)\sqrt{p_s}\exp[(j\omega_s t + j\phi_s(t)] \quad (1)$$

$$E_{\varepsilon k}(t) = \overrightarrow{r_k}\, b_k(t)\sqrt{\varepsilon_k p_s}\exp[(j\omega_s t + j\phi_k(t)] \quad (2)$$

Where all fields have the same nominal optical frequency *ω*, *ϕ(t)* represent the independent phase fluctuation of each optical source, p_s is the optical power in the desire signal, and ε_k is the optical power of the k_{th} interference relative to the signal. $b_{s,k(t)}$ =0,1 depending on whether zero or one is transmitted by the desired and interference signal at time t.

The total incident optical field on the photo detector can be written as for N crosstalk term

$$E_{ph}(t) = E_S(t) + \textstyle\sum_{k=1}^{N} E_{\varepsilon k}(t) \quad (3)$$

$$E_{ph}(t) = \overrightarrow{r_s} b_s(t)\sqrt{p_s}\, exp\,[(j\omega_s t + j\phi_s(t)] + \textstyle\sum_{k=1}^{N} \overrightarrow{r_k}\, b_k(t)\sqrt{\varepsilon_k p_s}\, exp\,[(j\omega_s t + j\phi_k(t)] \quad (4)$$

For unit detector responsivity and for worst-case assumption of identical polarization of signal and crosstalk, the photo current *i(t)* is given by

$$i_{ph}(t) = |E_{ph}(t)|^2$$

$$i_{ph}(t) = b_s^2(t)p_s + 2p_s \textstyle\sum_{k=1}^{N} b_s(t)b_k(t)\sqrt{\varepsilon_k}cos\theta_k(t) + p_s \textstyle\sum_{k=1}^{N} b_k^2(t)\varepsilon_k \quad (5)$$

Where $\theta_k(t) = \phi_k(t) - \phi_s(t)$,k=1,…..N, are random phase. Ignoring the small terms in the order of ε_k, the overall receiver noise in the photodetector is

$$n(t) = 2p_s \textstyle\sum_{k=1}^{N} b_s(t)b_k(t)\sqrt{\varepsilon_k}cos\theta_k(t) + n_g(t) \quad (6)$$

When ZERO is transmitted by the signal channel, there is no crosstalk and noise $n_0(t) = n_g(t)$, where $n_g(t)$ is the usual Gaussian noise in the receiver. When ONE is transmitted by the signal channel crosstalk generates a total noise

$$n_1(t) = 2p_s \textstyle\sum_{k=1}^{N} b_k(t)\sqrt{\varepsilon_k}cos\theta_k(t) + n_g(t) \quad (7)$$

For N interferers and Gaussian noise, the *pdf* of the noise in the received photocurrent can be obtained by integrating the Gaussian noise over all possible values of phase offset between signal and each interference [1, 2]. Assuming the phase difference between signal and interferers are independent and uniformly distributed between *(0, π),* the noise photocurrent pdf is given by

$$p_{nk}(y) = \frac{1}{\sqrt{2\pi\sigma}\pi^N} \times \left[\int_0^{\pi}..\int_0^{\pi} exp\left\{-\frac{\left(y-\sum_{k=1}^{N} A_K cos\theta_k\right)^2}{2\sigma^2}\right\}\right] d(\theta_1)\,...\,d(\theta_N) \quad (8)$$

Where $A_k=2\sqrt{\varepsilon_k}p_s$ and σ is the variance of thermal noise. The effect of crosstalk is maximum when phase difference is close to 0 and the pdf can be approximated by expanding the cosine term by first order Taylor series [1] up to the term $\theta_k{}^{2.}$

$$p_{nk}(y) = \frac{1}{\sqrt{2\pi\sigma}\pi^N} \times \left[\int_0^{\pi}..\int_0^{\pi} exp\left[-\frac{\left\{y-\sum_{k=1}^{N} A_K\left(1-\frac{\theta_k^2}{2}\right)\right\}^2}{2\sigma^2}\right]\right] d(\theta_1)..d(\theta_N) \quad (9)$$

