Study of Q-factor Estimation Model Based on Multi-Physical Impairments in Transparent Optical Networks

Jijun Zhao
School of Information Science and Electrical Engineering, Hebei University of Engineering, Handan, China
Email: zjijun@gmail.com

Kai Zhang, Lirong Wang
School of Information Science and Electrical Engineering, Hebei University of Engineering, Handan, China
Email: 666zk888@gmail.com
liukaironghua@163.com

Yi Wang
School of Science, Hebei University of Engineering, Handan, China
Email: onlab@qq.com

Abstract—**Optical networks are in the evolution of transparent architectures, the effects of the physical layer impairments are becoming more and more prominent. This paper setting out from multiple physical impairments, analyzes the effects as well as the diversity and complexity of the physical layer impairments in optical networks, investigates the issue of the current-related physical layer impairments estimation models which only consider a simple impairment, and at last, proposes a physical layer impairments estimation model considering multiple physical impairments based on the Q-factor. The results show that this model can be more accurate in estimating the state of physical layer impairments in the lightpath and make the physical layer impairments routing and wavelength assignment (PLI-RWA) algorithm more effective to avoid the effects of the physical layer impairments in routing.**

Index Terms—**Transparent optical networks; physical layer impairments; Q-factor; estimation model; PLI-RWA**

I. INTRODUCTION

Optical networks are evolving from traditional opaque optical networks and translucent optical networks to transparent optical networks[1]. In opaque optical networks, all the switching and routing nodes have optical-electronic-optical (O-E-O) conversions which can improve the quality of optical signals in order to make the optical signal reach long distances. As well as in translucent optical networks, a part of its nodes have the O-E-O conversion devices. Taking the availability and economy into account, the transmission range of optical signal is limited (eg.2000Km-2500Km)[2]. The emerging transparent optical networks use optical cross connects (OXCs) and optical add-drop multiplexer (OADM) to replace the demand for O-E-O conversion devices. The excellent characteristics of OXCs and OADM, such as transparency, economy, scalability, high degree of flexibility, large capacity and so on, make transparent optical networks become the first choice for the high speed Fiber Optical Communication Network in the future. In traditional opaque or translucent optical networks, the networks rely on the periodic conversion to ensure the quality of the signal and have a very low bit error rate (BER). But in transparent optical networks, the optical signal from the source node through the whole lightpath to the destination node remains in the optical domain. As there is no electrical regeneration device, transparent optical networks can provide huge bandwidth with low expenses which can effectively deliver various types of business signals and do not need to consider the format of optical signal. However, the same as there is no electricity regeneration device, the physical layer impairments generated by the non-ideal optical components which constitute the lightpath can accumulate along the lightpath, resulting in a distortion of the optical signal. With the transmission bandwidth of optical networks increasing, the adverse effects of physical layer impairments on transmission quality will become more and more prominent. It can significantly reduce the quality of the optical signal and lead to a high BER at the destination[3][4]. All in all, it seriously affects the transmission performance of optical networks.

In transparent optical networks, the physical layer impairments have the characteristics of diversity and complexity[5], which have a challenge to the solving of the routing and wavelength assignment (RWA) problem. The physical layer impairments are generally classified into linear physical layer impairments and non-linear

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physical layer impairments. The former are independent of the signal power and only affect each of the optical channels (wavelengths) individually, while the latter are very complex, which not only affect each channel but also cause crosstalk between them[6]. In order to ensure the Quality of Transmission (QoT) of optical networks, the study of how to circumvent the effect of physical layer impairments in RWA is very essential.

