Methodologies on Designing a Hybrid Shared-Mesh Protected WDM Network with Sparse Wavelength Conversion and Regeneration

Hui Zang[*], Renxiang Huang[**], and James Pan[***]
Sprint Advanced Technology Laboratories

ABSTRACT

In a wavelength-routed WDM optical network, having regeneration and wavelength conversion at every node is not cost-effective. However, in a nation-wide backbone network, regeneration is required for some lightpaths. With shared-mesh protection, wavelength-conversion is helpful in increasing the wavelength sharing among protection paths therefore can improve resource-utilization. In this work we study the problem of selecting wavelength-conversion and regeneration sites in such a network. We show that the wavelength converter placement problem can be formulated as an integer linear program and propose several heuristics for solving the sparse wavelength conversion and regeneration problem.

Keywords: wavelength-routing, WDM, lightpaths, mesh, shared-protection, wavelength-conversion, regeneration, ILP

1. INTRODUCTION

Next generation transport networks are expected to be hybrid with both all-optical cross-connects and OEO (optical-electrical-optical) cross-connects. Because OEO cross-connects are more expensive with the cost of transponders and less scalable with the growth of port counts, all-optical cross-connects are preferred. However, OEO conversion is still beneficial or necessary in core transport networks for at least two reasons: wavelength conversion and regeneration, which are elaborated below.

Wavelength-conversion has been known as a means to reduce wavelength blocking and increase network utilization. It has an effect on the protection scheme as well. In optical meshed WDM networks, mesh-based shared-path protection takes advantage of the mesh connectivity and achieves better resource utilization compared to 1+1 and SONET-ring protection schemes [1]. Wavelength conversion facilitates the sharing among protection resources and further improves the resource utilization. However, having wavelength-conversion at every node is usually not cost-effective. Wavelength conversion is usually achieved by converting the optical signal into electrical domain and regenerating back into the optical domain, i.e., at an OEO switch.

When a lightpath travels through the network, it sometimes requires regeneration. Some ultra-long-haul transmission technologies today can provide up to 3000km or even 4000km reach between a pair of back-to-back WDM systems. When a lightpath traverses multiple fibers and is switched between all-optical switches, this reach has to be reduced, however, given the fact that EDFA systems must be used together with all-optical switches to make up for the power loss at the OXCs, and EDFA systems will introduce extra noise into the transmission path. A lightpath must be regenerated before this reach, otherwise the signal will not be recoverable. Usually regeneration is only available at OEO switches. Note that we do not consider the case where all-optical switches are wrapped with WDM systems for regeneration.

To summarize, an OEO switch can be placed in the network wherever either wavelength conversion or regeneration is required. We call this type of placement a *sparse* placement. We consider a backbone network with a given physical topology and a set of traffic demands. Lightpaths are set up to satisfy the

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[*] hzang@sprintlabs.com; phone 1 650 375-4423; fax 1 650 375-4330; Sprint Advanced Technology Laboratories, One Adrian Court, Burlingame, CA 94010, USA;

[**] rhuang@sprintlabs.com; phone 1 650 375-4374; fax 1 650 375-4330; Sprint Advanced Technology Laboratories, One Adrian Court, Burlingame, CA 94010, USA;

[***] jpan@sprintlabs.com; phone 1 650 375-4027; fax 1 650 375-4330; Sprint Advanced Technology Laboratories, One Adrian Court, Burlingame, CA 94010, USA.

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traffic demands. OEO switches and OOO switches are placed in the network in such a way that the number of OEO switches is minimized to carry the given traffic. Where to place the OEO switches and how many of them are needed are the points of interests. In such a network, a lightpah can be successfully routed if and only if: 1) there is a common wavelength available on each link along the lightpath between two OEO switches; and 2) the lightpath does not exceed the reach limit before it can be regenerated at an OEO switch. Note that with mesh-based protection schemes such as shared-path protection, the protection paths are usually longer than the working paths, and have a more stringent requirement of regeneration. On one hand, choosing regeneration nodes has an important role of the overall length of the protection paths. On the other hand, choosing wavelength conversion sites is important to improve the sharing among protection resources. Therefore, it can greatly lower the network cost by choosing OEO sites properly.

