Physical Layer Impairment (PLI) Aware Lightpath Selection in WDM/DWDM Network

Vikram Kumar, Santos Kumar Das

Abstract
The demand for high data rate with low bit error rate (BER) and large bandwidth is highly satisfied in wavelength division multiplexing/dense wavelength division multiplexing (WDM/DWDM) network. However, the signal travelling inside the optical fiber can be affected by various physical layer impairments (PLIs). These impairments are caused due to fiber non-linearities and non-ideal nature of optical components. Dispersion is one of the PLI constraint, which affects the signal quality. It needs to be compensated for which this research work presents the approach of dispersion penalty (DP). It also suggests a PLI-aware lightpath selection algorithm based on DP.

1 Introduction

An optical network employing WDM/DWDM is the backbone of the next generation communication system. WDM/DWDM networks have an enormous bandwidth to satisfy emerging application such as video on demand, medical imaging, and distributed CPU interconnects. Optical network has evolved from traditional opaque networks toward all-optical network via translucent networks with the change in generations [1]. In WDM/DWDM network lightpath selection after routing and assigning a wavelength to each connection is termed as Routing and Wavelength As-

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signment (RWA) problem. RWA is a very complex problem which needs to be addressed before designing optical networks. To maintain the transparency of optical network regenerators are removed, as a result distorted signals can't be amplified during long distance transmission. Since transmitted signal remains in the optical domain, noise and distortion affects the quality of received signal. This occurs due to non-ideal nature of optical components and non-linearities of the optical fiber at the physical layer give rise to impairments known as PLI, which affects the signal strength [2]. PLI can be classified as linear and nonlinear impairments. Linear impairments (LIs) are static in nature, whereas non-linear impairment (NLIs) are dynamic in nature.

Many researchers are working on the RWA problem and suggested an algorithm to overcome the effect of various PLIs in order to set-up a lightpath. The authors in [3] have presented a comprehensive survey on various PLIs aware network design techniques, RWA algorithms, and PLI-aware failure recovery algorithm. This paper also suggested that dispersion is the most serious issue for systems operating at bit rate higher than 2.5 Gb/s. In [4], the authors have suggested an adaptive Quality of Transmission (QoT) aware routing technique incorporated with a new cost function based on the impairments. They have considered linear and non-linear impairments whose variance can be predicted. Jijun Zhao et al. [5] presents a bidimensional Quality of Service (QoS) differentiation framework to improve the network performance. In this framework, they have considered both PLIs and set-up delay as well as the impact of PLIs on QoT. In [6], a comprehensive survey on the impact of PLI on a transparent optical network is studied. It has presented a survey of various PLI-RWA algorithm discussed in the previous researches to have a better understanding of optical network. The authors in [7] have studied the static impairment-aware multicast RWA problem for transparent WDM network. They have formulated this problem mathematically with the help of integer linear programming (ILP) considering various impairments present in physical layer, such as optical power, amplified spontaneous emission (ASE) noise, crosstalk, and polarization effects. In [8], the authors have suggested a weighted mechanism for provisioning PLI-aware lightpath set-up in WDM network. Dominant PLIs considered are self- phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), and total noise. It has proposed a novel weighted approach that (i) selects the optimum launch power, (ii) knows the current network state, and (iii) assigns weight to the wavelength based on PLIs.

In this work, the estimation and management of PLI to provide efficient and qualitatively good lightpath to the end users is investigated. This paper considers dispersion as one of the PLI constraints and suggested a dispersion penalty (DP) approach to compensate the signal distortion occurring inside the optical fiber. DP is defined as the increase in input signal power in order to achieve the same SNR as that of an ideal system. The routing algorithm will select those paths which have lower values for DP such that impact of dispersion can be minimized. In other words, lower value of DP guarantees the lesser dispersion on that particular lightpath. The results indicate that only a few paths are suitable for wavelength assignment ensures higher blocking probability.