Expanding the square term and keeping term upto θ_k^2, the the pdf for noise when signal is transmitting 1 is given by

$$p_{nk}(y) = \frac{1}{\sqrt{2\pi\sigma}}\left\{\prod_{k=1}^{N} f(y)\right\} exp\left[-\frac{(y-\sum_{k=1}^{N} A_K)^2}{2\sigma^2}\right] \tag{10}$$

Where

$$f(y) = \sqrt{\frac{\sigma^2}{2\pi A_k(y-\sum_{k=1}^{N} A_k)}}\, erf\left[\pi\sqrt{\frac{A_k(y-\sum_{k=1}^{N} A_k)}{2\sigma^2}}\right] \tag{11}$$

III CALCULATION OF BER & PP

BER in the presence of in-band crosstalk is given by fraction of the received photocurrent pdf's that fall on the wrong side of some decision variable d, for each combination of data "1"s and "0" of the signal and crosstalk. Here we fallowed a simplified approach as given in [2] for extreme case when all interferers are transmitting "1", so that we have an upper bound for BER during our routing and wavelength assignment algorithm.

$$p_e = \frac{1}{2}p_{e0} + \frac{1}{2}\left[\frac{1}{2}p_{e1(b_k=0)} + \frac{1}{2}p_{e1(b_k=1)}\right] \tag{12}$$

Where $p_{e0} = \frac{1}{2}erfc\left(\frac{d}{\sqrt{2\sigma_{th}{}^2}}\right)$

$$p_{e1}(b_k = 0) = \frac{1}{2}erfc\left(\frac{I_S - d}{\sqrt{2\sigma_{th}{}^2}}\right)$$

$$p_{e1}(b_k = 1) = \frac{1}{2^{N+1}}\left\{\prod_{k=1}^{N} f(I_S - d)\right\}\sum_{k=1}^{N} erfc\left\{\frac{(I_S - \sum_{k=1}^{N} A_k)}{\sqrt{2\sigma^2}}\right\}$$

Here the weighting function *f(y)* is approximated as $f(I_s - d)$ to make the integral possible. σ^2 is the variance of the receiver noise when "1" is transmitted by the signal channel and σ_{th}^2 is the variance of the receiver thermal noise when "0" is transmitted. Expression for BER at the WDM receiver is given by [2].

$$p_e = \frac{1}{4}erfc\left(\frac{d}{\sqrt{2\sigma_{th}{}^2}}\right) + \frac{1}{8}erfc\left(\frac{I_s - d}{\sqrt{2\sigma_{th}{}^2}}\right) + \frac{1}{2^{N+3}}\left\{\prod_{k=1}^{N} f(I_s - d)\right\}\sum_{k=1}^{N} erfc\left\{\frac{(I_S - \sum_{k=1}^{N} A_k)}{\sqrt{2\sigma^2}}\right\} \tag{13}$$

From the above equation power penalty is found by comparing the photocurrent at the receiver that produces the same BER with and without crosstalk.

$$PP = 10log\left(\frac{I_s{}'}{I_s}\right) \tag{14}$$

IV. BER CONSTRAINED (BERC) RWA

Mitigating the effects of crosstalk in all optical networks is a difficult task because crosstalk lies in the same band as the desired signal and therefore cannot be filtered. But by selecting appropriate routes and wavelengths used by a call in a network at call arrival time, it is possible to minimize the impact of crosstalk. BER constrained RWA is a technique where the choice of a route depends on the network state as opposed to static schemes where routing is fixed. Fig.2 given bellow shows the algorithm proposed for routing and wavelength assignment taking no of crosstalk component into consideration. No of crosstalk component depends upon the present state of the network.