We refer to this problem as the Sparse OEO Placement (SOEOP) problem. It can be defined as follows. In a network of N nodes and a set of traffic demands, a working path and a protection path are set up to satisfy each traffic request under the shared-path protection scheme. The working path and the protection path must be appropriately regenerated such that the destination can receive a “good” signal from each path. The SOEOP problem is to choose K sites ($K < N$) to place OEO switches, such that all demands can be satisfied and the total number of wavelengths links is minimized. The procedure can be iterated on a group of K values to select the most cost-effective one. This problem is NP-hard since the wavelength-converter placement problem is NP-hard regardless of the protection type. To our knowledge, no previous work on SOEOP has been considered in a WDM mesh network where shared protection schemes are employed. Since solving the problem involves considering wavelength conversion requirement and regeneration requirement, we first study the sparse wavelength converter placement problem and sparse regeneration problem separately. We formulate the sparse wavelength converter placement problem using both an Integer Linear Programming approach and a heuristic approach, and propose an algorithm to solve the sparse regeneration problem. We then propose a heuristic to solve the joint wavelength-converter placement and regeneration-site selection problem.

The rest of the paper is organized as follows. Section 2 proposes an ILP for solving the sparse wavelength converter placement problem for shared-path protection. Section 3 proposes several heuristics for solving the sparse wavelength converter placement problem for shared-path protection. The sparse regeneration problem is examined separately as well as combined with the wavelength-converter placement problem in Section 4. Section 5 concludes the study.

2. SPARSE WAVELENGTH CONVERTER PLACEMENT FOR SHARED-PATH PROTECTION: ILP APPROACH

The wavelength converter placement (WCP) problem is an optimization problem and can be stated as follows. Given a physical topology G = (V, E), where V is the set of network nodes and E is the set of physical links, the number of wavelengths on each fiber, and a static traffic demand matrix, choose K wavelength-conversion sites ($K < N$) such that, when we route each connection request on the physical topology subject to shared-path protection constraints, the total number of wavelengths on all the links in the network (which we refer to as total number of *wavelength-links*) is minimized. We formulate this problem into an integer linear program (ILP). We use the following notations in the ILP formulations.

The following are given as inputs:
- N: number of nodes in the network.
- E: number of links in the network.
- W: number of wavelengths available on each link (the wavelengths are numbered from 1 through W, and the same number of wavelengths are available on all links.)
- Links = {<i, j>}: the set of unidirectional links in the network.
- $\Lambda_{N\times N}$= {$\text{dem}_{i,\,j}$}: the traffic demand matrix, where $\text{dem}_{i,\,j}$ is the number of lightpath requests between node pair (i, j).
- K: number of wavelength conversion sites in the network.

The ILP solves for the following variables:

- $F_{i,j}^{s,d,w}$ takes the value of 1 if wavelength w on link i → j is utilized by some working path between node pair (s, d); 0 otherwise.
- $S_{p,q}^{s,d,w}$ takes the value of 1 if wavelength w on link p → q is utilized by some protection path between node pair (s, d); 0 otherwise.
- $\delta_{p,q,i,j}^{s,d,w}$ takes on the value of 1 if wavelength w on link p → q is utilized by some protection path between node pair (s, d) when link i → j fails; 0 otherwise.
- $m_{p,q}^{w}$ takes on the value of 1 if wavelength w on link p → q is utilized by some protection path; 0 otherwise.
- wc_i takes on the value of 1 if a wavelength converter is placed at node i; 0 otherwise.

The ILP for solving the WCP problem with shared-path protection is as follows.

Objective: Minimize the total number of wavelength-links:

$$\text{Minimize} \sum_{w=1}^{W} \sum_{<i,j>\in Links} (m_{i,j}^{w} + \sum_{1\le s,d\le N} F_{i,j}^{s,d,w})$$

Subject to: ($1 \le s,d \le N,\ 1 \le w \le W$ if not specified)

