OSNR Based Quality Estimation in Optical Network

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***Abstract*—In the last few decades, optical technology has become much advance to transmit higher traffic over a long distance. In spite of this, physical layer impairments (PLIs) poses a great concern over the optical communication to meet the demand of next generation technology. Hence, PLI aware algorithm is a major factor to improve the quality of an optical network. This paper discuss the quality estimation based on optical signal-to-noise ratio (OSNR). This approach includes noise due to amplifier spontaneous emission (ASE) in optical fiber, multiplexer, demultiplexer, and coherent crosstalk in optical switches to present OSNR in a wavelength division multiplexing/dense wavelength division multiplexing (WDM/DWDM) networks. In this work, estimation of ASE noise power for different values of wavelength and bandwidth has been discussed. This paper also presents a routing and wavelength assignment (RWA) algorithm based on OSNR to improve the quality of transmission.**

***Index Terms*—Optical signal-to-noise-ratio ; wavelength division multiplexing ; routing and wavelength assignment; amplifier spontaneous emission noise; blocking probability.**

I. Introduction

The optical network is the most valuable and cost-efficient solution of the future need for high data rate and wider bandwidth. WDM/DWDM technology is the backbone of optical networks where data transmission occurs through assigned wavelengths [1]. In WDM/DWDM network, lightpath selection is a challenging issue which needs special attention before designing an optical network. RWA technique can be applied based on the desired value of OSNR which occurs due to linear and non linear impairment constraint present in the physical layer that leads to signal distortion. This impacts on quality of service (QoS) of the network [2]. Few PLIs that affects the QoS are ASE, polarisation mode dispersion (PMD), chromatic dispersion, etc. [3, 4].

In WDM/DWDM networks, routing process plays an important role in network performance. Many Routing algorithms have been proposed based on the heuristic approach which depends on defined PLI parameters. Some of the routing approaches are shortest path (SP) [5], hop count, least resistance weight (LRW) [6] etc. In an Optical network, PLI is a constraint for high speed data transmission and poses a concern in wavelength assignment.

RWA technique can be sub divided into two step process: first, a lightpath selection mechanism and secondly wavelength assignment based on PLIs [7]. The authors in [8] have presented a comprehensive survey on various PLIs aware network design techniques, and RWA algorithms. A heuristic algorithm based on graph coloring scheme has been developed to solve RWA problem in WDM networks [9]. The authors in [3] have developed a new impairment aware RWA algorithm. They have studied few impairments such as ASE noise, crosstalk, cross-phase modulation (XPM), self phase modulation (SPM), and four wave mixing (FWM). In [10], the authors have proposed a multi cost impairment aware RWA algorithm. They have calculated noise variance of a link to estimate the quality of transmission (QoT). In [11], the authors have proposed a bidimensional QoS differentiation framework in transparent optical network. This approach includes the PLIs and connection establishment delay for suggesting an algorithm in order to reduce the blocking probability.

Among the few PLI parameters, OSNR is a major parameter to be considered for the planning of quality based optical network. It is defined as the ratio of optical signal power to noise power over a specific spectral bandwidth. ASE noise is induced inside the channel with the addition of optical amplifier. However, this noise is very low but as the number of amplifier increases, more noise is induced. Also, they not only amplifies the weak signal but also amplifies the noise from all upstream amplifiers. When this reaches to a certain limit, amplifier will result in the degradation of link or network quality. Hence, the degradation of link or network quality motivates to improve the quality of transmission. This work also evaluates the network performance with respect to blocking probability which is a function of network load. It proposes a RWA algorithm which computes the lightpath between source and destination (s, d) pair. This algorithm implies OSNR-RWA algorithm by considering the signal quality degradation as a result of ASE noise power. Also, the comparison is done with the present existing algorithms.

The rest of the paper is organized as follows. Section II presents the system model. The proposed algorithm is presented in section III. Section IV discusses the numerical result and performance evaluation study by considering blocking probability. Finally, the conclusion of the work is discussed in section V.