In the past, studies usually estimate the effects of the physical layer impairments on the QoT through the establishment of a physical layer impairments model. In these studies, the construction and analysis of the physical layer impairments model is the key and foundation. Currently, the models are usually classified into two kinds in many studies: optical signal to noise ratio (OSNR) model[7][8][9] and Q-factor model[10][11][12].But most of these models usually only consider one kind of the physical layer impairments' effects or convert the effects of a few physical layer impairments into a index (eg. OSNR or Q-factor) which is used to estimate the quality of the optical signal. Apparently, these models above are not precise enough and also difficult to completely reflect the effects of all the physical layer impairments. Although increasing the number of impairments may lead to the increasement of the algorithm's complexity, but it can be more accurate to reflect the effects of the physical layer impairments in optical networks, so as to avoid using the link whose impairments are very serious and ensure the quality of the optical signal. In this paper, we re-examine the original model in multiple physical impairments environment and propose a Q-factor estimation model based on multiple physical impairments constraint. It can reflect the condition of optical networks more realistically.

The rest of this paper is organized as follows: Section II discusses the physical layer impairments and the detailed design of the Q-factor model. Section III describes the environment and related works of numerical simulations. The Q-factor model is subsequently applied to different reference network topologies, and the simulation results are shown in section IV. Finally. Section V concludes this paper and states the future work.

II. Q-FACTOR MODEL

The proposed Q-factor model is based on the accumulation of the physical layer impairments in the span of optical networks.

According to the various conditions of the optical span, such as light signals adding in or drop out, the number of channels, the length of the optical fiber and so on, this model calculate the whole impairments of the route. Fig. 1 shows the structure of a span in optical networks.

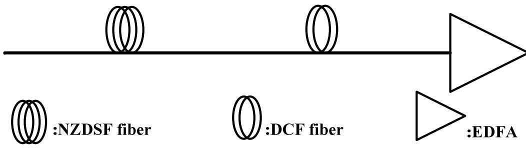


Figure 1. Structure of a span in optical networks

A link consists of many optical spans with magnifier function, assuming that all the span are the same and the parameters of the same type optical device are the same in optical networks. The link model for calculating the impairments is given by Fig. 2 and the structure of the node in WDM wavelength routing networks is shown in Fig. 3[12]. This node with 2W ports can handle N wavelengths and can add or drop K lightpaths respectively. From the above link model and the node structure, we can conclude that when a connection is set up, the light signal will undergo the source node, then multiple links and at last arrive at the destination node. In addition, at each link it will undergo the routing node as well as the corresponding optical span. The optical signal undergo different devices can introduce different physical layer impairments as shown in Fig. 2.

