Dynamic Wavelength Routing in WDM Networks under Multiple Signal Quality Constraints

Weiyi Zhang, Guoliang Xue, *Senior Member, IEEE*, Jian Tang, Krishnaiyan Thulasiraman, *Fellow, IEEE*

***Abstract*—Most research works in routing and design of optical networks assume that the optical medium can carry signals without any bit error. However, the physical impairments on the optical signal quality introduced by optical components, such as erbium-doped fiber amplifiers (EDFA) and optical cross connects (OXCs), must be considered in the routing and design problems of WDM networks in practice. In this paper, we studied the dynamic connection provisioning problem in WDM networks under multiple signal quality constraints. We present a polynomial time optimal algorithm that finds an active path for an incoming connection request with minimum network resource consumption. Simulation results show that our solution outperforms the previously best solution to the problem.**

Keywords: WDM networks, lightpath, routing algorithm, *OEO* modules, path provisioning

1. Introduction

Fiber optics have replaced copper to be the primary transmission medium. Wavelength Division Multiplexing (WDM) networks effectively increase single-link bandwidth from 10Mbps to over 160Gbps, consequently have been considered as a promising candidate for the next-generation backbone network by researchers in the field. There have been many previous works on routing and wavelength assignment (RWA) problem [2], [7], [8]. Most previous works have investigated the problems under the assumption that *the optical medium is an ideal one which can carry data signals without any bit error*. Under this assumption, the effects of transmission impairments on the signal quality of a connection do not need to be considered. However, at the present time, a wavelength-routed network faces several technical difficulties in overcoming the physical impairments introduced by optical components such as erbium-doped fiber amplifiers (EDFA) and optical cross connects (OXCs). Physical impairments, e.g., power loss, noises, and dispersions, impose fundamental constraints on the quality of signals in WDM optical networks [5], [11], [14]. Therefore, at the destination node, the received signal quality may be so poor that the bit-error rate (BER) could be too high to be acceptable, thereby making the lightpath unusable [1], [5], [9], [11].

In [9], the authors analyzed the impact of transmission performance in WDM networks under different routing strategies. In [5], the authors considered the impact of transmission impairments on the teletraffic performance in WDM networks. Huang *et al.* [4] proposed a physical layer hierarchical RWA model to evaluate optical signal-to-noise ratio (*OSNR*) and polarization mode dispersion (*PMD*) on a candidate lightpath, and decide whether to set up the lightpath on network layer.

However, the aforementioned works cannot recover the optical signal in a lightpath. With current technology, only *OEO* (optical-electrical-optical) conversion can solve such a problem [4], [13], [14]. The concept of *translucent networks* was proposed in [6]. In a *translucent WDM mesh network*, a small number of *OEO* modules are placed sparsely. With sparse *OEO* regeneration, an optical signal can travel as long as possible before its signal quality falls below a threshold.

How to provide lightpaths with sparse *OEO* conversion in *translucent* WDM mesh networks has been studied recently. In [10], considering a single signal constraint, a new 2-D Dijkstra's algorithm was provided to find a connection. In [14], considering the *OSNR* constraint, the authors provided several simple heuristics to find paths for connection requests. We note that both works considered only one signal constraint and both used a simple regeneration model. They also assumed that there is at most one regenerator on each node, and do not consider the regenerator shareability issue [13]. In [12], the authors provided a practical network model. With the consideration of multiple linear signal constraints, the authors proposed several heuristics to find paths for connection requests. *None of the previous works guarantees a feasible active path for an incoming connection request even when feasible paths exist*.

In this paper, we use the sophisticated network model proposed in [12], and propose a novel algorithm which can find working paths for incoming requests if feasible paths exist. Moreover, our algorithm can find an optimal solution which uses the minimum number of *OEO* modules. The rest of the paper is organized as follows. In Section 2, we introduce the transmission impairments in optical networks, and describe the network model used and the problem we study. This is followed by Section 3 with a study of the dynamic path provisioning problem. Performance evaluation of our algorithms is presented in Section 4. We conclude our work in Section 5, summarizing our contributions.

