Impact of Routing Approaches on Network-Layer and Physical-Layer in Wavelength Routed Optical Networks

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Abstract: The all-optical transparent wavelength routed network is a promising candidate for the next-generation backbone network to provide large bandwidth at low cost. Due to transmission impairments, present in fibers and optical components, may significantly affect the quality of a lightpath, and, hence, in wavelength routed transparent optical networks, the best routing optimization, which is determined only by network-layer performance, might not be the best one or even worse after physical-layer performance taken into account. In order to overcome the above limitation, in this paper, we propose that routing optimizations should be evaluated from both network-layer performance and physical-layer performance and the best routing optimization should be chosen based on the overall performances, not just the network-layer performance.

Keyword: Wavelength routed optical networks, routing optimization**,** network-layer performance, physical-layer performance, routing algorithm

I. Introduction

The all-optical transparent wavelength routed network is a promising candidate for the next-generation backbone network to provide large bandwidth at low cost. In such networks, a connection is set up via an all-optical WDM channel called a lightpath. Data signal of a lightpath is transmitted totally in the optical domain without any need for optical-to-electrical conversion/regeneration from source to destination, and this is called the transparency property of optical networks. Setting up a lightpath for each connection is done by using a routing and wavelength assignment (RWA) technique [1]. Intelligent RWA is an important issue for minimizing cost and better utilizing network resources, and in reality is an optimization problem. The cost objective function, for minimizing cost and best utilizing network resources, can be different forms; can minimize wavelength requirements of network, minimize number or total length of required fibers for network and so on. Each form of cost objective function introduces a routing optimization approach.

A large amount of RWA problems by different approaches have been investigated under the assumption that the physical layer is an ideal one to transmit data signal without any bit error [1-19]. In these approaches, only the constraints of network layer are considered in RWA problem and physical layer is assumed to be ideal without any transmission impairments. However, transmission impairments, present in fibers and optical components, may significantly affect the quality of a lightpath [20, 21], and, hence, in wavelength routed transparent optical networks, the best routing optimization, which is determined only by network-layer performance, might not be the best one or even worse after physical-layer performance taken into account.

In order to overcome the above limitation, in this paper, we propose that routing optimizations should be evaluated from both network-layer performance and physical-layer performance and the best routing optimization should be chosen based on the overall performances, not just the network-layer performance. Our work in this paper is trying to comprehensively evaluate some candidate routing algorithms, and then choose the one having the best overall performance for particular optical network.

In this paper, we have four sections that contribute to present our work and previous related works. In section 2, we derive the optical signal to noise ratio (OSNR) analytic model for wavelength routed optical network with optical cross-connects (OXCs). In section 3, we introduce two published routing optimizations and propose a new routing optimization. At the same time, we introduce the corresponding routing algorithms to solve above routing optimization problems. In section 4, we introduce method of performance evaluation for three routing optimizations, including: network-layer and physical-layer performance evaluation method, and through applying three routing algorithms (corresponding to three routing optimizations) to a sample network, we make the performance evaluations among the three routing optimizations and make conclusion to determine which routing optimization is the best for sample network, under given conditions. In section 5, through combining network-layer and physical-layer performance resulted from section 4, we make an overall performance evaluation, and our conclusions are given in sectionn6.

II. OSNR Analytic Model for Wavelength Routed Optical Networks

In this paper, we extended the previous work in [22], in which the OSNR is analyzed for transmission line with cascaded optical amplifiers, and we derived the OSNR analysis for wavelength routed optical network with cascaded optical amplifiers and optical cross-connects standing between source and destination nodes. Thus the signal transmission performance can be evaluated in the wavelength routed optical network. In an optical path, optical signal may have to pass through a number of optical cross-connects, fiber segments, and optical amplifiers. Thus, while propagating through the network, the signal degrades in quality as it loses power caused by fiber attenuation and encounters crosstalk at the OXC and also picks up amplified spontaneous emission (ASE) noise at the optical amplifiers.