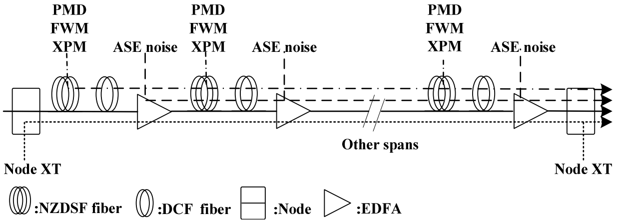


Figure 2. Model of a transmission link

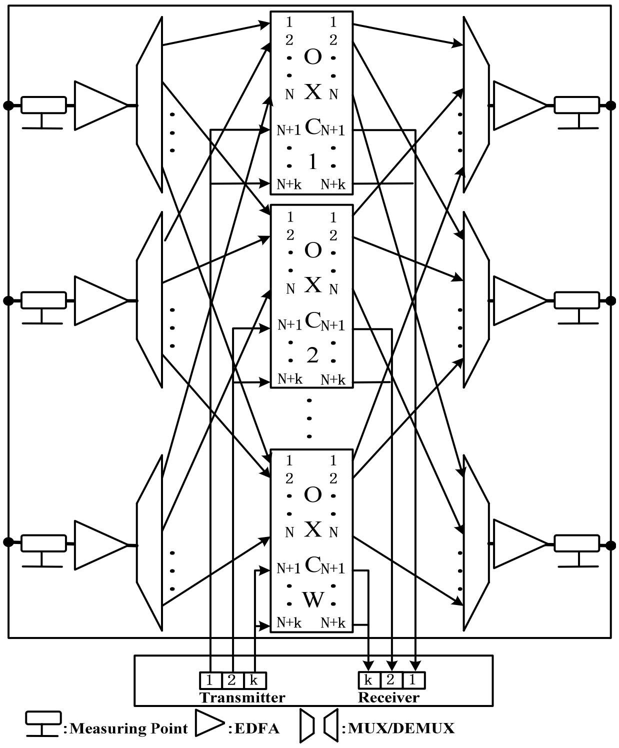


Figure 3. Network node conformation

In this paper, we considered five kinds of impairments such as the Amplifier Spontaneous Emission (ASE) noise, Polarization Mode Dispersion (PMD), Crosstalk (XT), Cross Phase Modulation (XPM) and Four Wave Mixing (FWM), which have a serious effect on the quality of optical signals. Nonlinear impairments such as the XPM and FWM represent a kind of unusual important physical layer impairments, this is due to that the noise power of these impairments is not only the simple accumulation of the impairments generated in each link even in the whole lightpath, but also varying the network's state. When XPM and FWM are calculated in each span, in contrast to the huge attenuation of the Non-Zero Dispersion Shifted Fiber (NZDSF)[13], the XPM and FWM generated in the Dispersion Compensation Fiber (DCF) can be neglected.

The effects of almost all the impairments can be reflected by the transmission BER which is a performance index of optical networks. Under the assumption of Gaussian noise distribution, there is a relationship between the Q-factor value and the transmission BER. The following equation describes the relationship between them:

$$BER = \frac{1}{2}\mathrm{erfc}\left(\frac{\mathrm{Q}}{\sqrt{2}}\right) \cong \frac{1}{\mathrm{Q}\sqrt{2\pi}} e^{-\frac{\mathrm{Q}}{2}} \tag{1}$$

where,

$$\mathrm{erfc}(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{\alpha^2}{2}} d\alpha$$

In the physical layer impairments estimation model, the effects of the physical layer impairments will be converted into the decrease of Q-factor value. According to the request of the QoT performance in the network, we use (1) to calculate the relevant threshold $\mathrm{Q}_{\mathrm{limit}}$. When there is a connection request, use the estimation model to calculate the Q-factor value of the signal at the destination node of the candidate lightpath, and compare it with $\mathrm{Q}_{\mathrm{limit}}$ to determine the candidate lightpath whether it can meet the QoT demand or not.

In this paper, we defined the probe channel and pump channels, as shown in Fig. 4. The channel on our lightpath of interest is the probe channel (eg. Lightpath 3) and the channels on its co-propagating lightpaths are the pump channels (eg. Lightpath 1,2,4) which can change varying the routing.

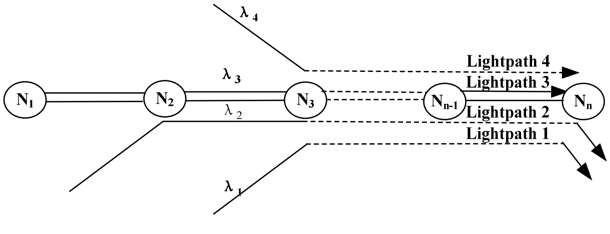


Figure 4. probe channel and pump channels

Assuming that the impairments are independent and all the signals in the channels are CW sources, the Q factor can be defined as (2)[14].

$$\mathrm{Q} = 10\log_{10}\frac{P_s}{\sigma_{total}+\sigma_0} \approx 10\log_{10}\frac{P_s}{\sigma_{total}} \tag{2}$$

where $\sigma_{\mathrm{total}}{}^2 = \sigma_{\mathrm{ase}}{}^2 + \sigma_{\mathrm{fwm}}{}^2 + \sigma_{\mathrm{xpm}}{}^2 + \sigma_{\mathrm{XT}}{}^2$, σ_0 is the standard deviation assigned to zeros of the signal (considering σ_{total}□ σ_0 , σ_0 was set 0); P_s is the peak power of the signal in the channel.

The following will discuss the impairments respectively which involved in Q-factor formula.