2. Problem formulation

A. Transmission Impairments in Optical Networks

Two *linear* impairments are considered in this paper: Amplifier Spontaneous Emission (*ASE*) and Polarization Mode Dispersion (*PMD*), which are regarded as the two key linear impairments that can be practically used to constrain optical layer routing [11]. These two impairments have been extensively discussed in many previous works [4], [6], [11], [13].

1) Polarization Mode Dispersion: PMD management requires that the time-average differential time delay between

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two orthogonal states of polarizations, $[\Delta_t]$, be less than a fraction α of the bit duration, $T = 1/B$, where B is the bit rate. A typical value for α is 0.1 [11]. Assume that a transparent segment consists of *M* fiber spans, where the kth span has length $L(k)$ and fiber *PMD* parameter $D_{PMD}(k)$. The average differential delay is expressed as:

$$B\sqrt{\sum_{k=1}^{M} D_{PMD}(k)^2 * L(k)} \leq \alpha \tag{1}$$

Assume that the length of a fiber span is integer, and all fiber spans have the same *PMD* parameters, i.e., $D_{PMD}(k) = D_{PMD}$, *PMD gives the constraint on the length of a lightpath with acceptable BER*:

$$L = \sum_{k=1}^{M} L(k) \leq \lfloor \frac{\alpha^2}{B^2 D_{PMD}^2} \rfloor = C_{PMD} \tag{2}$$

2) Amplifier Spontaneous Emission: ASE is the dominant noise in optical networks, and degrades the signal to noise ratio. An acceptable optical *SNR* level (SNR_{min}) which depends on the bit rate and transmitter-receiver technology needs to be maintained at the receiver. The upper bound on *M*, the maximum number of spans, is obtained using the OSNR constraint in [11]:

$$\sum_{k=1}^{M} n_{sp}(k)(G(k)-1) \leq \frac{P_L}{2hvB_o SNR_{min}} \tag{3}$$

where P_L is the average optical power at the transmitter, $G(k)$ and $n_{sp}(k)$ are the amplifier gain and excess noise factor, respectively, on the *k*th span, $h = 6.63 * 10^{-34} J/Hz$ is the Planck's constant, *v* is the carrier frequency, and B_o is the optical bandwidth. Assume the *M* optical spans introducing the same noise power and that each optical amplifier has the same power gain G. Then

$$M \leq \lfloor \frac{P_L}{2SNR_{min} n_{sp} hv(G-1)B_o} \rfloor = C_{ASE} \tag{4}$$

ASE can be understood as the constraint for the maximum number of links a lightpath may have.

B. Network Model

In this paper, we consider a *translucent network*, which is a wavelength-routed mesh network with the capability of sparse *OEO* regeneration [13]. Such a network consists of a number of wavelength-routing nodes with optional *OEO* modules and interconnected by optical fiber links. We assume that each link has a single fiber in each direction, while each fiber has a fixed number of wavelengths that are used to carry data. Each node has a fixed number of add and drop ports, through which the user data can access the network. The node has inherent regeneration resources because it provides the basic regeneration resource of *Tx/Rx* pairs. 3R (regenerate, reshape and retime) regenerators can be attached between a *Tx-Rx* pair to implement signal regeneration in the electronic domain. The combination of a transmitter, a receiver and an electronic 3R regenerator is called an *OEO module* [13]. Such a node model allows all-optical switching, by WRS switching, as well as *OEO* regeneration by using an *OEO* module on the node. The path from the source node to the destination node is divided into several segments by *OEO* regenerations at intermediate nodes, which are named *regeneration nodes*. Each segment is defined as a *regeneration segment* [13].

C. Problem Statement

We study a dynamic WDM routing problem of great interest to network service providers. A wavelength on a fiber is called as a *channel*. Terms *OEO module* and *regenerator* are used interchangeably in this paper. Throughout this paper, W, m, n denote the number of wavelengths per fiber, the number of links and the number of nodes of a network, respectively.