The normalized OSNR for a 1.55 µm WDM system with several optical transmission spans without intermediate node was showed in [22]. Transmission span means the distance between two optical amplifiers. And the equation is showed in Equ. (1), with following assumptions:

- Both optical gain and noise figure are uniform for all channels.
- Adjacent channel space is wide enough to keep crosstalk low.
- Signal transmission power is chosen to avoid the nonlinear effect in the optical fiber.

$$\begin{aligned} \mathrm{OSNR}_{\mathrm{norm}} &= \mathrm{G}_{\mathrm{preamp}} - (\mathrm{P}_{\mathrm{rec}} + \mathrm{NF}_{\mathrm{rec}}) \\ &\quad + \mathrm{P}_{\mathrm{out}} - 10\log_{10}(\mathrm{M}_{\mathrm{ch}}) - \mathrm{Loss}_{\mathrm{span}} \\ &\quad - \mathrm{NF}_{\mathrm{ASE}} - 10\log_{10}(\mathrm{Num}_{\mathrm{span}} + 1) \end{aligned} \quad (1)$$

Where OSNR is normalized to 0.1 nm bandwidth, and:

$\mathrm{P}_{\mathrm{rec}}$: the receiver sensitivity in dBm related with bit error rate (BER) and data rate for typical photonic receiver,

$\mathrm{NF}_{\mathrm{rec}}$: the receiver noise figure in dB,

$\mathrm{P}_{\mathrm{out}}$: the inline optical amplifier output power in dBm,

$\mathrm{G}_{\mathrm{preamp}}$: the Preamplifier gain in dB,

M_{ch} : number of wavelength channels in the transmission fiber,

$\mathrm{Loss}_{\mathrm{span}}$: the optical power loss at the distance of one span in dB,

$\mathrm{NF}_{\mathrm{ASE}}$: the optical amplifier noise figure in dB, and

$\mathrm{Num}_{\mathrm{span}}$: number of spans.

The function of OXC is to flexibly switch wavelengths among different input-output fibers. Because of the OXC's imperfect performance, the insertion loss and crosstalk are induced.

Assuming aligned polarizations, it has been shown in [23, 24] that the probability density function (PDF) for the resultant aggregate interference is approximately Gaussian, which leads to a power penalty given by Equ. (2).

$$\mathrm{PP} = -5\log_{10}(1 - 4\mathrm{Q}^2\mathrm{N}_{\mathrm{XT}}\varepsilon) \quad (2)$$

Where Q is the Q-factor corresponding to the reference BER, N_{XT} is number of interferers due to crosstalk are present with random phases, each with an intensity $\mathrm{I}_{\mathrm{XT}} = \varepsilon \mathrm{I}_{\mathrm{S}}$.

Here we apply the worst case used in [25] for the power penalty caused by incoherent crosstalk contributions. In an OXC with N input/output fibers and M λs on each fiber, assuming the OXC is fully loaded, each signal passing through the OXC will be interfered by M+N-2 crosstalk contributions, N-1 of which are leaked by the optical switch, and the other M-1 are leaked by the demultiplexer-/multiplexer pairs.

Based on above assumptions, the power penalty from crosstalk contributions in one OXC is as Equ. (3), and the power penalty from crosstalk contributions after L intermediate OXCs is as Equ. (4).

$$\begin{aligned} \max(\mathrm{PP}_{1\,\mathrm{OXC}}) &= -5\log_{10}[1 - 4\mathrm{Q}^2.\max(\mathrm{N}_{\mathrm{XT}})\varepsilon] \\ &= -5\log_{10}[1 - 4\mathrm{Q}^2(\mathrm{M} + \mathrm{N} - 2)\varepsilon] \end{aligned} \quad (3)$$

$$\begin{aligned} \max(\mathrm{PP}_{\mathrm{L\,OXC's}}) &= -5\log_{10}[1 - 4\mathrm{Q}^2.\max(\mathrm{N}_{\mathrm{XT}})\varepsilon] \\ &= -5\log_{10}[1 - 4\mathrm{Q}^2(\sum_{l=1}^{L}\mathrm{M}_l + \sum_{l=1}^{L}\mathrm{N}_l - 2\times \mathrm{L})\varepsilon] \end{aligned} \quad (4)$$

Where:

M_l: the number of wavelengths carried by each fiber in the l'th intermediate OXC, and

N_l : the number of input/output fiber ports to the l 'th intermediate OXC.