Demand between each node pair (s, d) is satisfied on working paths:

$$dem_{s,d} = \sum_{w=1}^{W} \sum_{\forall e:<s,e>\in Links} F_{s,e}^{s,d,w}$$

$$dem_{s,d} = \sum_{w=1}^{W} \sum_{\forall i:<i,d>\in Links} F_{i,d}^{s,d,w}$$

$$F_{i,s}^{s,d,w} = 0 \qquad \forall <i,s>\in Links$$

$$F_{d,e}^{s,d,w} = 0 \qquad \forall <d,e>\in Links$$

Flow conservation on working paths:

$$\sum_{w=1}^{W} \sum_{\forall i:<i,j>\in Links} F_{i,j}^{s,d,w} - \sum_{w=1}^{W} \sum_{\forall e:<j,e>\in Links} F_{j,e}^{s,d,w} = 0 \qquad 1\le j \ne s,d \le N$$

Per-wavelength based flow conservation on working paths depend on the node with or without wavelength conversion capability. When $wc_j = 0$, the following two in-equations translate into wavelength continuity constraint:

$$\sum_{\forall i:<i,j>\in Links} F_{i,j}^{s,d,w} - \sum_{\forall e:<j,e>\in Links} F_{j,e}^{s,d,w} \le MaxNodalDegree \times wc_j \qquad 1\le j \ne s,d \le N$$

$$\sum_{\forall i:<i,j>\in Links} F_{i,j}^{s,d,w} - \sum_{\forall e:<j,e>\in Links} F_{j,e}^{s,d,w} \ge -MaxNodalDegree \times wc_j \qquad 1\le j \ne s,d \le N$$

where MaxNodalDegree is the maximal nodal degree in the network.

Constraints on the number of rerouted lightpaths between node pair (s, d) when link i → j fails:

$$\sum_{w=1}^{W} F_{i,j}^{s,d,w} = \sum_{w=1}^{W} \sum_{\forall e:<s,e>\in Links} \delta_{s,e,i,j}^{s,d,w} \qquad \forall <i,j>\in Links$$

$$\sum_{w=1}^{W} F_{i,j}^{s,d,w} = \sum_{w=1}^{W} \sum_{\forall p:<p,d>\in Links} \delta_{p,d,i,j}^{s,d,w} \qquad \forall <i,j> \in Links$$

$$\delta_{p,s,i,j}^{s,d,w} = 0 \qquad \forall <p,s>,<i,j> \in Links$$

$$\delta_{d,e,i,j}^{s,d,w} = 0 \qquad \forall <d,e>,<i,j> \in Links$$

Flow conservation on protection paths:

$$\sum_{w=1}^{W} \sum_{\forall p:<p,q>\in Links} \delta_{p,q,i,j}^{s,d,w} - \sum_{w=1}^{W} \sum_{\forall e:<q,e>\in Links} \delta_{q,e,i,j}^{s,d,w} = 0 \quad 1 \le q \ne s,d \le N, <i,j> \in Links$$

Per-wavelength based flow conservation on protection paths depend on the node with or without wavelength conversion capability. When $wc_j = 0$, the following two in-equations translate into wavelength continuity constraint:

$$\sum_{\forall p:<p,q>\in Links} \delta_{p,q,i,j}^{s,d,w} - \sum_{\forall e:<q,e>\in Links} \delta_{q,e,i,j}^{s,d,w} \le MaxNodalDegree \times wc_q$$
$$1 \le q \ne s,d \le N, <i,j> \in Links$$

$$\sum_{\forall p:<p,q>\in Links} \delta_{p,q,i,j}^{s,d,w} - \sum_{\forall e:<q,e>\in Links} \delta_{q,e,i,j}^{s,d,w} \ge -MaxNodalDegree \times wc_q$$
$$1 \le q \ne s,d \le N, <i,j> \in Links$$

A working path and its protection path must be link-disjoint:

$$\delta_{i,j,i,j}^{s,d,w} = 0 \qquad \forall <i,j> \in Links$$

Two lightpaths protected by the same wavelength w on the same link p → q cannot go through the same link i → j:

$$\sum_{1 \le s,d \le N} \delta_{p,q,i,j}^{s,d,w} \le 1 \quad \forall <p,q>,<i,j> \in Links$$

Constraints indicating whether a wavelength w on link p → q is used by some protection path:

$$m_{p,q}^{w} \le \sum_{1 \le s,d \le N} \sum_{\forall <i,j>\in Links} \delta_{p,q,i,j}^{s,d,w} \qquad \forall <p,q> \in Links$$

$$N \times N \times E \times m_{p,q}^{w} \ge \sum_{1 \le s,d \le N} \sum_{\forall <i,j>\in Links} \delta_{p,q,i,j}^{s,d,w} \qquad \forall <p,q> \in Links$$