Definition 2.1: An *r-node* is a node with *OEO* modules equipped. *R-nodes* is the set of all *r-nodes*.

Definition 2.2 (Dynamic Reliable WDM Routing Problem): Given the following information of a translucent network:

1) New connection requests that arrive dynamically;
2) The network topology and the number of wavelengths W on each fiber;
3) The *R-nodes* in the network, and the number of *OEO* modules on each *r-node*;
4) Current network accommodation status. In other words, we know whether a *channel* is free or used.

The objective of the problems is to **satisfy each coming connection request with an active path, on which the signal quality received at *each node* must be recognizable**. A path which satisfies the signal quality constraints is a *feasible* solution. An *optimal* solution to this problem is a feasible path which uses the *minimum number of regenerators*, and consumes the *minimum number of free wavelengths* among all paths that use the minimum number of regenerators.

3. Dynamic Reliable WDM Routing Scheme

In this section, we propose a novel scheme to find an optimal solution to the Dynamic Reliable WDM Routing problem if there exists any feasible path. The request will be dropped by our scheme if there is no feasible solution.

A. Novel Graph Transformation

PMD and *ASE* constraints are bounded by C_{PMD} and C_{ASE}, which are both integers. In our algorithms, we use $\mathcal{C}1$ and $\mathcal{C}2$ to represent C_{ASE} and C_{PMD}, respectively. ASE_u and PMD_u denote the *ASE* and *PMD* cost on node u for the coming connection request. $ASE(u,v)$ and $PMD(u,v)$ are the *ASE* and *PMD* costs on edge (u,v).

Our algorithm uses a novel graph transformation to combine all information; *OEO* and *channel* usage, *PMD* and *ASE* cost, into a single auxiliary graph. We first present Algorithm 1 to construct an auxiliary graph G^{aux} from the original graph G.

In Line 2 and 3, on each wavelength plane λ_i, we split each node u in G into $W \times (\mathcal{C}1+1) \times (\mathcal{C}2+1)$ copies in the form $u^{\lambda_i}_{(c1,c2)}$, where $(c1, c2)$ is a possible (*ASE, PMD*) combination.

For each node $u \in G$, we process it according to two cases. CASE 1: if u is NOT a *r-node*: From Line 4 through Line 10, for each edge (u,v) in the original graph, a group of edges, from $u^{\lambda_i}_{(ASE_u,PMD_u)}$ to $v^{\lambda_i}_{(ASE_v,PMD_v)}$, are added into $G^{aux}_{\lambda_i}$. Each of these edges means that, given a path from s to node u with signal costs ASE_u and PMD_u on node u, if we extend the path by using (u,v) for the connection (s,d), then it has signal costs ASE_v and PMD_v when reaching node v, where ASE_v=ASE_u+$ASE(u,v)$ and PMD_v=PMD_u+$PMD(u,v)$ because no regeneration can be applied on node u. The cost of such an edge is 1, which is the cost of consuming a *new channel*.

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Algorithm 1 *Setup_Aux_Graph(G, G^{aux}, R-nodes)*