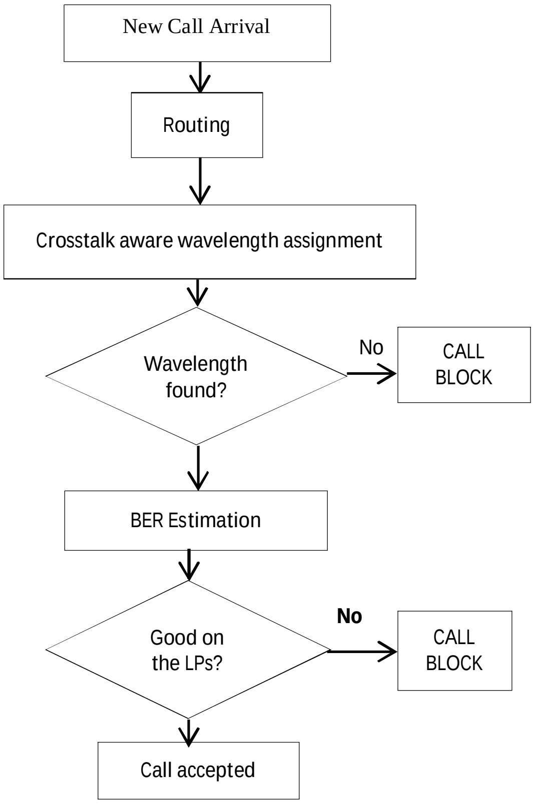

Fig. 2 Flowchart of BER constrained algorithm

V. SIMULATION AND RESULTS

The performance degradation due to in-band crosstalk depends very much on the no of crosstalk interferences. In fig. 3, the BER is plotted as a function of input power for different number of interfering channel (N). This figure shows that BER increases significantly as the no of crosstalk component increases. Here we have assumed that all interferers have same amount of crosstalk level. Fig.4 shows variation of power penalty as a function of crosstalk level for different no of interfering channel. Power penalty increases very rapidly as crosstalk level increases as well as the no of interfering channel increases.

We evaluated our algorithm on a topology given in fig.5 with 6 wavelengths per link in each direction and assumed that every node is reachable from any other node. We consider different traffic matrix and analyze the given topology. The simulation results show that BERC algorithm always select a path with minimum BER. Fig. 6 shows one of the randomly taken traffic matrix indicating the source, destination and the no of connection established between them. Now if we want to setup a connection between source A and destination D, then our algorithm chose the path A-B-C-D, which has minimum no of crosstalk component as compared to shortest path algorithm (A-E-G-D).The BER for the path chosen by their respective algorithm is give in the fig.7 .

We compare our algorithm with traditional shortest path (SP) and fixed alternate routing (FAR) algorithm for overall network performance in terms of blocking probability. Result (in fig. 7) show that BER constrained algorithm not only gives a guaranteed QoT but also reduces networks blocking probability. Another benefit of BER constrained algorithm is that it will distribute the entire traffic throughout the network so that a particular link will not be loaded with the maximum number of traffic.

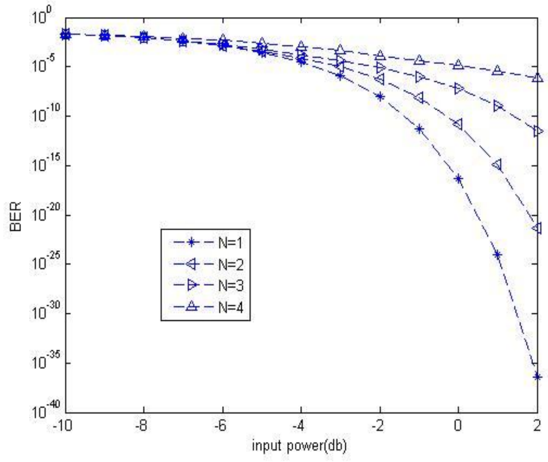

Fig.3. Plot of BER with the input power for different number of interfering channel

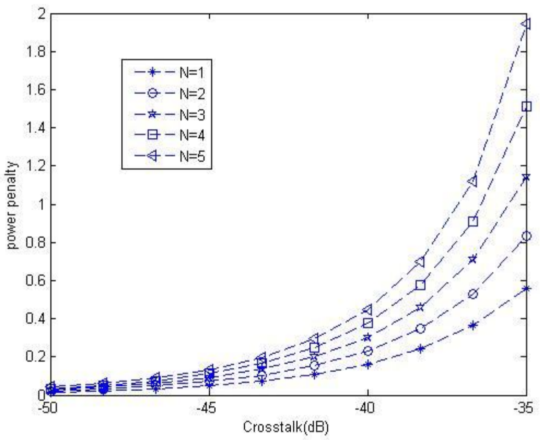

Fig. 4. Variation of power penalty with crosstalk level for different number of interfering channel