A. Amplifier Spontaneous Emission Noise

At the end of a lightpath and before optical-detection, the total ASE noise power on a lightpath L can be computed using (3):

$$ASE_L = \sum_{\mathrm{n}\in L} ASE(\mathrm{n}) \tag{3}$$

where *ASE(n)* is the sum of ASE noise power generated by Erbium-doped Optical Fiber Amplifiers (EDFAs) on a periodically amplified link n. The light power generated by an EDFA can be computed using (4):

$$P_{ase} = (G-1)F_n hfB_O \tag{4}$$

where *G* is the optical gain of the EDFA, F_n is the noise figure of the EDFA, *h* is the Planck constant, *f* is the frequency of the optical signal in the channel, B_o is the bandwidth of the channel.

After optical-detection, the ASE noise variance of the signal can be computed using (5):

$$\sigma_{ase}^2 = 2P_O ASE_L \tag{5}$$

where P_o is the power of the optical channel.

B. Crosstalk

The XT variance can be computed using (6)[15]:

$$\sigma_{XT}^2 = \rho^2 P_O P_{XT} \tag{6}$$

where ρ is the receiver sensitivity, P_{XT} is the sum of all terms XT noise power at the receiver.

C. Cross Phase Modulation

In WDM systems, the total XPM noise power generated by a probe channel can be computed using (7):

$$\sigma_{xpm}^2 = \overline{P(0)}^2 \sum_{i\in Num} \frac{1}{2\pi} \int_{-\infty}^{\infty} X(\omega) d\omega \tag{7}$$

$$X(\omega) = \left|H_{xpm,i}(\omega)\right|^2 \left|H_{filter}(\omega)\right|^2 PSD_i(\omega)$$

where $\overline{P(0)}$ is the average power of probe channel at the beginning of a optical link, Num is the number of the pump channels, $H_{xpm,i}(\omega)$ is the transfer function of XPM, $H_{filter}(\omega)$ is the transfer function of the optical filter and $PSD_i(\omega)$ is the power spectrum density of the channel *i* respectively.

For an optical link with N-span, the XPM transfer function of a pump channel λ_k relative to the probe channel λ_c is given by (8):

$$H(w) = \frac{1}{\overline{\overline{P_C(0,\ T)}}p_k(0,w)} \sum_{n=1}^{N} \int_{z=0}^{z=L_n} g(z,w)p_k(z,w)dz \tag{8}$$

$$p_k(z,w) = \frac{p_k(0,w)}{e^{(\alpha_{\mathrm{n}}z + jwzD_n(\lambda_c-\lambda_k) + jwD_n^I\Delta\lambda_{ck})}} \cos\left(\frac{w^2\lambda_k{}^2(D_n^I + \mathrm{z}\cdot D_n)}{4\pi c}\right) \tag{9}$$

$$g(z,w)=4e^{z\alpha_n}\overline{P_C(z,T)}\gamma_n\sin\left(\frac{w^2\lambda_c^{\ 2}(D_S-D^I_n-z\cdot D_n)}{4\pi c}\right) \quad (10)$$

where $\overline{P_C(z,T)}$ is the average power of the probe channel at position z, $P_k(z,w)$ is the power evolution function, *g (z ,w) i*s the new XPM transfer function, α_n is the fiber attenuation coefficient, D^I_n is the sum of dispersion from the beginning to the n-th span of the lightpath, L_n is the length of a fiber span, γ_n is the nonlinear coefficient of the fiber, D_n is the dispersion coefficient of the fiber, D_S is the residual dispersion of the link and c is the speed of light.

D. Four Wave Mixing

1) Mixing of three-photon. In the condition of three photons mixed into one photon, the frequency of the new photon is given by (11):

$$W_4=W_1+W_2+W_3 \quad (11)$$

2) Mixing of two-photon. The annihilation of two photons with frequency of W_1 and W_2 generate two new photons with frequency of W_1 and W_2. The variety of the frequency in this process is given by (12):

$$W_1+W_2=W_3+W_4 \quad (12)$$

For a WDM system, multiple combinations can generate FWM light in an optical signal channel and the total power of the FWM light can be computed using (13):

$$P_{fwm}=\sum_{\omega,n,q}P_{(\omega,n,q)} \quad (13)$$

where $P_{(w,n,q)}$ is the power of any FWM light generated by any multiple combinations with frequency W_ω, W_n and W_q. The noise caused by FWM can be computed using (14):

$$\sigma^2_{fwm}=2P_OP_{fwm} \quad (14)$$

The model of the PMD effect has association with a multiplicative factor. The Q-factor related to PMD can be defined as (15). After computing the Q-factor value related to PMD, we can superimpose it on the original Q-factor value.