1: **for** (each wavelength λ_i) **do**
2: From the wavelength graph G_{λ_i} of G, set up a wavelength graph $G^{aux}_{\lambda_i}$ with node set
3: $V^{G^{aux}}_{\lambda_i}$=$V^{G_{\lambda_i}} \times \{0, 1, \ldots, \mathcal{C}1\} \times \{0, 1, \ldots, \mathcal{C}2\}$ and edge set $E^{G^{aux}}_{\lambda_i}$:
4: **for** (each node $u \notin$ *R-nodes*) **do**
5: **for** (each undirected edge *(u, v)* in G_{λ_i} **do**
6: Add directed edges from $u^{\lambda_i}_{(ASE_u,PMD_u)}$ to $v^{\lambda_i}_{(ASE_v,PMD_v)}$ into $E^{G^{aux}}_{\lambda_i}$ iff:
7: ASE_v=ASE_u+$ASE(u,v)$ $\leq \mathcal{C}1$ and PMD_v=PMD_u+$PMD(u,v)$ $\leq \mathcal{C}2$;
8: Assign cost 1 to this edge;
9: **end for**
10: **end for**
11: **for** (each node $u \in$ *R-nodes*) **do**
12: **if** (there is free *Tx-Rx pair* on node u) **then**
13: Add a directed edge into $E^{G_{aux}}_{\lambda_i}$ from vertex $u^{\lambda_i}_{(ASE_u,PMD_u)}$ to vertex $u^{\lambda_i}_{(0,0)}$;
14: Assign cost $\mathcal{MN}$ to the edge;
15: **end if**
16: **for** (each undirected edge *(u, v)* in $E^{G_{\lambda_i}}$) **do**
17: Add directed edges from $u^{\lambda_i}_{(ASE_u,PMD_u)}$ to $v^{\lambda_i}_{(ASE_v,PMD_v)}$ into $E^{G_{aux}}_{\lambda_i}$ such that:
18: ASE_v=ASE_u+$ASE(u,v)$ $\leq \mathcal{C}1$ and PMD_v=PMD_u+$PMD(u,v)$ $\leq \mathcal{C}2$;
19: Assign cost 1 to this edge;
20: **end for**
21: **end for**
22: **end for**
23: **for** (each pair of wavelengths λ_i and λ_j) **do**
24: **for** (each node $u \in$ *R-nodes*) **do**
25: Connecting $u^{\lambda_i}_{0,0}$ and $u^{\lambda_j}_{0,0}$ with a new edge;
26: Assign cost ∞ to this edge;
27: **end for**
28: **end for**
29: The constructed auxiliary graph G^{aux} is composed by

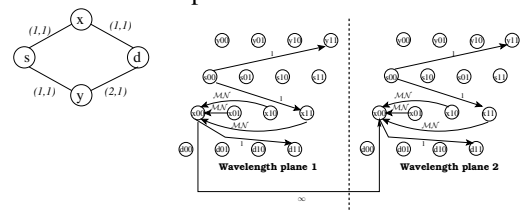
$$\text{node set } V^{G^{aux}} = \bigcup_{1 \leq \lambda_i \leq W} V^{G^{aux}}_{\lambda_i},$$

$$\text{and edge set } E^{G^{aux}} = \bigcup_{1 \leq \lambda_i \leq W} E^{G^{aux}}_{\lambda_i}$$

We do not add an edge if $ASE_v > C_{ASE}$ or $PMD_v > C_{PMD}$ because obviously such an edge is not on any feasible path.

CASE 2: if u is a *r-node*: From Line 11 through Line 21, if there is a free *Tx-Rx pair* on node u, it can apply regeneration. Thus, new edges are added from $u^{\lambda_i}_{(ASE_u,PMD_u)}$ to $u^{\lambda_i}_{(0,0)}$, which represents that the signal is cleared and restored. The cost of such an edge is $\mathcal{MN}(>> 1)$, which means using a regenerator has cost $\mathcal{MN}$. Meanwhile, node u can choose not to apply regeneration, This case is handled the same as the case that node u is not a *r-node* (Lines 16 - 20). In the FOR-loop in Lines 23-28, for each *r-node* u, we connect $u^{\lambda_i}_{0,0}$ and $u^{\lambda_j}_{0,0}$ for any two wavelength λ_i and λ_j. Such an edge represents that a wavelength conversion, together with regeneration, is applied at node u. The cost of such an edge is ∞ because we do not allow the wavelength conversion in this work.

Let us use an example to illustrate Algorithm 1. The original network is shown in Fig. 1(a), which consists of 4 nodes and 4 edges. Assume that only node x is a *r-node*. There are 2 wavelengths on each edge, and the costs of *ASE* and *PMD* are shown as the edge label for each edge. Both $\mathcal{C}1$ and $\mathcal{C}2$ are set to be 1 in the example.