Wavelength w on link i → j can only be utilized by either a working path or protection path:

$$m_{i,j}^{w} + \sum_{1 \le s,d \le N} F_{i,j}^{s,d,w} \le 1 \quad \forall <i,j> \in Links$$

Total number of wavelength conversion sites in the network should not exceed K:

$$\sum_{i=1}^{N} wc_i \le K$$

The above ILP provides an approach to solve the WCP problem with shared-path protection. It can be slight modified to solve the WCP problem with shared-link protection. However, the approach is only useful for small-scale problems, i.e., when both the network and the demand set are small. For this kind of small-scale problems, the ILP can be applied to obtain an optimal solution. For large-scale problems, heuristics must be developed and applied, and only sub-optimal solution can be obtained. Our goal here is to develop a “good” heuristic whose solution to the WCP problem is nearly optimal.

3. SPARSE WAVELENGTH CONVERTER PLACEMENT: HEURISTIC APPROACHES

In this section, we first propose four heuristic algorithms to solve the WCP problem; then analyze the complexity of the four heuristics; Finally, we present an algorithm to solve the routing and wavelength assignment (RWA) problem with sparse wavelength converter placement.

3.1. **Four heuristic algorithms**

Several heuristics are developed in [2] to selectively place wavelength converters in a network. The difference between the heuristics presented in this work and those presented in [2] are: 1) in [2], dynamic traffic is considered and the objective is to minimize blocking probability, while this work considers static traffic and the objective is to minimize resource requirement; and 2) no protection is considered in [2] while this work focuses on how to improve the sharing among protection resources. A heuristic can either place K converters one by one in sequence or place them all at once. The common characteristic of all heuristics we considered in this study is that they assign a function called *potential* $\tau(v)$ to each candidate node v, which indicated the suitability of placing a converter at that node. In sequence or all at once, converters are placed at nodes of the highest potentials. If the potential of a node does not depend on the converter placement status at other nodes, we call this potential a *static* potential and all K converters can be placed at once according to the potentials. However, if the potential of a node changes after we place a converter at one of the other nodes, we call this potential a *dynamic* potential and it can be reevaluated every time a converter is placed. Hence, we can put converters either all at once or one by one in this case. In this study, we consider the following heuristics:

I. Nodal degree: $\tau(v) = d(v)$, where $d(v)$ is the degree of node v in the network’s topology graph, i.e., how many nodes that node v is connected to.

II. Passing-through traffic: $\tau(v) = \sum_{l\in E(v)} w(l) + p(l)$, where $E(v)$ is the set of links that enter or leave node v, $w(l)$ is the number of wavelengths used for working traffic on link l which does not terminate at node v, and $p(l)$ is the number of wavelengths used for protection traffic on link l which does not terminate at node v. Both $w(l)$ and $p(l)$ may change after placing a converter in the network. If we choose to place all converters at once, $\tau(v)$ will only be evaluated when the network has no converters, and the K nodes with the highest $\tau(v)$ values will be chosen. Otherwise, we place the converters one by one and evaluate $\tau(v)$ for each v where no converter is placed after each placement. In this study, we use the static placement, i.e., evaluate the total traffic only when no converter is placed.

III. Passing-through protection traffic: similar to total traffic, but $\tau(v) = \sum_{l\in E(v)} p(l)$. This heuristic is motivated by the observation that wavelength-conversion can only improve the sharing among protection resources. Hence, the wavelength-links used for protection traffic at a node is used as the measurement of how potential a node is. Also similar to total traffic, $\tau(v)$ is only evaluated when no converter is placed.