2 System Model

WDM/DWDM system model is shown in Fig. 1. It comprises of clients, connection requests, provider edge routers (PERs), core routers (CRs), control manager (CM), and a central database (DB). This is a centralized system model, that has data plane as well as the control plane. Data plane deals with data transmission, where as control plane deals with the management of network resources. The topology provides information such as i) network connectivity, ii) availability of wavelengths, and iii) connection requests. Control manager maintains a traffic matrix (TM) for all the clients. It records a database table for physical layer constraints such as routing information, dispersion penalty (DP) matrices for all possible connection of any source-destination client pairs. CM performs a direct communication with optical core routers and updates its database.

The connection matrix, $C(i, j)$ between any router pair i and j of the physical topology can be represented as

$$T(i, j) = \begin{cases} 1 & \text{if there exist a link between } (i, j); \\ 0 & \text{otherwise} \end{cases}$$

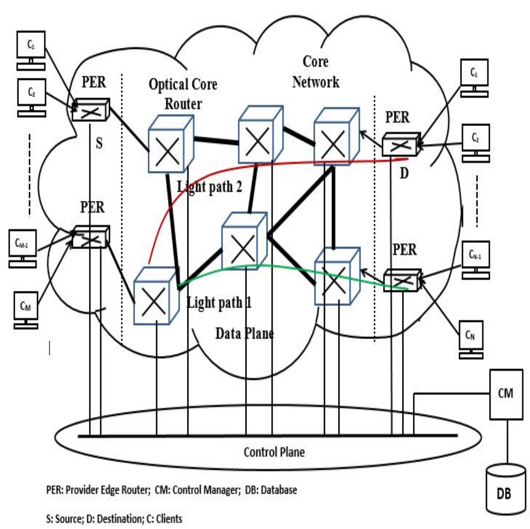

Fig. 1 System Model

Based on the system model, we have estimated and analyzed the Dispersion penalty.

2.1 Estimation and Analysis of Dispersion Penalty

Dispersion is defined as the broadening of light pulses as it travels along the fiber due to variation in the velocities of different spectral components. It can be categorized mainly as: chromatic dispersion (CD) and polarization mode dispersion (PMD). CD is a phenomenon, which degrades the signal quality caused by different spectral components travelling at their own velocities [9]. When a signal travels through different fiber links, then the resultant dispersion is the summation of dispersion caused due to individual links. Mathematically CD can be expressed as [10],

$$T_{cd}(i,j) = D_{cd}\sigma_{\lambda}L(i,j) \tag{1}$$

where, D_{cd} is the CD coefficient, σ_{λ} is the spectral width of the source (ranges from 40 nm-190 nm for LED), and $L(i,j)$ is length of the link(i,j).
Fiber is made up of silica (sio_2), which may contain some impurities due to the manufacturing process or may be due to an environmental condition like stress and temperature. These impurities lead to an obstacle for smooth movement of the signal inside the core of the fiber. As a result of this different polarization of optical signal occurs leading to different group velocities. Hence, the pulse spreads in the frequency domain. This phenomenon is called PMD. The different group delay is proportional to the square root of link length $L(i,j)$, it can be represented as [11],

$$T_{pmd}(i,j) = D_{pmd}\sqrt{L(i,j)} \tag{2}$$

where, D_{pmd} is the PMD coefficient.
Total delay in pulses caused due to dispersion is calculated as a summation of delay due to CD and PMD which is written as follows [12].

$$T_{total}(i,j) = \sqrt{(T_{cd}(i,j))^2 + (T_{pmd}(i,j))^2} \tag{3}$$

Now, the total delay for a source-destination (s,d) pair can be express as follows.

