Dynamic lightpath provisioning with signal quality guarantees in survivable translucent optical networks

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Abstract: This paper studies the problem of signal-quality-guaranteed lightpath provisioning in survivable translucent optical networks under dynamic traffic. A new protection scheme, called regeneration-segment protection (RSP), is proposed. Provisioning approaches with shared path protection and shared RSP are presented. Two main signal quality constraints are integrated with the provisioning problem. Different regenerator placement strategies for working path and protection path are employed. Joint path selection method is used to select the "optimal" working-protection pair. With the above considerations, survivable lightpath provisioning with signal-quality-guarantees is achieved in a cost-effective manner. Results show that in a moderate-size network, RSP has less blocking probability than path protection when the network load is low or modest. Besides, RSP obtains better performance in terms of recovery time than path protection in all network scenarios.

OCIS code: (060.4510) Optical communications; (060.4250) Networks.

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1. Introduction

The all-optical transparent network has been considered as a promising candidate for the next generation backbone network to provide large bandwidth at low cost. However, it is difficult to practically deploy transparent optical networks in backbone networks because transmission impairments induced by non-ideal transmission components restrict the maximum reach of a lightpath. On the contrary, the opaque optical network, in which each node is equipped with an opaque switch, has no restrictions related to the length of a lightpath, but has a deficiency of high cost. In order to strike a tradeoff between transparency and opaqueness, the translucent optical network is proposed to achieve a performance very close to an opaque optical network in terms of blocking performance and signal quality, but with large cost savings [1].Several strategies have been considered to design a translucent optical network. One of them is to use the technique called sparse regeneration [2]. In a translucent optical network implemented with sparse regeneration, every node contains a photonic cross-connect (PXC) fabric and an optional shared regenerator bank. This is the type of network considered in this paper.

Wavelength-Division-Multiplexing (WDM) optical networks are prone to component failures, and the failures would affect many users due to a higher degree of multiplexing being done over the network. Therefore, to provide survivability in WDM optical networks is indispensable. Lightpath provisioning in survivable ideal optical networks, in which transmission is considered error-free and no regeneration is needed, has been extensively studied for both static traffic and dynamic traffic. However, lightpath provisioning in survivable translucent optical networks is an open issue, and work are done only for static traffic. In [3, 4], the problem to design a survivable translucent optical network was formulated as an integer linear programming (ILP) problem, and these work focused on how to sparsely place regenerators in the network to minimize the number of regenerators and survive network failures at the same time. In [5, 6], the number of regenerators at a node was assumed to be known. In [5], the traditional resource sharing scheme was extended to include sharing of node devices, such as regenerators. In [6], the author presented an ILP formulation and a local optimization heuristic approach with an objective to minimize the wavelength-links and regenerators used.

This paper is devoted to study lightpath provisioning with signal-quality-guarantees in translucent optical networks under dynamic traffic. To the best of our knowledge, no prior work has been done on this issue. We first propose a new protection scheme called regeneration-segment protection (RSP). We show that RSP has advantages over path protection scheme. Then, we present provisioning approaches with path protection and RSP. In order to provide signal-quality-guaranteed lightpaths, we integrate two main signal quality constraints into the provisioning problem. In order to utilize resources efficiently, we employ different regenerator placement strategies to minimize the number of regenerators utilized on working paths, and maximize sharing of regenerators on protection paths, respectively. Besides, we use joint path selection method to select the working-protection pair with the minimum cost sum among multiple candidate working-protection pairs. In the simulations results, we can see that in a moderate-size network, RSP has less blocking probability than path protection when the network load is low or moderate. In addition, RSP obtains better performance in terms of recovery time than path protection in all network scenarios.

The rest of the paper is organized as follows. Section 2 provides the network model. The new protection scheme is introduced in Section 3. Section 4 presents optical signal quality constraints considered in this paper. Section 5 describes the details of provisioning approaches with path protection and RSP. The numerical results are presented and discussed in Section 6. Section 7 concludes the paper.