Through directly applying equ. (1) and (4), to a lightpath in a wavelength routed optical network, the OSNR relation for a lightpath is derived as equ. (5).

$$\begin{aligned} \mathrm{OSNR}_{\mathrm{norm}} &= \mathrm{G}_{\mathrm{preamp}} - (\mathrm{P}_{\mathrm{rec}} + \mathrm{NF}_{\mathrm{rec}}) \\ &\quad + \sum_{i=1}^{L+1}[\mathrm{P}_{\mathrm{out}} - 10\log_{10}(\mathrm{M}_{\mathrm{ch}_i}) - \mathrm{Loss}_{\mathrm{span}} \\ &\quad - \mathrm{NF}_{\mathrm{ASE}} - 10\log_{10}(\mathrm{Num}_{\mathrm{span}} + 1)]_{\mathrm{i'th\ Link}} \\ &\quad + 5\log_{10}[1 - 4\mathrm{Q}^2(\sum_{l=1}^{L}\mathrm{M}_l + \sum_{l=1}^{L}\mathrm{N}_l - 2\times \mathrm{L})\varepsilon] \end{aligned} \quad (5)$$

Where OSNR is normalized to 0.1 nm bandwidth.

III. Routing Optimization Approaches and Corresponding Routing Algorithms

Here we introduce two routing optimization approaches; mostly used in design the wavelength routed optical networks and our new routing optimization approach. The first routing optimization's objective is to minimize the maximum link congestion in the network. The second routing optimization's objective is to minimize the total length of routing paths. The objective of the third routing optimization, the proposed routing optimization, is to minimize the total length of routing paths constraint by the minimum number of hops. The first routing optimization is good for network scalability and the second routing optimization is good to minimize the length of routing path.

The third routing optimization is proposed based on the following factors:

- Minimum number of hops routing paths introduce the minimum total through traffic on the links and accumulate the minimum crosstalk from intermediate OXCs, but they might accumulate more ASE noise from optical amplifiers.
- Minimum distance routing paths accumulate the minimum ASE noise, but they might accumulate more crosstalk from intermediate OXCs and introduce more through traffic on the links.
- Choose the Minimum distance routing paths from the subset of minimum number of hops paths might have a good trade-off between above two routing paths.

To solve these routing optimization problems, routing algorithms are needed. For the first routing optimization problem with objective to minimize the maximum link congestion, extended work has been reported in [1-9], here we apply Baroni's Routing algorithm proposed in [9] and name it as Minimum Number of Hops Routing Algorithm (MNH's RA). For the second routing optimization problem with objective to minimize the total lightpath length, we apply the Minimum Distance Routing Algorithm (Min. Dist. RA), which is the Dijkstra algorithm [26] with the labels on the arcs as physical links distance. For the third routing optimization problem, we apply the Shortest-in-Minimum Number of Hops Routing Algorithm (Shortest-in-MNH's RA) proposed in the flow chart of Fig. (1).

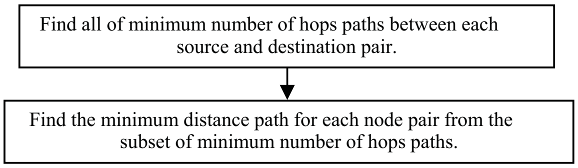


Figure (1): Flow chart of Shortest-in-MNH's routing algorithm

For wavelength assignment, we use wavelength assignment algorithm in [13] after each routing algorithm.

IV. Method of Performance Evaluation and Simulation Results for Different Routing Optimization Approaches

With three routing algorithms and wavelength assignment algorithm available, we design the sample network shown in Fig. (2), in different ways, which are determined by routing algorithms. Then we evaluate the routing algorithms from two aspects. One aspect is the network-layer performance comparison or routing performance comparison among the three routing algorithms, which is presented in section 4-1. Another aspect is physical-layer performance comparison or signal transmission quality comparison among the three routing algorithms, which is presented in section 4-2.

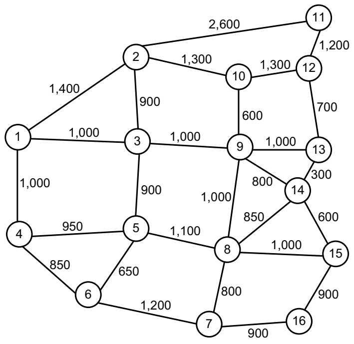


Figure (2): Sample network

The simulation results are based on following assumptions:

- One fiber-pair per link
- No link capacity limitation
- Logical layer is fully connected
- Traffic is uniform and each demand size is one
- Span distance between two amplifiers is 100 km
- OXC is at each node

A. Network-layer Performance

The routing results under different routing algorithms based on different routing optimizations are listed in Table (1).