(a) Network G (b) The constructed auxiliary graph G^{aux}

Fig. 1. Novel Graph Transformation

There are 2 wavelength planes in G^{aux}. Initially, all channels are free. We use wavelength plane G_{λ_1} for illustration since the operations are the same on both planes. For each node in the original network G, it is splitted into $(\mathcal{C}1 + 1) \times (\mathcal{C}2 + 1)$ copies. Each of them represents a possible (*ASE*, *PMD*) combination on the node. For example, node $y10$ means that the *ASE* cost at node y is 1, and the *PMD* cost is 0. Then we need to add edges into G^{aux}. Edges from $s^{\lambda_1}_{0,0}$ to $x^{\lambda_1}_{1,1}$ and $y^{\lambda_1}_{1,1}$, as well as edge ($x^{\lambda_1}_{0,0}$, $d^{\lambda_1}_{1,1}$) are added. The edge ($s^{\lambda_1}_{0,0}$, $x^{\lambda_1}_{1,1}$) implies that by taking edge (s, x) in G from source s, the *ASE* and *PMD* will both be 1 on node x. Each such edge has cost 1, which means that we consume one *free* channel by utilizing this edge for the connection. But no other edges can be added because either bound $\mathcal{C}1$ or $\mathcal{C}2$ would be violated. For the *r-node* x, we add edges from $x^{\lambda_1}_{(ASE_x,PMD_x)}$ to $x^{\lambda_1}_{(0,0)}$ with cost $\mathcal{MN}$, where $\mathcal{M}$ and $\mathcal{N}$ are the number of edges and nodes in G^{aux}, respectively. Using such an edge represents that a regenerator on node x will be used with a large cost $\mathcal{MN}$, which implies that *we would take all free channels for a connection if possible rather than use a regenerator*. Next, we connect $x^{\lambda_1}_{(0,0)}$ to $x^{\lambda_2}_{(0,0)}$ by a ∞-*cost* edge because wavelength conversion is not allowed in our algorithm. The constructed auxiliary graph G^{aux} is shown in Fig. 1(b).

B. Optimal Solution for Active Path Provisioning

After the auxiliary graph construction, Algorithm 2 is presented to find an *optimal* solution for active path provisioning.

To find an active path for request (s, d), we first need to have the auxiliary graph (Lines 1 - 3). Then from Line 4 through Line 10, we add some new edges which are particularly used for the incoming request. On each wavelength plane, we have new edges from $d^{\lambda_i}_{ASE_d,PMD_d}$ to $d^{\lambda_i}_{\mathcal{C}1,\mathcal{C}2}$. Such an edge means that if we can find a path to node d with signal costs less than threshold, we can reach the destination node in G^{aux}, $d^{\lambda_i}_{\mathcal{C}1,\mathcal{C}2}$ with no more cost. Moreover, from Line 11 to Line 14, vertically we connect $s^{\lambda_i}_{0,0}$ to $s^{\lambda_{i+1}}_{0,0}$ and $d^{\lambda_i}_{\mathcal{C}1,\mathcal{C}2}$ to $d^{\lambda_{i+1}}_{\mathcal{C}1,\mathcal{C}2}$. These edges represent that we can start from source node s at any wavelength plane, and stop at destination node d at any wavelength plane too. Once we finish adding the new edges, in Line 15 we use Algorithm 3 to find an optimal path for the request from $s^{\lambda_1}_{0,0}$ to $d^{\lambda_W}_{(\mathcal{C}1,\mathcal{C}2)}$. With the found path $\mathcal{AP}$ in G^{aux} from Algorithm 3, Algorithm 2 can get the path *activep* and *OEO* utilization in original graph G (Lines 16-18), or there is no feasible solution and the request is dropped in Line 20. In Line 18 of Algorithm 2, all edges added for this specific request (s, d) will be removed, and G^{aux} is changed back to its original version for future connection requests.