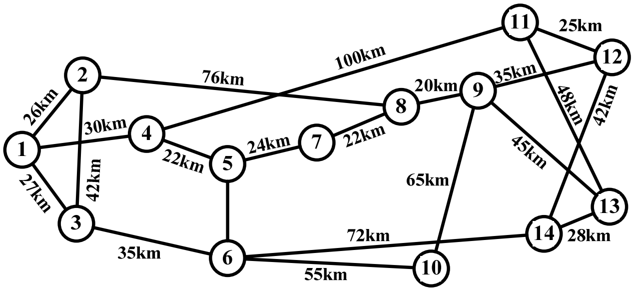
$$Q_{est}=\frac{\eta_{PMD}P_{cp}}{\sigma_{total}+\sigma_0}\approx\frac{\eta_{PMD}P_{cp}}{\sigma_{total}} \quad (15)$$

where η_{PMD} is the multiplicative factor[16], P_{cp} is a term when modeling filter concatenation impairment as an eye closure penalty[17].

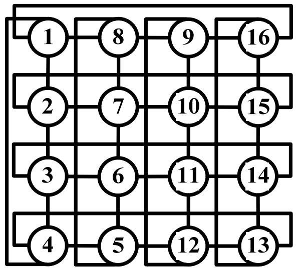
This Q-factor estimation model considers most important linear and non-linear physical layer impairments. Using the mathematical methods to quantitative calculate, it can estimate the condition of the physical layer impairments in optical networks more realistically.

III. NUMERICAL SIMULATIONS

In order to verify the property of the model, we use the NSF network (NSFNET) topology, which has 14 nodes and 21 bidirectional fiber links, and 16 nodes mesh toroid network (MESHNET)[15] topology with identical link length of 100 kilometers, which are depicted in Fig. 5.



(a) Topology of the NSFNET



(b) Topology of the MESHNET

Figure 5. Network topologies

We use a low signal power to ensure the validity of the signal analysis. We make the assumption that the connection request submitted to random Poisson distribution, the source/destination nodes are well-distributed among each node pair and the network node without the ability of the wavelength conversion. We also assume that the physical layer impairments are independent when multiple physical impairments are present at a time and there is no residual dispersion in each link.

We use the classic RWA algorithm to verify the performance of the proposed model. Using K-Shortest Paths (K-SP, K=3) algorithm to solve the routing sub-problem and First-fit (FF) algorithm to solve the wavelength assignment sub-problem.

Simulation algorithms work process:

1) RWA algorithm module. When there is a connection request, K-shortest paths are computed which are again processed in order. Then, use the FF algorithm to select an available wavelength from the available wavelengths.

2) The physical layer impairments constraint module. If there is no blocking caused by the lack of resources during the routing and wavelength assignment process, enable the proposed model to estimate the effects of the physical layer impairments on the path and obtain the Q-factor value. If the Q-factor value is lower than the Q_{limit} (eg. BER ≈ 2×10^{-28}, Q = 11dB) which is a pre-set threshold, the path will be blocked, otherwise respond to the connection request.

The flowchart of the algorithm is given by Fig. 6.