II. System Model and Node Architecture

The system model is presented in Fig. 1. It comprises of optical components such as transmitter, optical switch, multiplexer, demultiplexer, pre amplifier, post amplifier, and receiver. The system model considers signal distortion due to the effect of various optical components in a WDM network. This model helps to investigate the distribution of ASE noise power with respect to inversion parameter at different values of optical bandwidth (B_o) and wavelength (λ). In order to evaluate the signal quality, noise induced due to different optical components have been considered at each point and finally at the output i.e at a point h. The signal degradation due to OSNR with consideration of ASE noise in amplifiers over a fiber link can be presented as [12],

$$OSNR = \frac{g\,P_{in}}{2\,n_{sp}\,hf\,B_0\,(g-1)} \quad (1)$$

where, n_{sp} is the population inversion factor, h is the Planck's constant, B_0 is optical channel bandwidth, g is the amplifier gain, and p_{in} is the average amplifier input signal power. The ASE noise power P_{ASE}, can be computed based on noise induced by the amplifier (N_{amp}) and noise at the receiver (N_{out}). The system model, considers the induced noise at the output interface of each optical switches i.e. at points b and h. This occurs due to the energy transfer through adjacent signals travelling along the channel. The induced optical noise power at individual switches can be represented as [13],

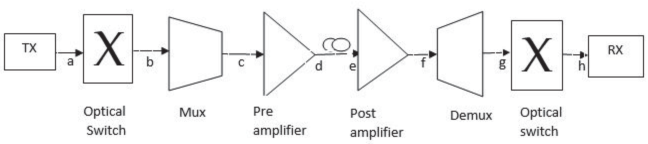

Fig. 1. System model

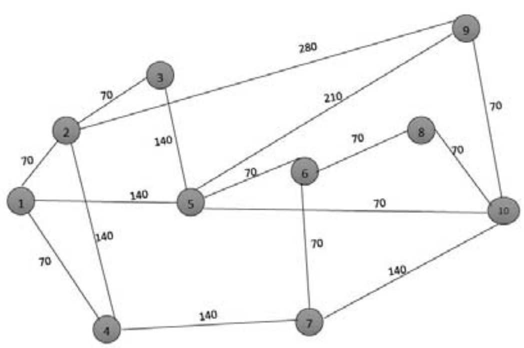

Fig. 2. An NSFNet topology

$$N_{switch} = \varepsilon \sum_{k=1}^{s} P_{sw_k}(\lambda) \quad (2)$$

where, $P_{sw_k}$is the optical transmitted power at k^{th} optical switch, ε is the isolation factor of individual switch, and s is the number of signals. Optical amplifiers will also amplify induce noise (N_{amp}) at points d and f that can be represented as [14, 15],

$$N_{amp} = \frac{hfB_0\,G_{amp}\,F_{amp}}{2} \quad (3)$$

where, f is the frequency of the optical signal, G_{amp} is the gain of the pre amplifier, and F_{amp} is noise factor of the amplifier. Gain of the amplifier can be further expressed as [16],

$$G_{amp} = \frac{G_0}{1+\frac{P_{out}}{P_{sat}}} \quad (4)$$

where, G_0 is the non saturated amplifiers gain, P_{out} is the output signal power, and P_{sat} is the output saturation power. As noise figure, F_{amp} depends on the input signal power (P_{in}) and it can be expressed as,

$$F_{amp} = F_0\left(1 + A_1 - \frac{A_1}{1+\frac{P_{in}}{A_2}}\right) \quad (5)$$

where, F_0 is the noise figure of optical amplifier, A_1 and A_2 are function parameters. There is also a possibility of noise generation due to four wave mixing (FWM) effect inside the optical fiber at point e. This nonlinear effect depends on different factors such as individual signal power of each channel, channel spacing, and total number of wavelengths present in a single fiber. FWM generated power, $P_{FWM}(\lambda)$ can be represented using equation proposed in reference [17] as,