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Algorithm 2 *Active_Path_Provision(G, s, d, R-nodes)*

1: **if** (auxiliary graph G^{aux} has not been constructed) **then**
2: *Setup_Aux_Graph(G, G^{aux}, R-nodes)*;
3: **end if**
4: **for** (each wavelength λ_i) **do**
5: **for** (ASE_d= 0; $ASE_d < \mathcal{C}1$; ASE_d++) **do**
6: **for** (PMD_d= 0; $PMD_d < \mathcal{C}2$; PMD_d++) **do**
7: Add *zero-cost* edges from node $d^{\lambda_i}_{ASE_d,PMD_d}$ to $d^{\lambda_i}_{\mathcal{C}1,\mathcal{C}2}$;
8: **end for**
9: **end for**
10: **end for**
11: **for** (i = 1; $i < W$; i++) **do**
12: Add a *zero-cost* edge from node $s^{\lambda_i}_{0,0}$ to node $s^{\lambda_{i+1}}_{0,0}$;
13: Add a *zero-cost* edge from node $d^{\lambda_i}_{\mathcal{C}1,\mathcal{C}2}$ to node $d^{\lambda_{i+1}}_{\mathcal{C}1,\mathcal{C}2}$;
14: **end for**
15: *QualifiedWorkingLP(G, G^{aux}, $s^{\lambda_1}_{0,0}$, $d^{\lambda_W}_{(\mathcal{C}1,\mathcal{C}2)}$)*;
16: **if** (an active path $\mathcal{AP}$ is found) **then**
17: return $\mathcal{AP}$;
18: Change the original G^{aux} back by removing edges added from Line 4 to Line 14;
19: **else**
20: Drop the connection request (s, d);
21: **end if**

Algorithm 3 *QualifiedWorkingLP(G, G^{aux}, $s^{\lambda_1}_{0,0}$, $d^{\lambda_W}_{(\mathcal{C}1,\mathcal{C}2)}$)*

1: **for** (each link e in G^{aux}) **do**
2: **if** (the channel on e is not free) **then**
3: remove e from G^{aux};
4: **end if**
5: **end for**
6: **for** (each node $u \in$ *R-nodes*) **do**
7: **if** (u has no more free OEO module) **then**
8: remove all incoming edges to node $u^{\lambda_i}_{0,0}$ and its all inter-layer edges;
9: **end if**
10: **end for**
11: Compute the shortest path *activep* from source $s^{\lambda_1}_{0,0}$ to destination $d^{\lambda_W}_{(\mathcal{C}1,\mathcal{C}2)}$ in auxiliary graph G^{aux};
12: **if** (there does not exist such a path *activep*) **then**
13: block the connection request;
14: **else**
15: Return the path $\mathcal{AP}$ corresponding to *activep* in G as working path candidate;
16: **end if**

In Algorithm 3, at first all used channels are removed because active paths cannot share channels (Lines 1-5). Then in the FOR-loop starting from Line 6, if a *r-node* u has no more free *OEO* module, we remove all edges to $u^{\lambda_i}_{0,0}$ because no regeneration can be applied, and $u^{\lambda_i}_{0,0}$ can not be reached. After updating the network, in Line 11, shortest path algorithm, say Dijkstra algorithm, can be used to find a shortest path from $s^{\lambda_1}_{0,0}$ to $d^{\lambda_W}_{(\mathcal{C}1,\mathcal{C}2)}$ in G^{aux}. We return the found path as an active path for the request (Line 15).

Let us use Fig. 2 for illustration of our approach on the network shown in Fig. 1(a). Once we have the auxiliary graph in Fig. 1(b), we add some new edges, which are marked by the dashed edges in Fig. 2. For example, we add an edge from $d01$ to $d11$ on each wavelength plane, and connect $s^{\lambda_1}_{00}$ to $s^{\lambda_2}_{00}$.

Then, a shortest path $activep$ $((s^{\lambda_1}_{00}, x^{\lambda_1}_{11}, x^{\lambda_1}_{00}, d^{\lambda_1}_{11}, d^{\lambda_2}_{11}))$ is found from node $s^{\lambda_1}_{(0,0)}$ to node $d^{\lambda_2}_{(1,1)}$ in this graph, which is marked by the thick red edges in Fig. 2. The path $\mathcal{AP}$ in G

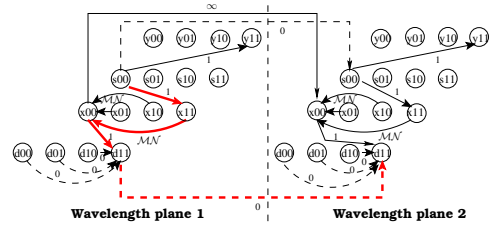

Fig. 2. Finding active path for connection (s, d).

for this example is (s, x, d) with cost $\mathcal{MN}+2$. We know that one OEO module needs to be utilized on node x with cost $\mathcal{MN}$, and the number of the consumed free channels is two.