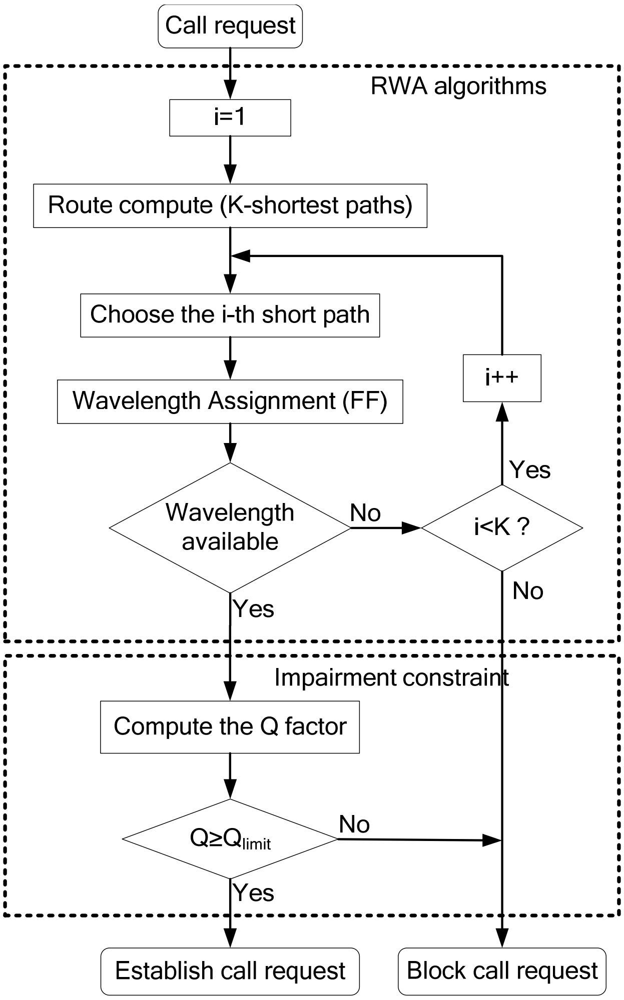


Figure 6. Flowchart of the algorithm

The parameters of the network are summarized in Table 1.

TABLE I.
PARAMETERS USED IN SIMULATION

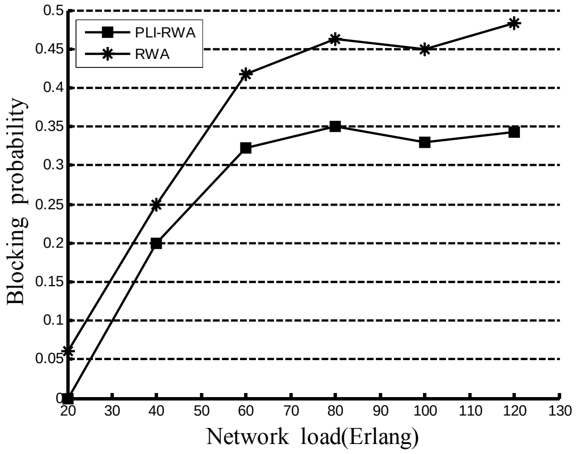
Parameter	Value	Parameter	Value
G	21.6dB	L_n	80Km
n_{sp}	1.5	γ_n	2/(Km*W)
α_n	0.25dB/Km	ρ	0.95A/W
D_n	4ps/(Km*nm)	B_O	40GHz
f	193.1THz	P_O	1mW
f_{step}	50GHz	Q_{limit}	configurable
c	299792Km/s	h	6.626×10^{-34} J / s

IV. SIMULATION RESULTS

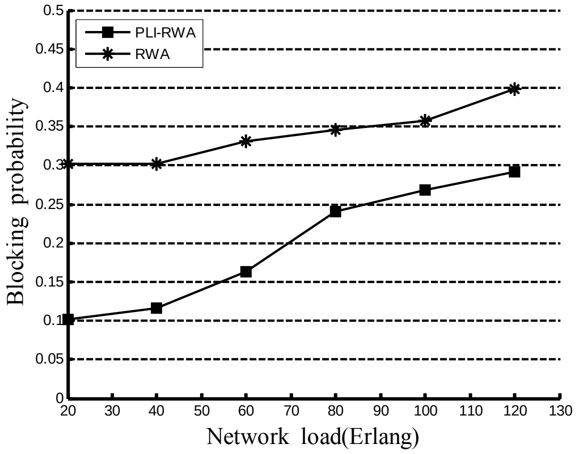
We have compared the blocking rate evaluated by using the above PLI-RWA algorithm with that using classic RWA algorithm for each network topology. In each algorithm, the method of routing and wavelength assignment is the same and the simulation environment is also the same. We consider 40 channels per fiber.