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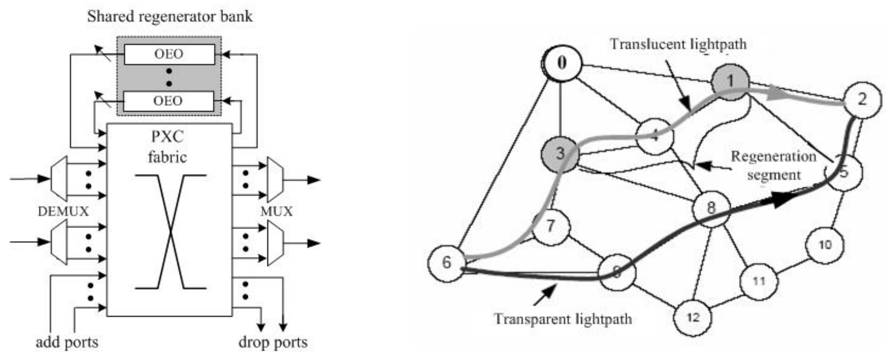
2. Network model

Figure 1(a) shows the node architecture considered in this paper. It mainly consists of a PXC fabric and a shared regenerator bank. The former provides wavelength switching functionality, while the latter contains a number of optical-electronic-optical (OEO) based regenerators. The regenerators are equipped with tunable transmitters, and hence can provide signal regeneration and wavelength translation functionality simultaneously. The number of regenerators at a node is fixed, but this number may vary from one node to another. Some hub nodes may have a larger number of regenerators, while some do not have any.



a. Node architecture   b. Example of a translucent optical network

Fig. 1. Network model

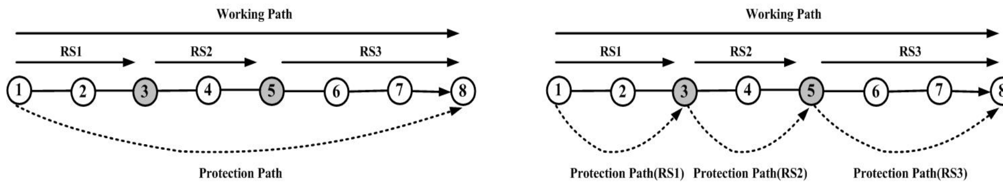
Figure 1(b) shows an example of a translucent optical network composed of nodes described above. There are two types of lightpaths in the network. The first is called transparent lightpath, in which no electronic regeneration is needed en route. The second is called translucent lightpath, in which there are some regeneration nodes en route for signal regeneration. In Fig. 1(b), lightpath (6-9-8-5-2) is a transparent lightpath, while lightpath (6-7-3-4-1-2) is a translucent lightpath because nodes 1 and 3 are used to regenerate the signal. A subpath between a neighboring transceiver is called a *regeneration segment* (RS). Each RS consists of one or more consecutive fiber links and is subject to the wavelength continuity constraint, i.e., all fiber links on the RS must use the same wavelength. However, wavelengths on two RSs may be different. In addition, a RS is qualified in terms of signal quality. That is, transmission impairments accumulated on a RS do not exceed a threshold. A transparent lightpath has only one RS, while a translucent lightpath has multiple RSs. In Fig. 1(b), subpaths (6-9-8-5-2), (6-7-3), (3-4-1) and (1-2) are RSs.

Wavelengths and regenerators are limited resources in translucent optical networks. Resource sharing in shared protection applies to both wavelengths and regenerators. The protection paths can share wavelength links and regenerators as long as their working paths are link-disjoint. Moreover, a working path and its protection path can also share a regenerator because they do not need the regenerators simultaneously if we consider only link failures.

3. Regeneration-segment protection

The protection schemes for surviving link failures in a mesh-based network are usually classified as path protection, segment protection and link protection by their rerouting [7, 8]. In this section, we present a new protection scheme, called regeneration-segment protection (RSP) for translucent optical networks.

Segment protection has been widely studied before. It divides a working path into several segments and protects each segment with a backup path. It is a promising scheme due to the features of high resource efficiency and short protection-switching time [8]. RSP is a special form of traditional segment protection. In traditional segment protection, a segment means any subpath that consists of a sequence of links. However, in RSP, a segment refers to a RS which is a particular subpath that terminates between two neighboring transceivers. Fig. 2 illustrates the concept of RSP. Purposely, we explain it in comparison with path protection. As shown in Fig. 2(a), the working path is a translucent lightpath which contains three RSs. Path protection provides an end-to-end protection path from the source node (node 1) to the destination node (node 8). When a failure occurs, the working path is replaced by the protection path. However, in RSP, as shown in Fig. 2(b), each RS on the working path is protected by a particular protection path. When a failure occurs, only the affected RS performs protection switching and the other unaffected RSs are oblivious to the failure. We can easily see that, for transparent lightpaths, RSP is just the same as path protection.