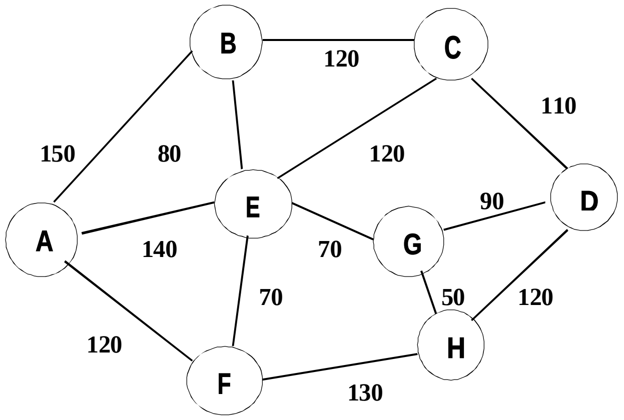

Fig.5. A sample mesh network with fiber length (in km) marked on each link

S/D	A	B	C	D	E	F	G	H
A	0	0	1	0	2	1	1	0
B	2	0	0	0	0	0	1	1
C	1	0	0	0	0	2	0	0
D	0	1	0	0	0	1	0	1
E	0	0	0	1	0	0	0	0
F	1	0	0	1	0	0	0	0
G	0	0	0	0	0	0	0	0
H	0	0	0	0	0	0	1	0

Fig.6. A Traffic Matrix Indicating the no of connection to be made between a particular source and destination

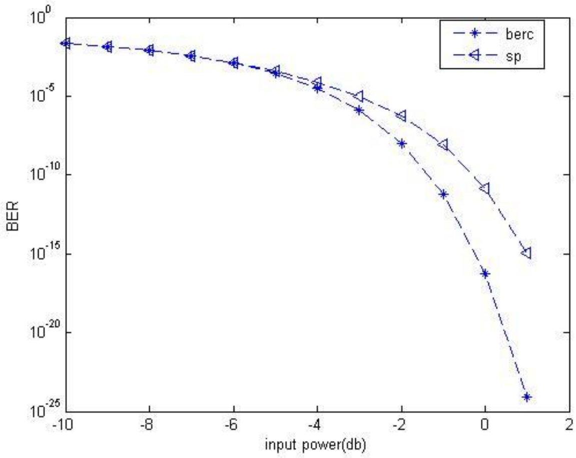

Fig.7. Plot of BER for the path selected by shortest path & BERC algorithm.

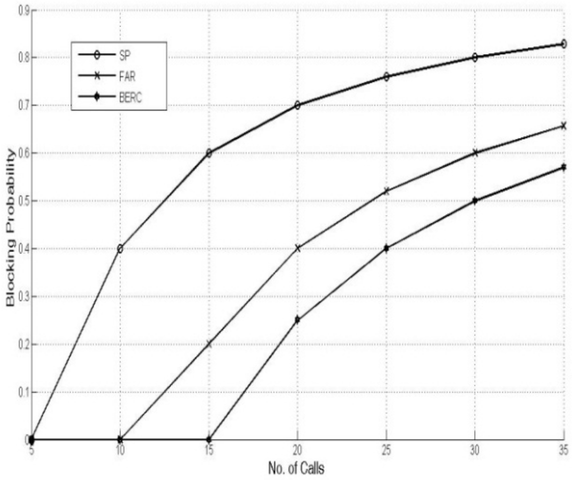

Fig.8. Average call blocking probability for SP, FAR and BERC RWA Algorithm

VI. CONCLUSION

BER and power penalties due to component crosstalk in a WDM receiver has been studied and computed results are shown as a function of number of interfering channel. The proposed RWA algorithm in this work exhibits desirable properties for optical networks operation, namely, low BER. This was achieved by making the choice of the route and wavelength dependent on both wavelength occupations in the network, as well as crosstalk.