The simulation results are shown in Fig. 7. Fig. 7 (a) compares the blocking rate of different algorithms in the NSFNET topology. Fig. 7 (b) compares the blocking rate of different algorithms in the MESHNET topology.

It can be seen from Fig. 7, compared with the classical RWA algorithm in both topologies, using the model can decrease the blocking rate in varying degrees. It shows that not only in regular network topology but also in irregular network topology, the model can effectively estimate the impairments in the network. In MESHNET topology, the blocking rate has a significant decline, which shows that the performance of the network is improved significantly. In NSFNET topology, the improving of the blocking rate is not obvious when there is a low load, but at the high load cases, the blocking rate of the two algorithms are greatly different. It shows that the model can obviously improve the network performance especially in regular networks and the large scale irregular networks with high load.



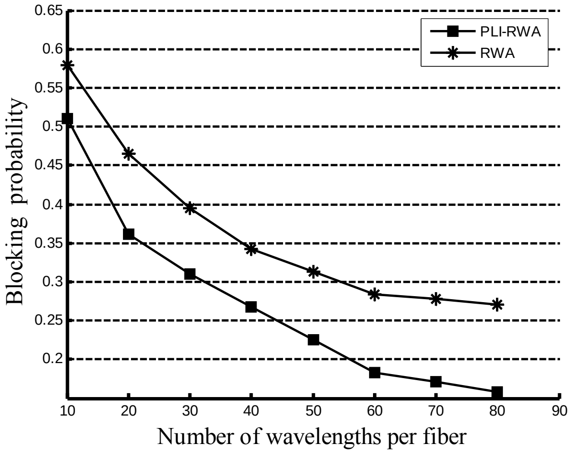
(a) Blocking probability in NSFNET topology



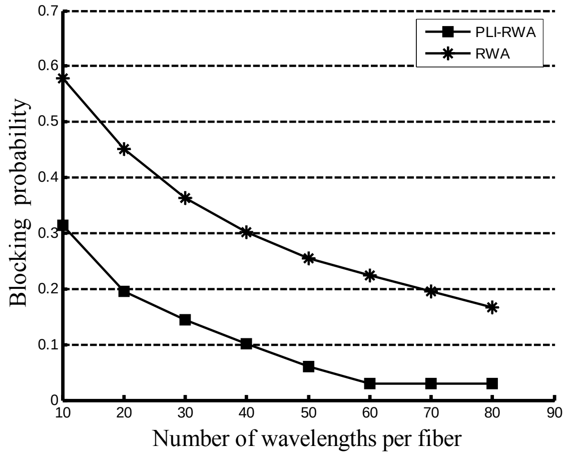
(b) Blocking probability in MESHNET topology

Figure 7. Simulation diagram of blocking probability/network load

In addition, we have simulated the evolution of the blocking rate, varying the traffic maximum available number of wavelengths in a single fiber to further illustrate the applicability of the model. The simulation results of the two algorithms in two kinds of topologies are shown in Fig. 8. It can be seen that the blocking rate when using the proposed model is lower. When the number of wavelengths <30, as the maximum available number of wavelengths increasing, the blocking rate decrease faster. This is because the blocking of the path is mainly caused by the lack of resources. But after that, with the increase of the maximum available number, the speed will slow down, especially in the classic RWA algorithm. When the number of wavelengths reaches a certain value, the blocking rate becomes stabilized. This shows that the blocking due to impairments becomes the main factors in the network.



(a) Blocking probability in NSFNET topology



(b) Blocking probability in MESHNET topology

Figure 8. Simulation diagram of blocking probability/ number of wavelengths per fiber

Finally, we use the average computation time of the algorithm to show the validity of the model. The simulation result is shown in Fig. 9.