$$T_{total}(s,d) = \sum_{\forall(i,j)\in(s,d)} T_{total}(i,j) \tag{4}$$

The dispersion in the fiber is a major constraint for high speed data transmission, as it increases the signal to noise ratio (SNR) or bit error rate (BER). As a result of this intersymbol interference (ISI) occurs between the various channels inside the fiber that controls the data rate. In order to maintain same SNR or BER at high speed transmission the system degradation should be compensated. For this, the signal power has to be increased to achieve the same SNR as that of the ideal system. This increase in power is called the dispersion penalty (DP). Dispersion penalty for link (i,j) is expressed in terms of bit rate and total delay as [13],

$$P_d(s,d) = -10log_{10}[1 - 0.5(\pi \times B(s,d))^2\sigma_t^2(s,d)] \tag{5}$$

where, $B(s,d)$ is the bit rate of a path and $\sigma_t(s,d)$ is total dispersion of a path. The maximum possible bit rate for a lightpath with source destination pair *(s,d)* can be computed as [13],

$$B(s,d) = \frac{\varepsilon}{10^{-6} \times T_{total}(s,d)} \quad (6)$$

where, the total dispersion of a fiber link, $\sigma_t(i,j)$ can be expressed as [12],

$$\sigma_t(i,j) = \sqrt{\sigma_c^2(i,j) + \sigma_n^2(i,j)} \quad (7)$$

where, $\sigma_c(i,j)$ is intramodal or chromatic broadening of pulses, and $\sigma_n(i,j)$ intermodal broadening caused by delay differences between the various modes. The term $\sigma_c(i,j)$ consist of pulse broadening due to both material and waveguide dispersion, it can be represented as follows,

$$\sigma_c(i,j) = \sigma_m(i,j) + \sigma_{wg}(i,j) \quad (8)$$

as σ_{wg} is negligible in compared to σ_m so,

$$\sigma_c(i,j) = \sigma_m(i,j) \quad (9)$$

and

$$\sigma_m(i,j) = \sigma_\lambda L(i,j) M \quad (10)$$

where, σ_λ is the spectral width of LED source light $\approx$ 50 nm, M is the material dispersion coefficient.
The intermodal dispersion, σ_n, is expressed as,

$$\sigma_n(i,j) = \sigma_s(i,j) \quad (11)$$

where, $\sigma_s(i,j)$ is rms pulse broadening due to intermodal dispersion for step index fiber. The expression for intermodal dispersion is expressed as,

$$\sigma_s(i,j) = \frac{L(i,j)(NA)^2}{4\sqrt{3}n_1 c} \quad (12)$$

where, $L(i,j)$ is the length of link, NA is the numerical aperture of the fiber, n_1 is the refractive index of the core and c is the speed of light.
All the above mention parameters are calculated for a single link and for the calculation of a (s,d) pair we need to take summation of all the links (i,j), those are represented as follows.

$$\sigma_s(s,d) = \sum_{\forall (i,j) \in (s,d)} \sigma_s(i,j) \quad (13)$$

$$\sigma_m(s,d) = \sum_{\forall (i,j) \in (s,d)} \sigma_m(i,j) \quad (14)$$

$$\sigma_t(s,d) = \sum_{\forall (i,j) \in (s,d)} \sigma_t(i,j) \quad (15)$$

Now, the dispersion penalty for a particular (s,d) pair is expressed as follows,

$$P_d(s,d) = -10\log_{10} \left[1 - 0.5\left(\frac{\pi\times\varepsilon}{10^{-6}}\right)^2 \times \left(\frac{1}{\sum\limits_{\forall(i,j)\in(s,d)} (D_{cd}\sigma_\lambda L(i,j))^2 + D_{pmd}^2 L(i,j)}\right)^2 \times \left(\sum_{\forall(i,j)\in(s,d)} \sigma_\lambda^2 L^2(i,j) M^2 + \sum_{\forall(i,j)\in(s,d)} \frac{L^2(i,j)(NA)^4}{48 n_1^2 c^2}\right) \right] \tag{16}$$