IV. Sequential minimum wavelength-links (SMWL): $\tau(v) = W\times|E| - \sum_{l\in E} w'(l,v) + p'(l,v)$, where E is the set of links in the network, $w'(l, v)$ is the number of wavelengths used for working traffic on link l, if a converter is placed at node v , and $p'(l, v)$ is the number of wavelengths used for protection traffic on link l, if a converter is placed at node v. Hence, $W\times|E|$ is the total number of available wavelength-links in the network, and $\sum_{l\in E} w'(l,v) + p'(l,v)$ is the number of wavelength-links that will be used in the network if a converter is placed at node v. Since $W\times|E|$ is a constant, maximizing $\tau(v)$ is equivalent to minimizing

$\sum_{l\in E} w'(l,v)+p'(l,v)$. *This heuristic places the next converter at a node which yields the minimum wavelength-links over all possible locations for the next converter.* This heuristic is called "sequential" because different from previous heuristics, it places the converters one by one and evaluates $\tau(v)$ after each placement.

3.2. Complexity analysis

Heuristic I utilizes a static function as $\tau(v)$, so it runs in constant time. Heuristic II and III both employ a dynamic function but evaluate the function only once. If each execution of the protection algorithm takes time T, then heuristic II and III both take time T. Note that the outcome of the protection algorithm is the number of wavelengths used on each link for working and protection traffic. Heuristic IV employs a dynamic function and evaluates the function dynamically after each placement. To place the first converter it must evaluated N nodes separately, to place the second converter it must evaluate $(N-1)$ nodes separately, … until all K converters are placed. Totally it must evaluate $(2N-K+1)K/2$ times. Because each execution takes time T, heuristic IV will take time $(2N-K+1)KT/2$, which is in the order of $O(K^2T)$. Note that heuristic IV takes much longer than the other heuristics but is still much faster compared to the exhaustive search which takes time $N!T/(K!(N-K)!)$.

3.3. Routing and wavelength-assignment

The routing and wavelength-assignment of working paths and protection paths for the given traffic requests in a network with sparse wavelength-converter placement can be solved using the layered graph shown in Figure 1. For a network with W wavelengths, W layers are plotted and each layer has the same topology as the original network. Each node has an *"image"* in every layer. For each of the wavelength-convertible nodes, its images are connected by $(W-1)$ edges, so that each wavelength can be converted to any of the other wavelengths at this node. For each traffic request, a pseudo source vertex (S) and a pseudo destination vertex (D) are added to the graph and connected to each of the images of the source node and the destination node, respectively. Dijkstra's shortest-path routing algorithm is applied to this graph to find the shortest path from the pseudo source to the pseudo destination, which will be the working path. Then, the edges that are used in the working path and cannot be used in the protection path, as required by different shared-protection schemes, (such as the edges representing a certain wavelength-link), are removed from this graph. To find the protection path with the maximum sharing among protection resources, we apply the *shortest-widest Bellman-Ford* algorithm [3] to the graph and find the shortest-widest path from the pseudo source to the pseudo destination.

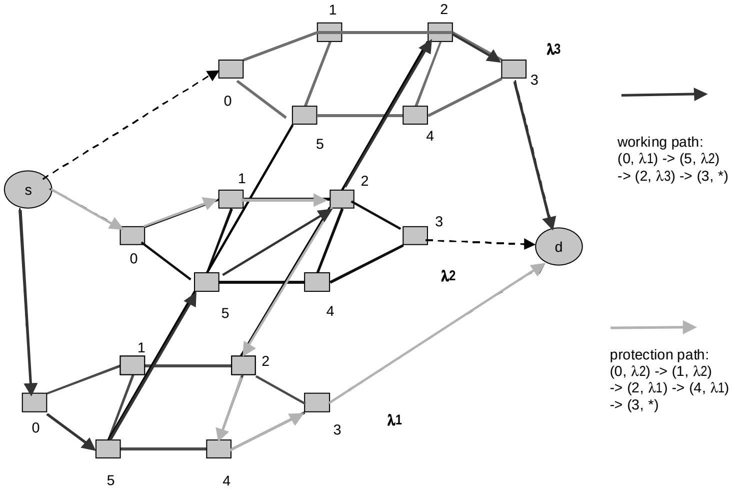

Figure 1 Routing and wavelength assignment for a connection from node 0 to node 3. Only node 2 and node 5 are wavelength-convertible. A layered graph is constructed. A working path and a protection path are computed on the layered graph.