From Table (1), we find that:

- The MNH's RA leads the least network required wavelength number and the maximum wavelength reusability. The Min. Dist. RA leads the maximum network required wavelength number and minimum wavelength reusability. The Shortest-in-MNH's RA leads slightly more required wavelength number and slightly low wavelength reusability than MNH's RA.
- The MNH's RA and the Shortest-in-MNH's RA leads the least total traffic on links, which means that MNH's RA and Shortest-in-MNH's RA make the network has better scalability than Min. Dist. RA does.

Table (1): Network routing results determined by different routing algorithms

Parameter	MNH's RA	Min. Dist. RA	Shortest-in-MNH's RA
Network Required Wavelengths Number (N_λ)	14	29	23
Wavelength Reuse Factor (ρ)	17.143	8.2759	10.4386
Average Hop Number	2.3750	2.4667	2.3750
Total Traffic on Links	570	592	570
Average Lightpath Length (km)	2335.4	2090.8	2129.2
Maximum Lightpath Length (km)	5850	4200	5000
Total Lightpath Length (km)	560500	501800	511000
Average Signal Transmission Delay (ms)	15.46	13.88	14.84

routing optimizations, from three aspects: lightpath length and average signal transmission delay in section, signal transmission limitations due to linear dispersion, and signal transmission limitation due to degraded OSNR.

From Table (1), we find that The Min. Dist. RA leads to minimum total lightpath length, minimum average lightpath length and minimum signal propagation delay. MNH's RA leads to maximum total lightpath length, maximum average lightpath length and maximum signal propagation delay.

In wavelength routed optical networks, signal linear dispersions include signal chromatic dispersion (CD) and signal polarization mode dispersion (PMD). These kinds of signal distortions pose the limitation to signal transmission distance, which is related to the signal transmission bit rate and the fiber's characterization.

An idea of the transmission limitations imposed by CD can be obtained by assuming that the pulse spreading due to CD should be less than a fraction ε of the bit period, which is presented in [27]. And this limit can be expressed as Equ. (6).

$$B\lambda\sqrt{|D|\frac{L}{c}} < \sqrt{0.4\varepsilon} \tag{6}$$

Where:

B : the signal transmission bit rate,

λ : the operating wavelength which is 1550 nm,

$|D|$: the fiber CD coefficient at the operating wavelength,

c : the velocity of light which is 3×10^8 m/s,

ε : the pulse spreading to bit period ratio which for 2 dB power penalty is 0.491, and

L : signal transmission length in km.

Signal transmission due to PMD is as equ. (7). [27]

$$D_{PMD}\sqrt{L} < \frac{\alpha}{B} \tag{7}$$

Where:

α : the ratio of average differential delay due to PMD to bit
period which for 1 dB power penalty is 0.1, and

D_{PMD} : the fiber PMD coefficient in $ps/\sqrt{km}$.

Different cases are studied, such as signal transmission at different speeds, and signal transmission on different types of fibers. In Table (2), we list the assumed CD coefficients ($|D|_{SSMF}$) and ($|D|_{NZDSF}$) for standard single mode fiber (SSMF) and Non-Zero Dispersion Shifted Fiber (NZDSF), as well as the assumed PMD coefficient (D_{PMD}) for fibers.

Table (2): The assumed transmission characteristics

Parameter	Value
Operation Wavelength	1550 nm
Fiber CD Coefficient ($\|D\|_{SSMF}$)	17 ps/nm.km
Fiber CD Coefficient ($\|D\|_{NZDSF}$)	2 ps/nm.km
Fiber PMD Coefficient (D_{PMD})	0.1 $ps/\sqrt{km}$ or 0.5 $ps/\sqrt{km}$

According to Equ. (6) and (7), we calculate the transmission length limit from CD and PMD at different bit rates, 2.5 Gb/s (OC-48) and 10 Gb/s (OC-192) with assumed CD coefficient and PMD coefficient. The signal transmission limitation caused by linear dispersion is listed in Table (3).

