Cost Analysis of Grooming Ports for IP-over-WDM Network Protection

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Abstract

In this work, the network cost associated with the protection of IP-over-WDM networks is studied. In such networks, traffic grooming is an important issue since it is not possible to set up lightpaths between every pair of label switching routers. This, however, increases cost due to the introduction of optical transceivers and electronic switching. In this work we evaluate the cost of protecting an IP-over-WDM network, using two cost functions, which capture the transceiver and electronic switching costs. The minimum cost problem is mathematically formulated for two protection schemes: IP LSP protection and WDM lightpath protection. The cost effectiveness of the two protection schemes is compared.

1. Introduction

The explosion in the popularity of the Internet has caused a dramatic increase in data traffic. The Internet is dominated by applications and services based on the Internet Protocol (IP) and this trend is expected to continue [1]. It is therefore evident that service providers should seriously consider infrastructures optimized for the dominant data, which is the IP. These factors have encouraged investigation on IP-over-WDM networks where the IP traffic is sent directly over the wavelength division multiplexing (WDM) network [2].

Today, telecommunication networks must provide uninterrupted service to their customers, that is, network survivability must be guaranteed. When using WDM, this becomes even more important because of the huge amount of traffic carried by fibers [3]. In what concerns to protection, the advantages of using WDM lightpath protection are that: protection can be applied to all traffic streams in a lightpath; and the restoration is contained within the network where the failure occurs, improving restoration latency and network stability. On the other hand, in IP-over-WDM networks, resources are used more efficiently when protection is provided to individual IP label-switched paths (LSPs). However, many signaling messages can be generated for the recovery of every IP LSP [4].

Survivability requires extra capacity and equipment raising the cost that network operators must sustain when compared to an unprotected network. In this article the cost associated with the protection of IP-over-WDM networks is discussed. First, the relevant cost functions are discussed. Then the minimum cost problem is mathematically formulated for IP LSP and WDM lightpath protection, using the cost functions found, and cost effectiveness is compared.

2. Network architecture

In IP-over-WDM networks, optical crossconnects (OXCs) are connected by optical fibers and provide lightpath services to the IP network having a collection of label switching routers (LSRs) that establish IP LSP connection requests. That is, the optical core network is the serving entity, providing end-to-end optical connections, while the IP layer acts as a client. It is assumed that each physical edge connecting nodes includes two optical fibers for transmission on both directions and that an edge failure affects both fibers on it. The terms link and optical fiber are used interchangeably.

The LSRs multiplex data streams up to the capacity of a lightpath. The assumed node architecture is shown in figure 1 [5, 6]. The LSR is connected to the OXC by optical fibers and will be equipped with wavelength transmitters and receivers.

3. Relevant cost functions

To evaluate the cost of implementing a protection scheme, it is necessary to identify the relevant network

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**Note:** The text might contain minor formatting issues due to the nature of the conversion process. The focus is on preserving the content's accuracy and clarity.
costs. In IP-over-WDM networks, since it is not possible to set up lightpaths between every pair of LSRs, traffic grooming must be done at intermediate nodes where independent lower-rate traffic streams can be multiplexed onto lightpaths. This, however, increases the network cost due to the introduction of optical transceivers and electronic switching. Therefore, in traffic grooming scenarios the following cost functions can be considered [7]:

- **Total number of lightpaths.** This is motivated by the observation that each lightpath requires a transceiver at its origin and terminal node and that terminating a lightpath requires electronic switching capacity.

- **Maximum number of lightpaths terminating/originating at a node.** This minimizes the electronic switching or transceiver cost at the node where it is maximum. That is, it sets a limit on the equipment (hence cost) of a node.

### 4. Minimum cost problem formulation

When capturing the number of grooming ports for IP LSP protection it must be considered that each working (primary) lightpath requires a transmitter and a receiver at its end nodes and no backup lightpaths exist. For WDM lightpath protection each working lightpath requires a transmitter and a receiver at its end nodes which can be used by the corresponding backup lightpath. Wavelength conversion and tunable transmitters and receivers are assumed.