3 Lightpath set-up Algorithm

To compute an optimal path, an algorithm is explained below, it is used to get M possible lightpath using Floyd-Warshall approach [14]. This search algorithm is used to support multiple constraints. However, this computation uses two constraints i.e., path length and threshold DP. In addition to the estimation of DP, comparison with the threshold value is also done in order to obtain lightpath of better quality. Further, the availability of wavelength is being checked and lightpath is decided for setting up the connection. The lightpath not satisfying the above criterion are blocked, and accordingly blocking probability is calculated for a set of source destination (s,d) pair having load L and wavelengths λ is expressed as follows [15]:

$$P_{b(L,\lambda)} = \frac{\frac{L^\lambda}{\lambda!}}{\sum_{i=0}^{\lambda} \frac{L^i}{i!}} \tag{17}$$

where, $P_{b(L,\lambda)}$ is the blocking probability, i is the i^{th} link for a (s,d) pair.

4 Numerical Result and Discussion

An NSF(National Science Foundation) network topology as shown in Fig. 2 is used for numerical analysis, it consist of 10 nodes and 16 links. This is a noble work, previously using this concept there is no literature found. So, we can not compare our result with any previous methods. All the numerical results were carried out using MATLAB, the system parameter considered are shown in Table 1 [10]. This paper presents a lightpath selection mechanism based on quality parameters such as bit rate and dispersion penalty for finding the best suitable connection. DP should be as low as possible for better network performance. Floyd-Warshall algorithm has been employed to calculate all possible path between a particular set of (s,d) pair

Algorithm 1 DP Based path computation

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connection request R arrives for a (s,d) pair
calculate K shortest path of R by the shortest path algorithm number the K shortest path as
  1,2,....K in accordance with a ascending order of the length
calculate the threshold path length
for (i^th shortest path (i≤ K))
    if (path length ≤ threshold path)
        if (DP ≤ threshold)
            if (wavelength available)
                optimal lightpath connection
                  established
            else
                Path is blocked
            end if
        end if
    end if
    Compute the blocking probability
end for
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having several links. For example, it has considered node 2 as a source and node 8 as a destination, i.e., (2, 8) pair.

Table 1 Simulation Parameters [11]

Parameters	Value
Pulse broadening ratio, ε	0.182
Pulse broadening factor, σ	0.1
PMD coefficient, D_{pmd}	0.5 ps/$\sqrt{km}$
CD coefficient, D_{cd}	18 ps/nm-km
Material dispersion coefficient, M	250 ps/nm-km
Numerical aperture, NA	0.30
Core refractive index, n_1	1.50
Speed of light, c	2.9999$\times10^8$ m/s
Source spectral width, σ_λ	50 nm

There are total 43 lightpaths for this (s,d) pair. These all possible lightpath are labelled as 'lightpath index number' for the ease of representation for DP variation over individual lightpath. Fig. 3 shows the variation of bit rate for different set of paths. Bit rate is higher for starting set of lightpath as compared to the later set of lightpath. This depicts that the effect of impairments is dominant on the longer paths. Now, using the literature mentioned in sect. 3 dispersion penalty has been calculated for all these paths using (5). The plot for DP vs all possible path for (2, 8) pair is shown in Fig. 4 . In order to estimate the lightpath quality the threshold limit of DP is taken as 2 dB [13], so out of 43 paths only 29 paths fall under this condition as shown in Fig. 6. Now the second condition is applied, i.e. threshold path span

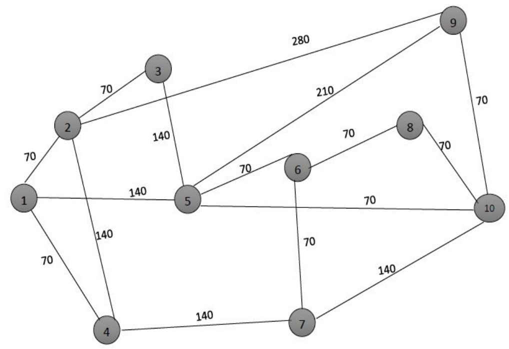

Fig. 2 An NSFNet topology

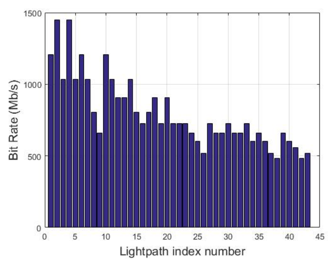

Fig. 3 Bit Rate of all possible path for source to destination pair (2,8)