a. Path protection

b. Regeneration-segment protection

Fig. 2. Illustration of path protection and regeneration-segment protection

Compared with path protection, RSP brings us the following two advantages similar to other segment protection schemes. First, more resource sharing can be achieved. As described in Section 2, two protection paths can share wavelength links and regenerators when their working RSs (or working paths in path protection) do not traverse the same link. Since a translucent lightpath consists of multiple RSs, the probability of two RSs traversing the same link is typically lower than the probability of two translucent lightpaths traversing the same link. As a result, RSP has better resource sharing than path protection. Second, RSP has a shorter recovery time. The end-to-end protection entity is a RS in RSP, as opposed to a path in path protection. The working-protection pair for a RS is usually shorter than that for a translucent lightpath in terms of hop count, and therefore, RSP is expected to achieve shorter recovery time.

However, RSP have a disadvantage just like link protection. In RSP, every RS is protected by a particular protection path. Multiple such protection paths are cascaded to protect the working path. If the RSs are too short, it seems that RSP would work ineffectively.

4. Signal quality constraints

In the section, we discuss two signal quality constraints that restrict the maximum reach of a lightpath [9]: optical signal-to-noise ratio (OSNR) and polarization mode dispersion (PMD). We denote a RS from node a to node b as (a,b), the number of links along the segment as M, and the link index as k.

4.1 Optical signal-to-noise ratio

OSNR is a major contributor to bit-error-rate (BER). OSNR at the receiver can not exceed a threshold, $OSNR_{min}$, dependent on the required BER and transmitter-receiver technology, such as forward-error-correction (FEC). Let $OSNR_b$ represent the received OSNR at node b of RS (a,b). OSNR constraint can be described as:

$$OSNR_b \geq OSNR_{\min} \tag{1}$$

With an intermediated parameter, Q-factor, the relationship of BER and $OSNR_{min}$ is given by [10]:

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$$BER(Q) \cong (\frac{1}{\sqrt{2\pi}}) \cdot (\frac{\exp(-Q^2/2)}{Q}) \quad (2)$$

$$OSNR_{\min} = \frac{(1+r)(1+\sqrt{r})^2}{(1-r)^2} \cdot \frac{Be}{Bo} \cdot Q^2 \quad (3)$$

Where r is the extinction ratio of the transmitted optical signal, which is defined as the ratio of the mean peak powers in "0" and "1" bits at the transmitter, B_e is the electrical bandwidth (typically, $B_e = 0.75 \times B$, B is the digital bit rate of the signal) and B_o is the optical bandwidth for OSNR measurement (a typical value of B_o is 12.6Hz or 0.1nm for a given optical spectrum analyzer)). For example, for a BER of 1.0 x 10^{-16}, we have $Q = 8.0$. Let B = 10Gb/s, $r = 0.15$ and assume FEC bring a gain of 5dB on OSNR. We get $OSNR_{min}$ to be 20.67dB without FEC, and 15.67dB with FEC. Moreover, if we set a system margin of 3 dB to allow other impairments such as nonlinear effects, we can get the requirement of $OSNR_{min}$ to be 23.67dB without FEC, and 18.67dB with FEC.

In optical networks, amplified spontaneous emission (ASE) introduced by optical amplifiers such as erbium-doped fiber amplifiers (EDFAs) is the dominant noise source. Different wavelengths on the same link may have slightly different ASE noise powers. By ignoring such a difference, ASE noise power of the jth EDFA on the kth fiber link along a RS can be expressed as [11]:

$$P_{ASE}(k, j) = 2n_{sp}(k, j) \cdot (G(k, j) - 1) \cdot h \cdot v \cdot B_o \quad (4)$$

Where $n_{sp}(k,j)$ is the spontaneous emission factor, $G(k,j)$ is the small-signal gain, h is the Planck constant, ν is the optical frequency, and B_o is the optical bandwidth.

Assume the loss in a span can be exactly compensated by an EDFA. Then, ASE noise power on RS (a,b) can be described as:

$$P_{ASE}(a,b) = \sum_1^M \left(\sum_{j \in Link(k)} P_{ASE}(k, j) \right) \quad (5)$$