Each IP LSP request has a certain bandwidth requirement and must have end-to-end protection. The set of possible bandwidth requirements considered is \{OC-3, OC-12, OC-48, OC-192\} where the bandwidth of an OC-\(y\) channel is approximately \(y \times 51.84\) Mb/s [8]. The bandwidth of a lightpath is assumed to be OC-192. To make the minimum cost problem formulation less difficult to solve the following will be assumed:

- **Precomputed working lightpaths.** Working lightpaths are mapped to the physical network and can be selected to become part of the virtual topology (set of working lightpaths that will carry IP LSPs).

- **Clustering of connections with the same source, destination and bandwidth requirement.** The formulations force all OC-\(y\) IP LSP connection requests from the source node \(s\) to the destination node \(d\) to take the same route. This means that the problem formulation will have a smaller number of constraints when compared with the no clustering case.

The output of the next integer linear programming (ILP) problems includes the virtual topology, working IP LSPs and protection for working IP LSPs. When IP LSP protection is used, backup IP LSPs must be computed for working IP LSPs. For WDM lightpath protection, backup lightpaths must be computed for working lightpaths. The bandwidth of lightpaths and the wavelength channels, in IP LSP and WDM protection respectively, can be shared by backups if their primaries are link-disjoint not failing at the same time. The IP LSP requests are given by a traffic matrix set where a matrix in such set represents a group of connections requiring the same bandwidth. The input information includes:

- \(G(\mathcal{N}, \mathcal{L})\) WDM network, where \(\mathcal{N}\) is the set of nodes and \(\mathcal{L}\) the set of links.

- \(\mathcal{Z}\) Set of working lightpaths, already mapped, that can become part of the virtual topology. The source and destination nodes of a working lightpath \(z \in \mathcal{Z}\) are given by \(s_z\) and \(d_z\) respectively.

- \(\hat{v}_n,m\) One if working lightpath \(z \in \mathcal{Z}\) uses link \(nm \in \mathcal{L}\); zero otherwise.

- \(\mathcal{Y}\) Granularities of IP LSP connection requests; \(\mathcal{Y} = \{3, 12, 48, 192\}\).

- \(\Lambda\) Traffic matrix set where \(\Lambda = \{\lambda_y\}\) for \(y \in \mathcal{Y}\). The number of OC-\(y\) IP LSP connection requests from the source node \(s\) to the destination node \(d\) is given by \(\Lambda_{y}^{s,d}\).

- \(\mathcal{F}\) Set of physical edges (possible failures) where physical edge \(e \in \mathcal{F}\) connecting nodes \(n\) and \(m\) includes both links \(nm\) and \(mn\) \(\in \mathcal{L}\).

- \(\mathcal{P}_f\) Set of working lightpaths affected by failure \(f \in \mathcal{F}\), that is, \(\mathcal{P}_f = \{z \mid \exists nm \in f, \hat{v}_n,m = 1\}\).

- \(h\) Maximum number of hops allowed for working IP LSPs.

![Figure 1. Node architecture for IP-over-WDM networks.](image-url)
Number of wavelength channels available at each link.

$C$ Bandwidth of a lightpath. Assumed to be equal to OC-192.

The variables common to IP LSP and WDM lightpath protection are:

$\xi_z$ Number of copies of working lightpath $z \in \mathcal{Z}$ in the virtual topology. A reference to working lightpath $z$ includes all the copies.

$\tau_i$ Maximum number of input/output grooming ports at node $i \in \mathcal{N}$.

$P_{\text{max}}$ Maximum number of input/output grooming ports at all nodes.

$\beta_{z,s,y}^{d}$ One if the route of the OC-$y$ working IP LSPs from node $s$ to node $d$ includes working lightpath $z \in \mathcal{Z}$; zero otherwise.

The objective functions to minimize the number of grooming ports are the same for IP LSP and WDM lightpath protection and are the following:

**F1** - Minimize total number of input and output grooming ports:

$$\text{Minimize} \sum_{z \in \mathcal{Z}} 2 \cdot \xi_z$$  \hspace{1cm} (1)

**F2** - Minimize maximum number of input/output grooming ports at nodes:

$$\text{Minimize } \max_i (\max( \sum_{z \in \mathcal{Z} : s = i} \xi_z, \sum_{z \in \mathcal{Z} : d = i} \xi_z))$$  \hspace{1cm} (2)