4. SOLVING THE SPARSE REGENERATION PROBLEM

4.1. The requirement of regeneration

Figure 2 shows the transmission system view of a typical lightpath. A lightpath is a transmission path between two end OXCs. It might traverse several other OXCs which might be either all-optical or OEO. Between any two OXCs there can be a chain of Erbium-Doped Fiber Amplifiers (EDFAs) or Raman amplifiers. The fiber segment between any two amplifiers or an amplifier and an OXC is called a span. The regeneration requirement for a lightpath mainly comes from degraded Optical Signal to Noise Ratio (OSNR). A lightpath must be regenerated by an OEO OXC before its OSNR becomes too low; otherwise the signal cannot be correctly received. Assume the power of signal is kept constant by the use of amplifiers. At the same time, amplifiers are also a major source of noise. The degradation of OSNR is caused by the accumulation of noise power by a cascaded amplifier chain. For standard transmission systems, amplifiers are places at a 25dB span loss distance. In an all-optical cross-connect, in order to compensate the signal power loss when it traverses through the switch fabric (such as the mirror matrix etc.), amplifiers are usually used before and/or after the switch fabric. These amplifiers also introduce noise into the transmission path. Therefore even in an Ultra-Long-Haul (ULH) system the signal can go as far as 3000km or 4000km without regeneration, these figures are usually referring to a back-to-back transmission system without switching. The propagation distance will be far less than these values and varies from path to path with the switching of all-optical switches.

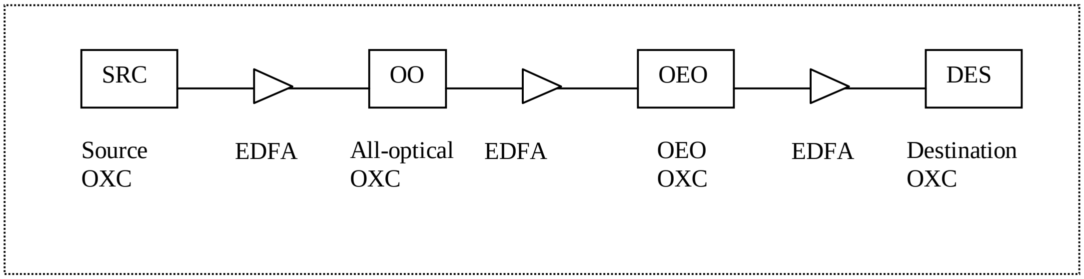

Figure 1 A typical lightpath from transmission perspective.

4.2. The calculation of OSNR

In an optical transmission system with N amplified fiber spans, the dominant noise comes from the amplified spontaneous emission (ASE) of the EDFAs or Raman amplifiers. Each amplifier contributes to the total ASE noise by $P_N = 2 \times n_{sp} h f_c (G_n - 1) B_o$, where n_{sp} is the spontaneous emission factor; G_n is the gain of the n^{th} amplifier; B_o is the optical bandwidth resolution of the optical spectrum analyzer; f_c is the optical frequency for a particular wavelength; and h is the plank constant. The total ASE noise will be $P_{ASE} = \sum_{n=1}^{N} P_n$. It is common that the optical amplifier in a system works in saturation mode, and the gain is a little bit smaller than the loss but can be safely approximated to the span loss. If we assume that the optical signal power is kept the same in each span which is a result of exact compensation of the span loss by the amplifier, the OSNR after N spans will be $OSNR_N = P / P_{ASE}$, where P is the signal power after each span.

The following are the value or computation of each parameter:

- $n_{sp} = 10^{\frac{NF}{10}} / 2$, or, NF= 10 log10 (2 n_{sp}). NF is the noise figure and usually ranges from 4 to 6 dB for EDFAs. We can choose 5dB for computation simplicity.
- G_n is assumed to be 25 dB for normal span, or 30 dB for an all-optical OXC. Note that its linear form ($10^{\frac{G_n}{10}}$) instead of dB should be used in the equation.
- B_o = 25e9 Hz
- $f_c = \dfrac{3e8}{(1550e-9)\times 1.47}$, for a wavelength at 1550nm. 1550 should be replaced when calculating the optical frequency for other wavelengths. The wavelengths in C-band usually range from 1530nm to 1565nm.
- h = 6.63 e –34 [J/Hz]