$$\begin{aligned} P_{FWM}(\lambda) &= P_{ijk}(\lambda) \\ &= \frac{\eta}{9} D^2 \gamma^2 P_i P_j P_k e^{-\alpha d}\left[\frac{\left(1-e^{\alpha d}\right)^2}{\alpha^2}\right] \end{aligned} \quad (6)$$

where, η is the FWM efficiency, γ is the nonlinear coefficient, P_i, P_j, and P_k are input signal powers at signal frequencies f_i, f_j, and f_k respectively. Finally optical output signal power (P_{out}) can be evaluated at point h with consideration of gains and losses along the signal propagation as [16],

$$P_{out} = \frac{G_{amp_{Pre}}\,e^{-\alpha d}\,G_{amp_{Post}}}{L_{Switch}^2\,L_{Mux}\,L_{Demux}}\,P_{in} \quad (7)$$

where, $G_{amp_{Pre}}$ and $G_{amp_{Post}}$ are the linear gain of the pre and post amplifier, α is the attenuation constant, and d is the length of optical fiber.

The noise power present at the system output, N_{out} can be calculated from the source node a to destination node h as shown in Fig. 1 along with lightpath. For this noise due to individual components at respective points is to be calculated. Noise at point h is due to multiplexer, demultiplexer, pre & post amplifier and both optical switches and it is represented as,

$$(N_{out})_h = \frac{G_{amp_{Pre}} e^{-\alpha d} G_{amp_{Post}}}{L_{Mux} L_{Demux} L_{Switch}^2} N_{in} \quad (8)$$

where, N_{in} is the transmitted input noise power. Noise at point g is due to single optical switch, multiplexer, demultiplexer, and pre & post amplifier. This is represented with following equation.

$$(N_{out})_g = \frac{G_{amp_{Pre}} e^{-\alpha d} G_{amp_{Post}}}{L_{Mux} L_{Demux} L_{Switch}} \varepsilon \sum_{k=1}^{n} P_{Sw_1,k}(\lambda) \quad (9)$$

Noise at point f is due to multiplexer, single optical switch, and pre & post amplifier, which can be written as below.

$$(N_{out})_f = \frac{G_{amp_{pre}} e^{-\alpha d} G_{amp_{Post}}}{L_{Mux} L_{Switch}} \times \frac{hfB_0}{2} \left(F_{amp_{Pre}} + \frac{F_{amp_{Post}}}{e^{-\alpha d} G_{amp_{Pre}}} \right) \tag{10}$$

Noise inside the optical fiber along the points d and e is due to FWM. Also components like multiplexer, pre amplifier, and single optical switch induce the distortion. This can be represented with the following equation.

$$(N_{out})_{d-e} = \frac{G_{amp_{Pre}}}{L_{Mux} L_{Switch}} \sum_{k=1}^{m} P_{FWM_k}(\lambda) \tag{11}$$

Noise at the pre amplifier terminal i.e. at point c is induced only due to optical switch. This can be represented with the following equation.

$$(N_{out})_c = \varepsilon \sum_{k=1}^{s} P_{Sw_2,k}(\lambda) \tag{12}$$

The final expression for N_{out} is the summation of all the individual noise at respective terminals. Hence the noise at the receiver is represented as follows.

$$N_{out} = (N_{out})_h + (N_{out})_g + (N_{out})_f + (N_{out})_{d-e} + (N_{out})_c \tag{13}$$

This can further expressed in generalized form as follows.