If we use P_l to represent the launched signal power at node a, $OSNR_b$ can be calculated as:

$$OSNR_b = P_l / P_{ASE}(a,b) \quad (6)$$

4.2 Polarization mode dispersion

PMD is caused by the time delay between two orthogonal polarizations of light traveling at different speeds through an optical fiber. As the channel bit rate increase to 10Gbps and beyond, PMD strongly affects the transparent transmission length in optical networks. Let $\Delta t_{PMD}(a,b)$ denote the PMD value of RS (a,b). PMD management requires that the PMD value of a RS be less than a fraction a of the bit duration, that is:

$$\Delta t_{PMD}(a,b) \le \frac{\alpha}{B} \quad (7)$$

Where B is the digital bit rate of the signal and α is the maximum dispersion fraction in a bit interval that is acceptable for the receiver. A typical value for α is 0.1. According to [9], $\Delta t_{PMD}(a,b)$ can be expressed as:

$$\Delta t_{PMD}(a,b) = \sqrt{\sum_1^M D_{PMD}^2(k) \cdot L(k)} \quad (8)$$

Where $D_{PMD}(k)$ is the fiber dispersion parameter at the kth optical link that has a length $L(k)$. Typically, $D_{PMD}(k)$ has a value ranging from 0.1 to 0.5 $ps/\sqrt{km}$ depending on the fiber technology on the link.

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5. Survivable lightpath provisioning in translucent optical networks

In this section, we discuss survivable lightpath provisioning approaches with shared path protection and shared RSP in translucent optical networks using signal quality constraints described in Section 4. The provisioning approach with path protection seeks a working path and a link-disjoint protection path, while the provisioning approach with RSP seeks a working path and link-disjoint protection paths for all RSs that belong to the working path.

5.1 Procedures of survivable lightpath provisioning

Provisioning procedures with path protection and RSP are presented in Fig. 3. We divide the problem of establishing a lightpath (working path or protection path) into three separate phases: routing, regeneration placement and wavelength assignment. In the following, we first discuss theses problem one by one.

Provisioning procedure with path protection

1 Compute K candidate working routes with W_i representing the ith ($1 \le i \le K$) route and CW_i as the cost of W_i.
2 For each candidate working route, W_i, do:
   a. Place regenerators using the regenerator placement algorithm.
   b. Assign wavelength to each RS using the wavelength assignment algorithm.
   c. Calculate CW_i.
   d. Compute K link-disjoint candidate protection routes with $P_j(i)$ representing the jth ($1 \le j \le K$) route and $CP_j(i)$ as the cost of $P_j(i)$.
   e. For each candidate protection route, do:
      (1) Place regenerators using the regenerator placement algorithm.
      (2) Assign wavelength to each RS using the wavelength assignment algorithm.
      (3) Calculate $CP_j(i)$.
   f. Find $P^*(i)$ with $CP^*(i) = MIN\ (CP_j(i))$, and select $P^*(i)$ as the protection path for W_i.
3 Find W^* with $CW^* = MIN\ (CW_i + CP^*(i))$ and select W^* as the working path.

Provisioning procedure with regeneration-segment protection

1 Compute K candidate working routes with W_i representing the ith ($1 \le i \le K$) route and CW_i as the cost of W_i.
2 For each candidate working route, W_i, do:
   a. Place regenerators using the regenerator placement algorithm with $RS(i,k)$ representing the kth RS.
   b. Assign wavelengths to each RS using the wavelength assignment algorithm.
   c. Calculate CW_i.
   d. For each RS, $RS(i,k)$, compute K link-disjoint candidate protection routes with $P_j(i,k)$ representing the jth ($1 \le i \le K$) route and $CP_j(i,k)$ as the cost of $P_j(i,k)$.
   e. For each candidate protection route, do:
      (1) Place regenerators using the regenerator placement algorithm.
      (2) Assign wavelength to each RS using the wavelength assignment algorithm.
      (3) Calculate $CP_j(i,k)$.
      (4) Find $P^*(i,k)$ with $CP^*(i,k) = MIN\ (CP_j(i,k))$, and select $P^*(i,k)$ as the protection path for $RS(i,k)$.
3 Find W^* with $CW^* = MIN\ (CW_i + \sum_k CP^*(i,k))$ and select W^* as the working path.

Fig. 3. Procedures of survivable lightpath provisioning for translucent optical networks

5.2 Routing algorithm

Since routing problem with multiple constraints is NP-complete [12], we calculate K candidate routes for both working path and protection path to simplify the problem. Besides, we use joint path selection method proposed in [13] to select the working-protection pair with the minimum cost sum among multiple candidate working-protection pairs. The cost functions will be discussed in Section 5.4.

As shown in Fig.3, in path protection, we first compute K candidate working routes, then compute K link-disjoint paths as candidate protection routes, and finally select the minimum cost working-protection pair. The provisioning procedure of RSP is similar to that of path protection, except that K link-disjoint candidate protection paths are computed for each RS on the working path.