As shown in Fig. 9, the average computation time of the PLI-RWA algorithm with the model is longer than the classical RWA algorithm. This is due to that the former algorithm has to use the model to collect the impairments that the signal suffered in the process of signal transmission in the election of route and wavelength assignment, then to quantitatively calculate them and to verify the quality of the signal, which lead to an increase of the computational time. While the latter algorithm only considered the path's length and the idle wavelength between two nodes. This shows that taking into account the effects of physical layer impairments in algorithms in order to enable the signal to circumvent the effect of physical layer impairments and obtain a higher QoT is at the cost of computational time. The effects of physical layer impairments is becoming a more and more serious problem and the calculation of the physical layer impairments especially the nonlinear impairments is very complex, taking a comprehensive consideration, the model can significantly improve the network's performance however the average computation time of the algorithm using the model only increase about 100% in this paper.

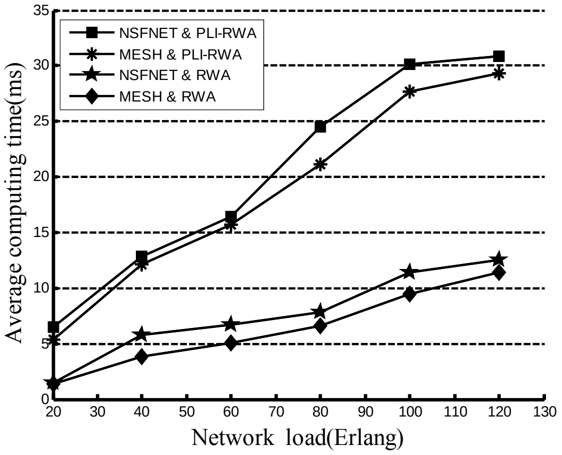


Figure 9. Comparison of the average computing time of different algorithms and topologies

V. CONCLUSIONS

In this paper, we proposed a novel analytical model for estimating the effects of physical layer impairments in transparent optical networks. The model is based on the Q-factor. It is not only can quantitatively calculate those mentioned physical layer impairments, but also can take any physical layer impairment into account when it is necessary. We also presented the simulation of the proposed model in impairment-constraint routing, combined the model with classic RWA algorithm, the results show that this model is more suitable in complex optical networks.

In our research, we haven't combined the constraint of the model with the awareness of physical layer impairments and also haven't proposed our new algorithm framework. According to the intelligence needs of optical networks, the proposing of an adaptive physical layer impairments awareness and constrained RWA algorithm is our work in future.

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Jijun Zhao Birthdate: Sept. 1970. He received his Ph.D. degree in Electromagnetic Field and Microwave Technique from Beijing University of Posts (BUPT), Beijing, China, in 2003. He accomplished postdoctoral researcher at the ZTE Corporation (ZTE).

He is now a Professor in Hebei University of Engineering, Handan, China. His current research interest includes the next generation optical networks, broadband communication networks and wireless sensor networks. Prof. Zhao has been the principle/co-investigator in several research projects funded by the National High Technology Research and Development Program of China (863 Program), the National Natural Science Foundation of China (NSFC), and other important foundations. He is a senior member of Chinese Optical Society(COS) and also a member of Optical Society of America (ACM) and China Computer Federation(CCF).

Kai Zhang Birthdate: Dec. 1987. He earned his B.S. degree from Hebei University of Engineering, Handan, China, in Automation in 2010. And at the same time he was allowed to entrance this university again for further study without examination. At present, he is studying at Hebei University of Engineering for M.S. degree in Optical Networks. His research is mainly focus on physical layer impairments and RWA in optical networks. He is a student member of CCF.

Lirong Wang Birthdate: May 1973. She received her B.S. degree from Hebei University, Baoding, China, in Applied Physics and the M.S. degree in Optical Networks from Hebei University of Engineering, Handan, China, in 1994, 2009. Her main research interest is routing technology in optical networks. She is now teaching at Handan Polytechnic College, Handan, China.

Yi Wang Birthdate: Nov. 1979. He received his B.S. degree from Hebei Normal University, Shijiazhuang, China, in Physics in 2002. Since 2011, he is studying for his M.S. degree from Hebei University of Engineering, Handan, China. His research is on Optical Fiber Communications, and he is also a lecturer and works at School of Science, Hebei University of Engineering.