$$\begin{aligned} N_{out} = & \frac{G_{amp_{Pre}} e^{-\alpha d} G_{amp_{Post}}}{L_{Mux} L_{Demux} L_{Switch}^2} N_{in} \\ & + \frac{G_{amp_{Pre}} e^{-\alpha d} G_{amp_{Post}}}{L_{Mux} L_{Demux} L_{Switch}} \varepsilon \sum_{k=1}^{n} P_{Sw_1,k}(\lambda) \\ & + \frac{G_{amp_{pre}} e^{-\alpha d} G_{amp_{Post}}}{L_{Mux} L_{Switch}} \\ & \times \frac{hfB_0}{2} \left(F_{amp_{Pre}} + \frac{F_{amp_{Post}}}{e^{-\alpha d} G_{amp_{Pre}}} \right) \\ & + \frac{G_{amp_{Pre}}}{L_{Mux} L_{Switch}} \sum_{k=1}^{m} P_{FWM_k}(\lambda) + \varepsilon \sum_{k=1}^{s} P_{Sw_2,k}(\lambda) \end{aligned} \tag{14}$$

N_{out} can also be represented as P_{ASE}. The ratio of P_{out} and N_{out} gives the $OSNR_{out}$. Considering a single route with i^{th} node, P_{out_i} is represented as follows,

$$P_{out_i} = \left(\frac{G_{amp_{Pre}} \, e^{-\alpha d} \, G_{amp_{Post}}}{L_{Mux} \, L_{Demux} \, L_{switch}} \right) P_{out_{i-1}} \tag{15}$$

and N_{out_i} is represented as follows.

$$\begin{aligned} N_{out_i} = & \frac{G_{amp_{Pre,i}} e^{-\alpha d_i} G_{amp_{Post,i}}}{L_{Mux} L_{Demux} L_{Switch}} N_{out_{i-1}} \\ & + \frac{G_{amp_{Pre,i}} e^{-\alpha d_i} G_{amp_{Post,i}}}{L_{Mux} L_{Demux} L_{Switch}} \varepsilon \sum_{k=1}^{n} P_{Sw_{i,k}}(\lambda) \\ & + \frac{G_{amp_{Pre,i}} e^{-\alpha d_i} G_{amp_{Post,i}}}{L_{Mux} L_{Switch}} \\ & \times \frac{hfB_0}{2} \left(F_{amp_{Pre,i}} + \frac{F_{amp_{Post,i}}}{e^{-\alpha d_i} G_{amp_{Pre,i}}} \right) \\ & + \frac{G_{amp_{Pre,i}}}{L_{Mux} L_{Switch}} \sum_{k=1}^{m} P_{FWM_{i,k}}(\lambda) + \varepsilon \sum_{k=1}^{s} P_{Sw_{i+1,k}}(\lambda) \end{aligned} \tag{16}$$

III. OSNR BASED ROUTING ALGORITHM

The least resistance weight (LRW) and shortest path (SP) algorithms proposed in reference [6, 18] uses a weight function to select the optimal path. The computation of weight metrics, $w_{i,j}$ is done for a (i, j) link pair which is equivalent to shortest path and represented as [18],

$$w_{i,j} = l_{i,j} \tag{17}$$

where, $l_{i,j}$ is the length of physical connection between (i, j) link.
The weight metrics function, $w_{i,j}$ for LRW approach is calculated for individual link and represented as [6],

$$w(i,j) = \begin{cases} \frac{\lambda_{\max}^T}{\lambda_{i,j}^A} & \lambda_{i,j}^A \neq 0 \\ \infty & \lambda_{i,j}^A = 0 \end{cases}$$

where $\lambda_{i,j}^A$ is the wavelength availability on link (i, j), $\lambda_{i,j}^T$ is the total number of wavelengths at link (i, j), and λ_{max}^T is the maximum number of wavelength available on the link such that $\lambda_{max}^T = max(\lambda_{i,j})^T$. Based on the algorithms 1 this paper proposes an OSNR-RWA technique which depends on the previous link together with the present connection. The noise induced at the i^{th} link is determined with the help of noise accumulated in the previous link. Therefore, a weighted approach is not considered here as it was applicable in traditional methods such as SP and LRW. It considers OSNR as a cost function metrics in which paths are selected based on threshold OSNR.