In both schemes, we assume that each link has the same cost and use the K-shortest path algorithm to calculate the K candidate working path. To obtain K link-disjoint candidate protection paths, we prune the links belonging to the working path/segment before running the K-shortest path algorithm.

5.3 Regenerator placement algorithm

Regenerator placement for a lightpath determines which nodes on the lightpath are chosen as regeneration nodes and which regenerator at a regeneration node is selected. Although a regenerator can be placed for both signal regeneration and wavelength conversion, only the first case is considered in this paper. By placing regenerators at some intermediate nodes, the required signal quality of a lightpath is guaranteed.

Regenerator placement algorithm

Input: a *maximum transparent segment* (i,…,j).

1. If the segment belongs to a working path, do: from node j to node i, node j is set as regeneration node if it has free regenerators and the first free regenerator is selected, otherwise, node j-1 is checked, and this procedure is repeated until node i.
2. If the segment belongs to a protection path, do:
   a. From node j to node i, node j is set as regeneration node if it has a regenerator used by the corresponding working path and this regenerator is selected, otherwise, node j-1 is checked, and this procedure is repeated until node i.
   b. If step a fails, do: from node j to node i, node j is set as regeneration node if it has sharable regenerators used by other protection paths and the first sharable regenerator is selected, otherwise, node j-1 is checked, and this procedure is repeated until node i.
   c. If step b fails, do: from node j to node i, node j is set as regeneration node if it has free regenerators and the firs free regenerator is selected, otherwise, node j-1 is checked, and this procedure is repeated until node i.

Fig. 4. Regenerator placement algorithm

Assume a lightpath (s,…,i,…,j,…,d) from the source s to the destination d, traverse nodes i and j. The regeneration nodes are determined in order from node s to node d. Also, assume node i is the last regeneration node has been determined and subpath (i,…,j) is the *maximum transparent segment* from node i to node d, which means Inequalities (9) – (11) are satisfied simultaneously.

$$OSNR_j \geq OSNR_{\min} \tag{9}$$

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$$\Delta t_{PMD}(i,j) \le \frac{\alpha}{B} \tag{10}$$

$$OSNR_{j+1} < OSNR_{\min} \quad or \quad \Delta t_{PMD}(i,j+1) > \frac{\alpha}{B} \tag{11}$$

One node should be chosen as regeneration node from node $i+1$ to node j and one regenerator at the regeneration node should be selected.

The regenerator placement algorithm is presented in Fig. 4, in which a strategy to minimize the number of regenerators is used for working path, while another strategy to maximize sharing of regenerators is employed for protection path.

5.4 Wavelength assignment algorithm

In fact, a regenerator in our node architecture can serve for both signal regeneration and wavelength conversion. But in this paper, we focus primarily on transmission impairments as the only need for regenerators. Wavelength assignment is conducted at the basis of a RS. A RS should be subject to the wavelength continuity constraint, i.e., all fiber links on the RS must use the same wavelength. However, two RSs can use different wavelengths since a regenerator can do wavelength conversion at the same time. We use the First-Fit method to assign a free wavelength for a RS in the working path, while we assign a free or sharable wavelength for a RS in the protection path with an aim to maximize the sharing of wavelength links. The wavelength assignment algorithm is presented in Fig. 5.

Wavelength assignment algorithm

Input: a *regeneration segment* (*a*,*b*)

1 If the segment belongs to a working path, use First-Fit method to assign a free wavelength for this segment.
2 If the segment belongs to a protection path, the wavelength on which the segment achieves minimum cost is selected.

Fig. 5. Wavelength assignment algorithm

5.5 Cost functions

The cost functions define the cost of a wavelength, a regenerator and a path. They help to evaluate a feasible working-protection pair. Before introducing the cost functions, we define the following notations:

- $C(\lambda)$: Cost of a free wavelength on a link.
- $C(r)$: Cost of a free regenerator at a node.
- $C_w(\lambda)$: Cost of a wavelength used by a working path.
- $C_w(r)$: Cost of a regenerator used by a working path.
- $C_p(\lambda)$: Cost of a wavelength used by a protection path.
- $C_p(r)$: Cost of a regenerator used by a protection path.
- *CW*: Cost of a working path.
- *CP*: Cost of a protection path.