Theorem 3.1: For any connection request, Algorithm 2 can correctly find a connection in $O(W \cdot \mathcal{C}1 \cdot \mathcal{C}2 \cdot m)$ time if a feasible path exists. In addition, the connection uses the minimum number of regenerators. Among all possible connections which use the minimum number of regenerators, the computed path uses the minimum number of free wavelengths. □

PROOF. Following the construction of G^{aux} in Algorithm 1, we observe that G^{aux} has a path *activep* from $s^{\lambda_1}_{(0,0)}$ to $d^{\lambda_W}_{(\mathcal{C}1,\mathcal{C}2)}$ if and only if there is a corresponding feasible path $\mathcal{AP}$ from s to d in graph G. In addition, because in G^{aux} we remove all edges which would bring the violation to signal constraints, any path must reach a node $d^{\lambda_i}_{(pmd,ase)}$ where $pmd \leq \mathcal{C}1$ and $ase \leq \mathcal{C}2$. This proves the correctness of the algorithm.

To construct an auxiliary graph (Line 2 of Algorithm 2), each wavelength plane of the auxiliary graph has $O(n \cdot \mathcal{C}1 \cdot \mathcal{C}2)$ nodes, and $O(\mathcal{C}1 \cdot \mathcal{C}2 \cdot (m+n))$ edges. Totally G^{aux} has $O(W \cdot n \cdot \mathcal{C}1 \cdot \mathcal{C}2)$ nodes and $O(W \cdot \mathcal{C}1 \cdot \mathcal{C}2 \cdot (m+n) + W^2)$ edges. In next two FOR-loops (Line 4-14), we add $O(W \cdot \mathcal{C}1 \cdot \mathcal{C}2)$ more edges. Then Algorithm 3 is called in Line 15 to find a path. In Algorithm 3, first it takes $O(W \cdot \mathcal{C}1 \cdot \mathcal{C}2 \cdot m)$ time to remove the used edges (Lines 2-4). Then $O(W \cdot \mathcal{C}1 \cdot \mathcal{C}2 \cdot n)$ time is spent to update the edges incident with the regeneration nodes. In Line 11 of Algorithm 3, it takes $O(W \cdot \mathcal{C}1 \cdot \mathcal{C}2 \cdot (m+n))$ time to find a shortest path in the *acyclic* graph G^{aux} [3]. Finally we use $O(n)$ time to find the path $\mathcal{AP}$ and return. Thus, Line 15 of Algorithm 2 takes $O(W \cdot \mathcal{C}1 \cdot \mathcal{C}2 \cdot (m+n))$ time. In total, we can find that the time complexity of Algorithm 2 is $O(W \cdot \mathcal{C}1 \cdot \mathcal{C}2 \cdot m)$ because m is larger than n since the network G is connected.

In our approach, the cost of using a free channel is 1, and the cost of using a free OEO module is $\mathcal{MN}$. Hence for a connection, we would use as many as $\mathcal{MN}$ free channels instead of one free OEO module (note that there are at most $\mathcal{N}$ free channels can be used on a *path*). Therefore our algorithm can find a solution with the minimum usage of regenerators, and the minimum consumption of channels while using the minimum number of OEO modules. ■

4. PERFORMANCE EVALUATION

We implemented our algorithm of this paper (denoted by AP-OPT in the figures), and compared it with the previously best heuristic in [12] (denoted by HW-SPF+Trace-back in the figures). A well-known network is used to study the routing capability of the algorithms. Thus, *connection blocking probability* is the main performance criteria. Different numbers of wavelengths (W) on each fiber and different numbers of *r-nodes* are tested. For each test case, we generated different

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random connection requests. A connection request is generated at each time unit with random source and destination, and has a life time which is set to a random integer uniformly distributed in [1,100]. The network used for our tests is the Pacific Bell network (15 nodes and 21 links), shown in Fig. 3. Each link is labeled by its length in kilometers. The system parameters are set to typical values as in [11].