Algorithm 1 OSNR-RWA

Connection request R arrives for a (s, d) pair;
Check the available wavelength using first fit algorithm;
Calculate K shortest path of R by the shortest path algorithm;
Arrange the k shortest path as 1,2,....k in accordance with ascending order of the length;
for (i^{th} shortest path $(i \leq k)$)
    Assign the wavelength
    Calculate the OSNR
    if ($OSNR \leq OSNR_{threshold}$)
        Establish the connection
    else Block the connection
    end if
    i=i+1
end for

IV. RESULT AND DISCUSSION

A National Science Foundation Network (NSFNet) is a North-American topology that consists of 10 nodes and 16 links as shown in Fig. 2 has been taken into consideration for numerical analysis. Few system parameters are assumed and shown in Table 1. The proposed routing algorithm is used to establish the connection for a call request has been explained in algorithm 1.

TABLE I
SYSTEM PARAMETERS

Parameters	Value
Amplifier saturation power, P_{sat}	16 dBm
OSNR threshold	7.4 dB for BER = 10^{-9}
PMD coefficient, D_{pmd}	0.5 ps/$\sqrt{km}$
Optical bandwidth, B_0	70 GHz
Electrical bandwidth, B_e	4 GHz
Channel spacing, Δ_f	100 GHz
Initial wavelength , λ_i	1553.3 nm
Attenuation coefficient, α	0.2 dB/Km
Tap loss, L_{tap}	1dB
Multiplexer loss, L_{mux}	3dB
Demultiplexer loss, L_{demux}	3dB
Optical switch loss, L_{switch}	3dB
Amplifier noise figure, F_0	3.162 (5 dB)
Noise factor model parameter, A_1	100
Noise factor model parameter, $A2$	4 W
Switch isolation parameter, ϵ	-40 dB
pulse broadening factor, δ	0.1

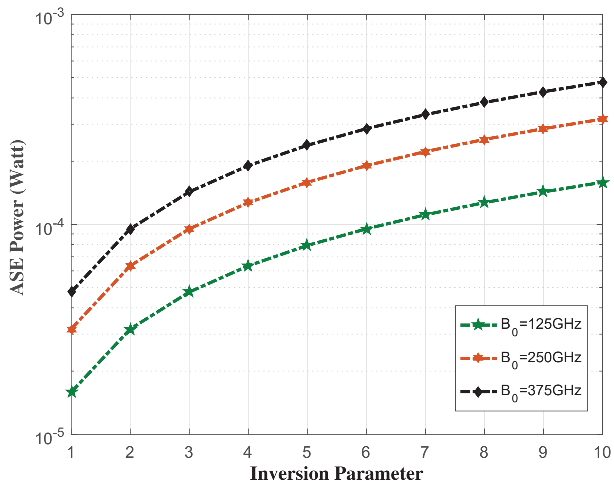

Fig. 3. Comparison of ASE noise power versus inversion parameter at different optical bandwidths

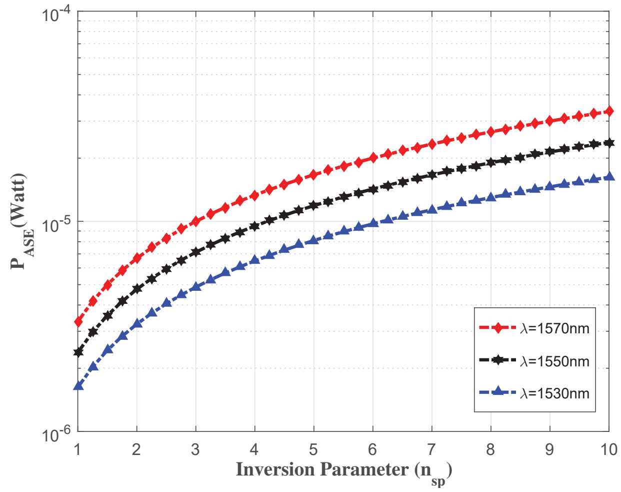

Fig. 4. Comparison of ASE noise power versus inversion parameter at different wavelengths