Generally, we assign a larger value to $C(r)$ than $C(\lambda)$ because regenerators are usually considered more rare resources than wavelengths in the network. In addition, since a working path uses network resources exclusively, we have: $C_w(\lambda) = C(\lambda)$, and $C_w(r) = C(r)$. However, a protection path will share a wavelength or a regenerator with other protection paths, or share a regenerator with its working path, and accordingly, the cost of the specific wavelength or regenerator should be significantly reduced. We define $C_p(\lambda)$ and $C_p(r)$ as:

$$C_p(\lambda) = \begin{cases} \varepsilon_1 \times C(\lambda) & \text{if } \lambda \text{ is usd by other protection paths and sharable} \\ C(\lambda) & \text{if } \lambda \text{ is free} \end{cases} \quad (12)$$

$$C_p(r) = \begin{cases} 0 & \text{if } r \text{ is used by the corresponding working path} \\ \varepsilon_2 \times C(r) & \text{if } r \text{ is used by other protection paths and sharable} \\ C(r) & \text{if } r \text{ is free} \end{cases} \quad (13)$$

Where ε_1 and ε_2 are small constants such as 0.01.

The path cost is the sum of costs of all wavelengths and regenerators on a path *p*. Therefore, *CW* and *CP* can be calculated by:

$$CW = \sum_{\lambda \in p} C_w(\lambda) + \sum_{r \in p} C_w(r) \quad (14)$$

$$CP = \sum_{\lambda \in p} C_p(\lambda) + \sum_{r \in p} C_p(r) \quad (15)$$

6. Numeric results

In this section, we evaluate the proposed provisioning approaches in this paper. USA network as shown in Fig. 6, is used for the study. The node architecture is shown as Fig. 1(a). The link lengths in km are labeled on the link. Each link represents two unidirectional fibers in opposite directions. The number of wavelengths on each fiber is 16. We assume that EDFAs are placed every 80km along a fiber link, and the loss in a span can be exactly compensated by an EDFA. Other physical parameters are provided in Table 1. For simplification, these parameters are assumed to be the same on all links.

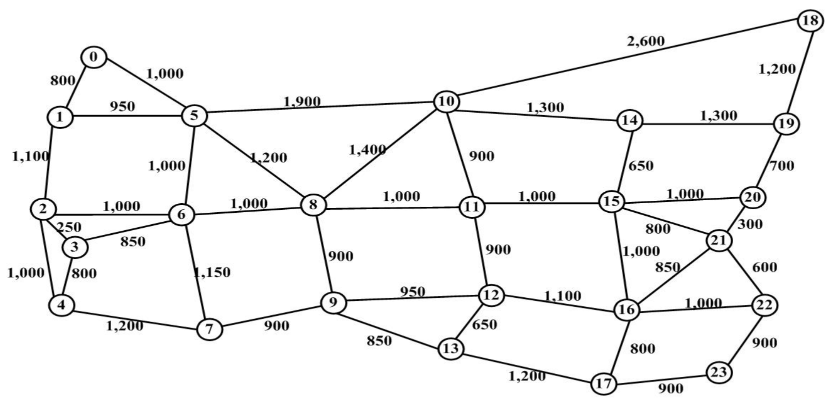

Fig. 6. Topology of USA network

In order to evaluate the algorithms under different network scale, we use a network scalar β (β ≤ 1), with which we multiply the original length of all fiber links inside the original network to change the link distance for our study. We assume the number of regenerators at each node is equal, which is denoted as N_r. We also assume that the lightpath-arrival process is Poisson and the lightpath-holding time follows a negative exponential distribution. The cost of a wavelength channel is assumed to be 1, while the cost of a regenerator is 10. The parameters, ε_1 in Eq. 12 and ε_2 in Eq. 13, are set to 0.01. We use *K*-shortest path algorithm to calculate the candidate routes and set *K* to 10 for both working and protection paths. In every experiment, 10^6 lightpath requests are simulated, which are uniformly distributed among all node pairs.