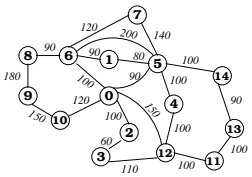
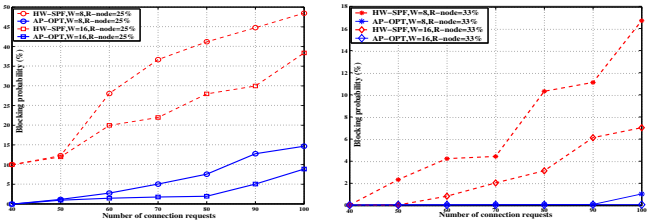


Fig. 3. The 15-node/21-link Pacific Bell network.

When a connection request arrives, we use both algorithms to compute a path. If we can find a feasible path, we reserve the corresponding network resources, including regenerators and free channels. Otherwise the connection request is dropped. Once a connection is expired, all resources used by it are released. Our numerical results are presented in Fig. 4, where each figure shows the average of 100 runs. It's worth noting that we have also tested both algorithms on some randomly generated network topologies. The results are similar. Therefore we only present the results for Pacific Bell Network here due to the page limit. In Fig. 4(a) and 4(b), we compared



(a) With 25% *r-nodes* (b) With 33% *r-nodes*

Fig. 4. Performance comparisons between AP-OPT and HW-SPF

the routing capability between two algorithms with randomly generated *r-nodes* which constitutes 25% and 33% of all nodes, respectively. On each *r-node*, as in [13], the number of *OEO* modules is assumed the same as the number of wavelengths on a fiber. 40 to 100 connections were generated and injected into the network one by one. We can observe that AP-OPT has noticeable lower blocking probability than HW-SPF+trace-back heuristic for all scenarios. For example, with the setting of $W = 16$, *R-nodes* constituting 25% of all nodes, and the number of connection requests being 70, AP-OPT achieved the blocking probability of 2%. Note that a blocking probability obtained by HW-SPF+Trace-back heuristic is about 22%. Another interesting observation is that the number of *r-nodes* has more significant effect than the number of wavelengths per fiber at reducing the blocking probability. For example, given 33% *R-nodes* and $W = 8$, HW-SPF+Trace-back has better performance than it has with more wavelength ($W = 16$) but less *R-nodes* (25%). Similar property can also be observed from the results of our algorithm. In Fig. 5, we compare the consumptions of *OEO* modules and free channels between two algorithms, which is represented by the *y*-axle. And *x*-axle represents the ratio of the number of *r-nodes* in the network. Dynamic connection requests are kept being inserted into the network until both algorithms accommodated 100

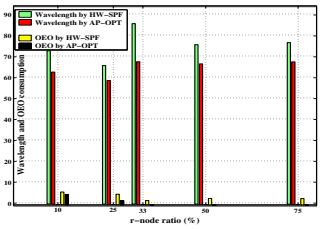


Fig. 5. Network resource consumption with 100 satisfied connections

connections. From the Fig. 5, it shows that AP-OPT uses less number of *OEO* modules and free channels than HW-SPF+Trace-back does in all testing cases. This confirms our analysis at the end of Section 3.

5. Conclusions

In this paper we considered the dynamic reliable routing problem in WDM networks under multiple signal quality constraints. We proposed a novel algorithm that can return a lightpath for a connection request if one exists. The connection uses the minimum number of *OEO* regenerators. Also the computed path consumes the minimum number of free wavelengths, among all connections which use the minimum number of regenerators. Simulation results demonstrated that our algorithm outperforms the previously best heuristic in [12].

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