Table (3): The transmission length limit due to linear dispersion at different bit rates and on different types of fibers

2.5 Gb/s (OC-48)			10 Gb/s (OC-192)		
CD Limit		PMD Limit	CD Limit		PMD Limit
SSMF	NZDSF	0.1 $ps/\sqrt{km}$ 0.5 $ps/\sqrt{km}$	SSMF	NZDSF	0.1 $ps/\sqrt{km}$ 0.5 $ps/\sqrt{km}$
230.82 km	1962 km	1.6×10^5 km 6400 km	14.4261 km	122.62 km	1×10^4 km 400 km

In our sample network design simulation, we use the concept of Unacceptable Paths Number (UPN) and Percentage of Unacceptable Paths Number (UPN%) [20, 21], to estimate the unqualified lightpaths.

Table (4): UPN% due to linear dispersion in different cases

Routing Algorithm / Case			UPN%		
			MNH's RA	Min. Dist. RA	Shortest-in-MNH's RA
2.5 Gb/s (OC-48)	CD	SSMF	100%	100%	100%
		NZDSF	57.5%	50.83%	50.67%
	PMD	0.1 $ps/\sqrt{km}$	0%	0%	0%
		0.5 $ps/\sqrt{km}$	0%	0%	0%
10 Gb/s (OC-192)	CD	SSMF	100%	100%	100%
		NZDSF	100%	100%	100%
	PMD	0.1 $ps/\sqrt{km}$	0%	0%	0%
		0.5 $ps/\sqrt{km}$	99.17%	99.17%	99.17%

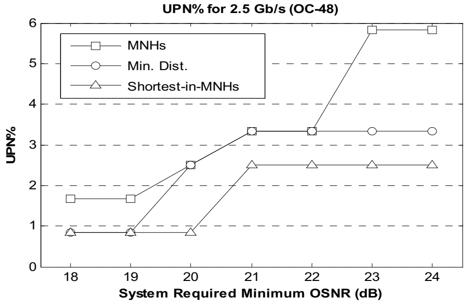
The unacceptable path means that the lightpath is beyond the maximum length, which is constraint by CD limitation or PMD limitation. Here, UPN% = (Unacceptable Paths Number)/(Total Paths Number).

Table (4) shows UPN% due to linear dispersion in different cases. Table (4) shows that, in the case of OC-48 and NZDSF fiber, MNH's RA leads the maximum failure paths caused by CD and Min. Dist. RA leads the minimum failure paths caused by CD. Also, in the case of OC-192 and 0.5 $ps/\sqrt{km}$ fiber, all of three Routing Algorithms lead to the same failure paths caused by PMD.

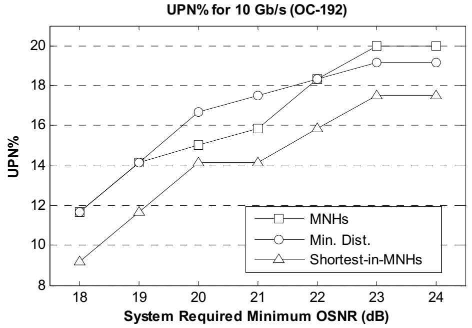
In order to determine the UPN% due to degraded OSNR, we use Equ. (5) for OSNR calculation. In our simulation, the assumed input values for variables are listed in Table (5). Different cases are studied, one is from different signal transmission bit rate such as 2.5Gb/s (OC-48) and 10Gb/s (OC-192), and another is from different system required minimum OSNR value, which is ranged from 18 dB to 24 dB. Finally the simulation results are compared and plotted in graphs in Fig. (3-a) in the case of 2.5 Gb/s and in Fig. (3-b) in the case of 10 Gb/s.

Table (5): The assumed variable values for OSNR simulation input

Parameter	Value
Q-factor (Q)	6 for BER=10^{-9} 7 for BER=10^{-12}
Preamplifier Gain (G_{preamp})	24 dB
Optical Amplifiers Noise Figure (NF_{ASE})	4 dBm
Receiver Noise Figure (NF_{rec})	4 dBm
Fiber Attenuation (α)	0.15 dB/km
Ratio of each Crosstalk Contribution Intensity to main Signal Intensity (ε)	-44 dB
Optical Amplifiers Output Power (P_{out})	24 dBm
Receiver Sensitivity (P_{rec})	-46 dBm for OC-48 -41 dBm for OC-192



(a): 2.5 Gb/s (OC-48)