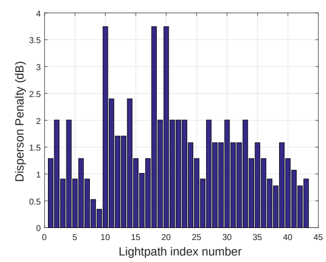

Fig. 4 DP of all possible paths for source destination pair (2, 8)

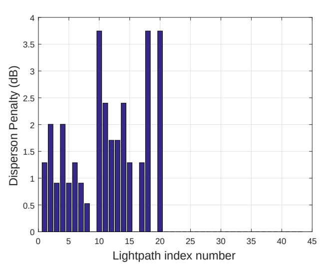

Fig. 5 DP $\leq DP(d_{th})$ for source destination pair (2, 8)

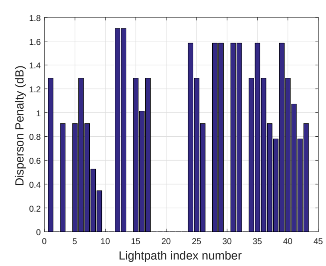

Fig. 6 DP $\leq$ 2 dB for source destination pair (2, 8)

(average path length). It is observed that only 17 paths are satisfying the criterion as shown in Fig. 5. Now this work considered both the constraints i.e. DP and threshold path span and only those path are selected which satisfies both. The optimal shortest path is obtained between (2, 8) pair, which is suitable for wavelength assignment is shown in Fig. 7. Therefore, out of 43 lightpaths only 10 lightpaths have lesser DP desirable for larger bandwidth and high data rate transmission under the influence of PLIs. As per the proposed algorithm, the optimal lightpath connection will be 2-9-5-10-8 for source destination pair $(2,8)$

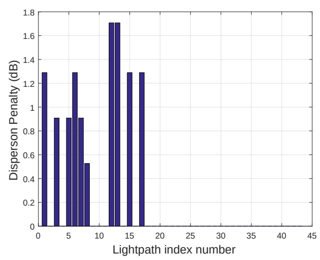

Fig. 7 Dispersion penalty plot of optimal paths for source destination pair (2, 8)

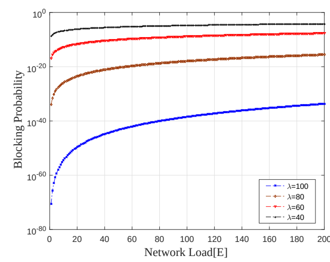

Fig. 8 Network blocking probability for different number of wavelengths

The performance of the algorithm is analyzed by computing blocking probability for the incoming connection requests. The blocking probability of the network, which is illustrated in (17), depends on the number of wavelengths, traffic load, and the number of nodes. In this work, number of nodes = 10 and number of channels are varied. Figure 8 depicts the reduction in blocking probability with an increase in the number of wavelengths allocated per node. Traffic load is varied and a set of wavelength i.e. 40, 60, 80, 100 have been considered in this work.

5 Conclusion

This paper investigates the dispersion effect on the signal quality in transparent WDM/DWDM network. It also presents an impairment aware lightpath quality estimation algorithm based on the dispersion. This algorithm focuses on optimal lightpath selection with a lower value of DP. It addresses the routing and wavelength assignment problem from PLI point of view. Another advantage is that this approach can be effectively used to estimate the blocking probability, where the number of wavelength is different on each link.

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