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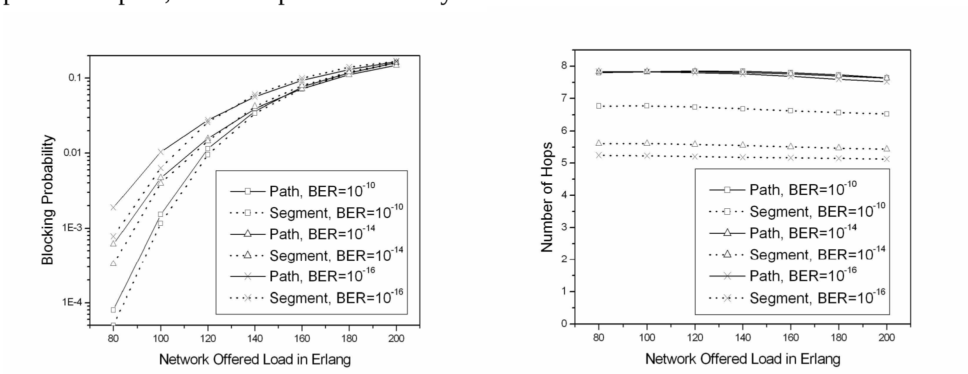
Table 1. Physical parameters used in the simulations

Parameter	value
Channel bit rate (B)	10 Gb/s
Wavelength (λ)	1550 nm
ASE factor of EDFA(n_{sp})	1.5
Small-signal gain of EDFA (G)	22 dB
Fiber PMD parameter (D_{PMD})	0.1 $ps/\sqrt{km}$
Launched signal power (P_l)	1 mW
Extinction ratio of transmitted optical signal (r)	0.15
Optical bandwidth for OSNR measurement (B_o)	12.6 GHz(0.1nm)
Gain of FEC on OSNR	5dB
System margin for OSNR	3dB

We evaluate the performances in terms of blocking probability and recovery time under various network scenarios. For path protection, recovery time for a lightpath can be calculated based on the hop count of the working-protection pair. For regeneration-segment protection, recovery time for a RS can be calculated based on the hop count of the working RS and its protection path, since the protection entity is a RS.



a. Blocking probability b. Hop count of working-protection pair

Fig. 7. Network performances for different required BER, with $\beta = 0.5$ and $N_r = 20$

Figure 7 compares the performances of RSP with that of path protection for different values of required BER, with $\beta = 0.5$ and $N_r = 20$. From Fig. 7(a), we make the following observations: (a) For the same required BER, RSP obtains lower blocking probability than path protection when the load is low or modest, but this improvement is weakened with decreasing of the required BER. This is because RSP can achieve better resource sharing as discussed in Section 3. With a lower required BER, this advantage is more obvious since a lightpath is likely to contain more RSs. (b) Both protection schemes have similar blocking probability for the same required BER when the load is high. The reason for this is that, when the load is high, some RSs become very short due to unavailability of regenerators at some nodes, which leads to RSP work inefficiently. Accordingly, for RSP, the advantage of better resource sharing is counteracted by the disadvantage of inefficient resource utilization. (c) The blocking probabilities for both protection schemes increase when the required BER decreases. This is because that, for a lower required BER, more regenerators are needed to clean the transmission impairments for a lightpath, which results in higher blocking probabilities.

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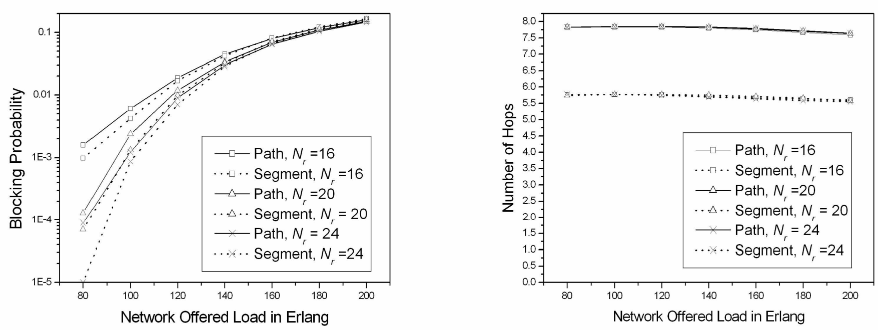
Figure 7(b) shows that in all cases, the number of hops of the work-protection path pair does not increase, but decreases a little with the increasing of offered load. The reason for this is that, with the increasing of offered load, a connection may use a long path as its working path. However, long working paths use more regenerators and are more difficult to find protection paths than short ones. As a result, connections using long working paths are more likely to be blocked than connections using short working paths, which leads to the decreasing of number of hops of the work-protection path pair.