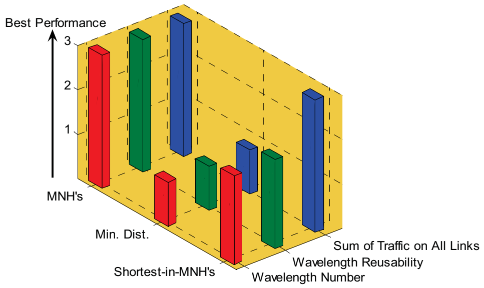
(b): 10 Gb/s (OC-192)

Figure (3): UPN% due to degraded OSNR vs. required minimum OSNR value under different Routing Algorithms

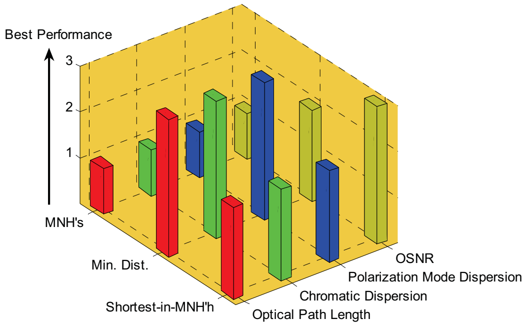
Fig. (3) shows that, in terms UPN% due to degraded OSNR, MNH's RA leads the worst performance, and Our Shortest-in-MNH's RA leads the best performance among the three routing algorithms.

V. Overall Performance Evaluation

In previous section, we already compared and analyzed the network-layer performance and physical-layer performance separately. In order to have an overall evaluation to each routing algorithm, we use three level scores to represent best, good, worst levels. The three level scores chosen are ‘3’, ‘2’, ‘1’, in which ‘3’ means the best one.



(a): network-layer performance



(b): physical-layer performance

Figure (4): Evaluation score based on (a) network-layer performance and (b) physical-layer performance vs. each routing algorithm

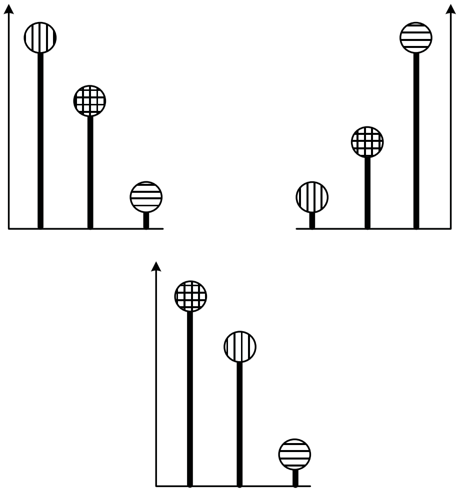


Figure (5): Overall evaluation comparison

In Fig. (4-a), we show the evaluation score based on network-layer performance for sample network versus each routing algorithm. In Fig. (4-b), we show the evaluation score based on physical-layer performance for sample network versus each routing algorithm. And finally in Fig.(5), we illustrate the overall evaluation comparison among the three routing algorithms.

From Fig. (4), we find that among the three routing algorithms: MNH’s RA leads the best network-layer performance, but leads the worst physical-layer performance; Min. Dist. RA leads the worst network-layer performance, but leads the best physical-layer performance; our Shortest-in-MNH's RA leads the physical-layer performance close to the best one, and also the network-layer performance close to the best one.

From Fig. (5), we find that among the three routing algorithms, Our Shortest-in-MNH's RA leads the best overall performance, for sample network.

VI. Conclusions

In wavelength routed transparent optical networks, different routing optimizations lead to different routing results, which might impact the signal transmission performance. Therefore, in this paper, different routing optimizations are evaluated and compared from two aspects. One is from the network-layer performance on ideal optical network (without considering network equipments), which is the approach in all of previous works. And another is from the physical-layer performance on realistic optical network (with considering network equipments), which is the approach we are proposing in this paper.

From simulation results, we find that:

- Different routing optimizations lead to different routing results, and they do impact the physical-layer performance.
- The Routing Optimization based on trade-off strategy (Shortest-in-MNH's RA) leads the best overall performance, combing network-layer performance and physical-layer performance.

In previous works, the assumption of ideal optical networks leads the routing optimization only focuses on network-layer performance. Therefore the routing optimization of minimizing link congestion is mostly used to design network, since it yields the best network-layer performance. However, in real optical networks, network equipments are installed and they are not perfect, and signal is degraded when crossing them. Therefore in our work, we use the real optical network with considering network equipment installed, the routing optimization is not only focus on network-layer performance, but also the physical-layer performance.

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