REFERENCES

[1]. Sarah D. Dods, Trevoer B. Anderson, "" Calculation of bit-error rates and power penalties due to incoherent crosstalk in optical networks using taylor series expansions," *j. Lightwave Technoloy., vol.23,No.4,pp.1828-1836,April.2005*

[2]. Santu Sarakar and Nikhil R. Das, "Study of component crosstalk and obtaining optimum detection threshold for minimum bit-error-rate in a WDM receiver," *j. Lightwave Technology., vol.27,No.19,pp.4366-4373,Oct.2009*

[3]. Jun He, Maite Brandt-Pearce and Suresh Subramaniam, " QOS-Aware wavelength assignment with BER and latency Constraints for All-Optical networks," *j. Lightwave Technology., Vol.27,No.5,pp.462-474,March 2009*

[4]. Marcelo R. Jimenez, Rogerio Passy, Marco A. Grivet and Pierre Von Der, "Computation of power penalties due to intraband crosstalk in optical system," IEEE *Photonics Technology Letters, Vol.15, No.1, pp 156-158, Jan.2003.*

[5]. Keang-Po Ho, "Analysis of homodyne crosstalk in optical networks using Gram-Charlier Series", *j. Lightwave Technology., Vol.17, No.2, pp.149-154, Feb- 1999.*

[6]. Yunfeng Shen, Kejie Lu and Wanyi Gu, " Coherent and Incoherent crosstalk in WDM networks ", *j. Lightwave Technology., Vol.17,No.5,pp.462-474,May 2003*

[7]. I. T. Monroy and E. Tangliongga, "Perfomance evaluation of optical crossconnects by saddlepoint approximation," *J. Lightwave Technol. vol. 16, pp. 317–323, Mar. 1998.*

[8]. T. Kamalakis and T. Sphicopoulos, "Asymptotic behavior of in-band crosstlalk noise in WDM networks," *IEEE Photon. Technol. Lett. vol. 15, pp. 476–478, Mar. 2003.*

[9]. Chava Vijay Saradhi and Suresh Subramaniam, " Physical Layer Impairments Aware Routing (PLIAR) In WDM Optical Network: Issues and Challenges," *IEEE Communication Surveys & Tutorials, vol. 11, no. 4, pp.109-129.fourth quarter.2009*

[10]. Y. Huang et al., " Connection Provisioning With Transmission Impairments Consideration in Optical WDM Networks With High Speed Channels," *IEEE/OSA J. Lightwave Technol., vol. 23, no. 3, pp. 982-993, Mar 2005*

[11]. I. Tomkos et al., " Impairment Constraint Based Routing in Mesh Optical Networks," *proc. OFC 2007*

[12]. C. Politi et al., " Physical Layer Impairment Aware Routing Algorithm based on Analytically Calculated Q-Factor," *proc. OFC 2006*

[13]. R. Ramaswami and K. Sivrajan, *Optical Networks: A Practical Perspective*. Morgan Kauffman 2001

[14]. G.P.Agrawal, *Fibre Optic Communication System*. Wiley Interscience,1992

[15]. H. Zang et al., " A review of Routing and Wavelength Assignment Approaches for Wavelength Routed Optical WDM Networks", *Optical Network Mag., vol.1, no.1, jan 2000*

[16]. D. Banerjee, B. Mukherjee, "A Practical Approach for routing and Wavelength Assignment in Large Wavelength Routed Optics Networks," *IEEE Journal on Selected Areas in Communications, , 1996, Vol. 14, pp903-905.*

[17]. R. Ramaswami, K. N. Sivarajan, "Routing and Wavelength Assignment in All Optical Networks," *IEEE /ACM Transactions on Networking, 1995. Vol. 3, pp489-500.*

[18]. Z. zhang, Y. Q. Zhang, X.Chu, B. Li, "An overview of Virtual Private Network: IP VPN and Optical VPN", *Photonic Network Communication, 2004, Vol. 7, pp213-225.*

[19]. Siamak Azodolmolky, Mirosław Klinkowski, Eva Marin, Davide Careglio, Josep Solé Pareta and Ioannis Tomkos, "A survey on physical layer impairments aware routing and wavelength assignment algorithms in optical networks", *Computer Networks 53, 926–944, 2009.*

[20]. Vasilis Anagnostopoulosa, Christina (Tanya) Politib, Chris Matrakidisb, and A. Stavdasb, "Physical Layer Impairment Aware Wavelength Routing Algorithms", *Optics Communications, Volume 270, Issue 2, Pages 247-254, 15 February 2007.*