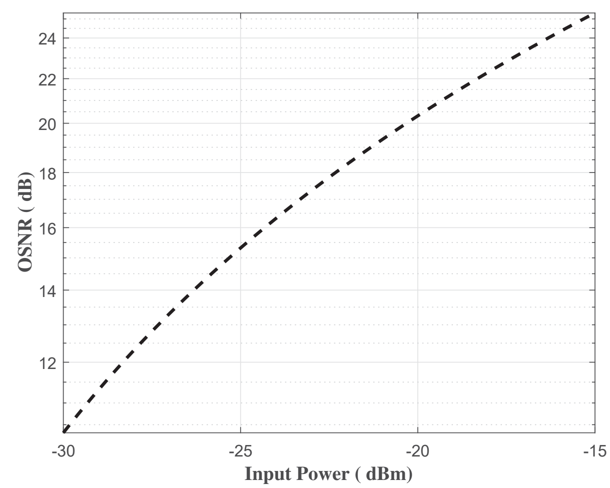

Fig. 5. OSNR versus input signal power (in dBm)

Fig. 3 shows ASE noise power (P_{ASE}) distribution versus inversion parameter (n_{sp}) at optical bandwidth (B_0) for B_0 equals 125 GHz, 250 GHz, and 375 GHz. The plot indicates how the P_{ASE} increases with higher B_0. Fig. 4 presents (P_{ASE}) versus n_{sp} at different wavelengths with a constant amplifier gain of 24 dB. It shows that P_{ASE} has a higher value for higher wavelength. This paper observes that (P_{ASE}) is maximum for those channels which transmit data at an optical bandwidth (B_0) of 375 GHz and wavelength (λ)= 1570 nm. Therefore, it shows that the effect of ASE noise power is more prominent over those channels which are transmitting signals at higher wavelength and optical bandwidth. Fig. 5 presents the (P_{ASE}) versus input signal power. In this case, OSNR increases with increase in input power that may degrade the system performance. Fig. 6 shows the system performance with the variation of network load by considering NSFNet topology for different routing schemes. From the simulation study, it is clearly visible that the proposed algorithm gives better performance as compared to LRW and SP algorithms. If some routes are busy, then OSNR of those lightpaths will be high. Therefore OSNR-RWA algorithm will not consider them for wavelength assignment which results in lower blocking probability.

V. CONCLUSION

This work presents a mathematical model for ASE noise power in an optical network. This model is basically a presentation of OSNR degradation along an optical channel for each and every lightpath connection. It considers the gain saturation in the optical amplifier, also ASE noise power, coherent crosstalk due to optical switches, and noise due to multiplexer and demultiplexer. The network performance has been analysed by using the OSNR-RWA algorithm for solving the RWA problem. From the literature survey and simulation

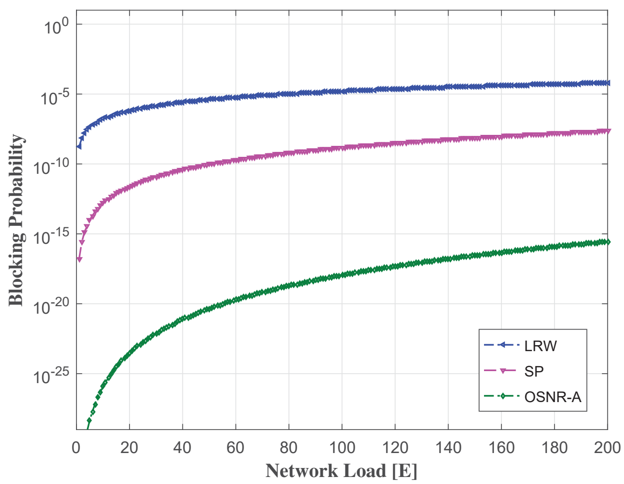

Fig. 6. Blocking probability versus network load for different RWA schemes

results, it is concluded that the network performance of the proposed algorithm in terms of BP is better than the other wavelength assignment techniques.

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