4.3. **Heuristic approaches for selecting sparse regeneration sites**

Several heuristics for solving the WCP problem can also be applied to selecting regeneration sites, such as Heuristic I (nodal degree) and Heuristic II (passing-through traffic). Please refer to Section 3 for details. We also introduce the following heuristic:

V. Sequential minimum unsatisfied lightpaths: In this heuristic, fixed-routing is applied (Suurballe's algorithm [4] can be applied to compute a min-cost working path and protection path pair) and a fixed wavelength (e.g., 1550nm) is assumed during computation for simplicity. The simplified assumption is acceptable because when the wavelength changes from 1530nm to 1565nm, f_c does not change much. We still use the potential function $\tau(v)$ (see Section 3) to choose the regeneration sites. The heuristic attempts to evaluate $\tau(v) = M - un(v)$ for each node *v* where *M* is a big constant number and *un(v)* is defined to be the number of lightpaths whose regeneration requirement is not satisfied. The fewer unsatisfied lightpaths there are when selecting node *v* as a regeneration site, the more likely that node *v* is selected. Note that the number *un(v)* includes both working paths and protection paths. If for a lightpath request, neither its working path nor its protection path is satisfied, two will be counted towards *un(v).*

4.4. **Combined Heuristic for solving the SOEOP problem**

In the previous sections and subsections we have examined and solved the sparse wavelength converter placement (WCP) and sparse regeneration sites selection problems separately. In practice they have to be considered jointly if the number of OEO sites are fixed (with value *K*). We propose the following heuristic:

VI. Sequential minimum weighted wavelength-links and unsatisfied lightpaths: $\tau(v) = M - (A \times \sum_{l \in E} w'(l,v) + p'(l,v) + B \times un(v))$, where *M* is still a big (constant) number and *A*, *B* are constant weights. Because regeneration requirements must be satisfied so we usually choose B >> A. Recall that *w'(l, v)* is the number of wavelengths used for working traffic on link *l*, if a converter is placed at node *v*; *p'(l, v)* is the number of wavelengths used for protection traffic on link *l,* if a converter is placed at node *v*; and *un(v)* is the number of lightpaths whose regeneration requirement is not satisfied. The RWA algorithm introduced in Section 3.3 is applied every time a site is assumed to be OEO for each lightpath request, and the resulted routing and wavelength(s) are used in the computation of OSNR of the both the working and protection lightpaths.

5. CONCLUSIONS

In a wavelength-routed WDM optical network, having regeneration and wavelength conversion at every node is not cost-effective. However, in a nation-wide backbone network, regeneration is necessary for some lightpaths. With shared-mesh protection, wavelength-conversion is helpful in increasing the wavelength sharing among protection paths therefore can improve resource-utilization. In this paper we show how to choose wavelength conversion and regeneration sites in such a network to satisfy each traffic demand as well as minimize the total resource usage. We formulated the wavelength converter placement problem as an integer linear program. We also proposed several heuristics for solving the sparse wavelength conversion and regeneration problem which are summarized below:

- Two heuristics which can be applied to both wavelength-converter placement and regeneration sites selection:
  - to choose nodes with the maximum nodal degree (Heuristic I)
  - to choose nodes with the maximum passing-through traffic (Heuristic II)
- Two heuristics for wavelength-converter placement
  - to choose nodes with the maximum passing-through protection traffic (Heuristic III)
  - to choose nodes with lead to the minimum wavelength-links usage (Heuristic IV)
- A heuristics for regeneration sites selection only:
  - to choose nodes which lead to the minimum number of lightpaths whose regeneration requirement is not satisfied when fixed routing is applied and fixed wavelength-assignment is assumed (Heuristic V)
- A heuristic for combined wavelength-converter placement and regeneration sites selection:
  - to choose nodes which lead to the minimum number of lightpaths whose regeneration requirement is not satisfied when adaptive routing and wavelength-assignment is applied (Heuristic VI)

The purpose of the paper is to systematically analyze the SOEOP problem from a methodology perspective. As our ongoing work we are examining the proposed heuristic algorithms. Preliminary results have shown that the sequential algorithms perform better than the static algorithms for solving the wavelength-converter placement problem and the regeneration sites selection problem separately. We expect that the adaptive-routing based approach (Heuristic VI) performs better than the fixed-routing based approach (Heuristic V) in resource efficiency.

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