Figure 7(b) also indicates that the average hop count of working-protection pair in RSP is smaller than that in path protection, which means shorter recovery time is achieved for RSP. This is because that the protection entity of RSP is RS, while the protection entity of path protection is the whole path. The figure also shows that in path protection, the required BER nearly has no effect on the performance, while in RSP, performance decreases with decreasing of the required BER. The reason for this is that, since path protection is an end-to-end protection scheme, for a given connection request, the working and protection paths are the same for different BER values if there are enough regenerators in the paths. However, in RSP, lower BER value will lead to shorter working segments, which results in the number of hops of working-protection pair decreases with decreasing of the BER value.



a. Blocking probability

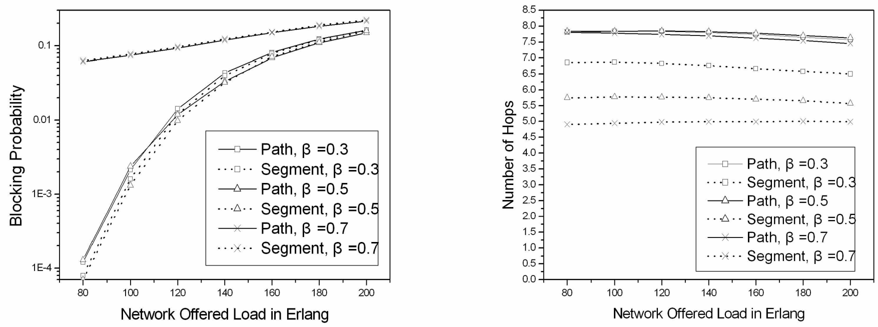
b. Hop count of working-protection pair

Fig. 8. Network performances for different values of N_r, with $\beta = 0.5$. The required BER follows $10^{-16} : 10^{-14} : 10^{-10} = 1 : 1 : 1$

Figure 8 compares the performances of RSP with that of path protection for different values of N_r, with $\beta = 0.5$ and the required BER following the distribution $10^{-16} : 10^{-14} : 10^{-10} = 1 : 1 : 1$. Fig. 8(a) shows that the blocking probabilities of both protection schemes decrease when N_r increases. It is obvious that a larger value of N_r means more regenerators in the network and leads to lower blocking probabilities. For the same value of N_r, the curves in Fig. 8(a) have similar trend to the ones in Fig. 7(a), and can be explained similarly.

Figure 8(b) indicates that the average hop count of working-protection pair in RSP is much smaller than that in path protection as shown in Fig. 7(b). The figure also shows that the value of N_r nearly has no impact on the network performance for both protection schemes.

Figure 9 compares the performances of RSP with that of path protection for different values of β, with $N_r = 20$ and the required BER following the distribution $10^{-16} : 10^{-14} : 10^{-10} = 1 : 1 : 1$. In Fig. 9(a), we observe that the blocking probabilities decrease significantly when β decreases from 0.7 to 0.5, but this decrease stops when β decreases from 0.5 to 0.3. The reason for this is that, when β equals 0.7, more regenerators are needed to regenerate a lightpath in such a large-size network. As a result, the blocking probability becomes higher because less free regenerators can be assigned to the following requests. However, when β equals 0.5, the network performance can be improved a certain extent because regenerators serve for wavelength conversion at the same time. We also observe that for the same value of β, the curves in Fig. 9(a) have similar trend to the ones in Fig. 7(a).



(a) a. Blocking probability

(b) b. Hop count of working-protection pair

Fig. 9. Network performances for different values of β, with N_r = 0.5. The required BER follows $10^{-16} : 10^{-14} : 10^{-10} = 1 : 1 : 1$

Figure 9(b) shows that the average hop count of working-protection pair in RSP is smaller than that in path protection as shown in Fig. 7(b). The figure also indicates that for RSP, the average hop count of working-protection pair decreases when β increase. This is because that a lightpath will contain more RSs and a RS will become shorter in a large-size network than in a small-size network. Thus, the length of the RS and its protection path will become smaller.

Based on the results discussed above, we can conclude that, in a moderate-size network, RSP has less blocking probability than path protection when the network load is low or modest. Besides, in terms of recovery time, RSP obtains better performance than path protection in all network scenarios.

7. Conclusion

In this paper, we study dynamic lightpath provisioning with signal-quality-guarantees in survivable translucent optical networks. We propose a new protection scheme, called regeneration-segment protection (RSP). We present provisioning approaches with shared path protection and shared RSP taking into account two main signal quality constraints. With the proposed approaches, signal-quality-guaranteed and survivable lightpath provisioning in translucent optical network is achieved in a cost-efficient manner. Simulation results show that in a moderate-size network, RSP has less blocking probability than path protection when the network load is low or modest. Besides, RSP obtains better performance in terms of recovery time than path protection in all network scenarios.