This has a compact notation and, in practice, is implemented by the following objective function and constraints:

$$\text{Minimize } P_{\text{max}}$$  \hspace{1cm} (3)

where

$$\tau_i \geq \sum_{z \in \mathcal{Z} : s = i} \xi_z, \forall i \in \mathcal{N}$$  \hspace{1cm} (4)

$$\tau_i \geq \sum_{z \in \mathcal{Z} : d = i} \xi_z, \forall i \in \mathcal{N}$$  \hspace{1cm} (5)

$$\tau_i \leq P_{\text{max}}, \forall i \in \mathcal{N}$$  \hspace{1cm} (6)

Constraints 4 and 5 force the maximum number of input/output grooming ports at a node to be greater or equal to the number of lightpaths emanating and terminating, respectively, at the node. Constraint 6 imposes an upper limit to the maximum number of input/output grooming ports at a node. The following two constraints are common to WDM and IP LSP protection.

- Primary routes for working IP LSPs:

$$\sum_{z \in \mathcal{Z}} \beta_{z,s,y}^{d} - \sum_{z \in \mathcal{Z}} \beta_{z,y}^{s} = \begin{cases} 1, & \text{if } s = i \\ -1, & \text{if } d = i \\ 0, & \text{otherwise} \end{cases}, \forall s, d, i \in \mathcal{N}, \forall y \in \mathcal{Y}$$  \hspace{1cm} (7)

- Limitation of number of hops in working routes:

$$\sum_{z \in \mathcal{Z}} \beta_{z,y}^{s} \leq h, \forall s, d \in \mathcal{N}, \forall y \in \mathcal{Y}$$  \hspace{1cm} (8)

- Integer and binary assignments:

$$\beta_{z,y}^{s} \in \{0, 1\}; \text{int } \xi_z, \tau_i, P_{\text{max}}$$  \hspace{1cm} (9)

In constraint 7 a route is built for all set of OC-$y$ working IP LSPs, guaranteeing flow conservation. Constraint 8 limits the number of hops (lightpaths) in the route of the working IP LSPs, that is, the number of opto-electronic conversions is limited.

### 4.1. WDM lightpath protection additional constraints

The next variable is specific to the ILP formulation using WDM lightpath protection:

$\theta_{nm}^z$ Number of wavelength channels used in link $nm \in \mathcal{L}$ to build the backup lightpath of working lightpath $z \in \mathcal{Z}$ in the virtual topology.

The constraints necessary for lightpath protection at the WDM layer are:

- Backup lightpaths of virtual topology working lightpaths:

$$\sum_{m:nm \in \mathcal{L}} \theta_{nm}^z - \sum_{m:nm \in \mathcal{L}} \theta_{mn}^z = \begin{cases} \xi_z, & \text{if } s_z = n \\ -\xi_z, & \text{if } d_z = n \\ 0, & \text{otherwise} \end{cases}, \forall z \in \mathcal{Z}, \forall n \in \mathcal{N}$$  \hspace{1cm} (10)

$$\xi_z(p_{nm}^z + p_{mn}^z) + \theta_{nm}^z + \theta_{mn}^z \leq \xi_z, \forall z \in \mathcal{Z}, \forall nm, mn \in \mathcal{L}$$  \hspace{1cm} (11)

- Limitation of wavelength channels per link and bandwidth of lightpaths:

$$\sum_{s, d \in \mathcal{N}, y \in \mathcal{Y}} y * \Lambda_{p}^{s, d} * \beta_{z,y}^{s, d} <= C * \xi_z, \forall z \in \mathcal{Z}$$  \hspace{1cm} (12)

$$\sum_{z \in \mathcal{Z}} \xi_z * p_{nm}^z + \sum_{z \in \mathcal{P}_f} \theta_{nm}^z \leq W, \forall nm \in \mathcal{L}, \forall f \in \mathcal{F}$$  \hspace{1cm} (13)
The following results were obtained for the network in figure 2 using CPLEX 8.0. The traffic matrices used for OC-3, OC-12, OC-48 and OC-192 connection requests were randomly generated using different uniform distributions. Uniformly distributed random numbers between 0 and 16 were generated for OC-3, between 0 and 8 for OC-12, between 0 and 4 for OC-48, and between 0 and 2 for OC-192. The set of mapped lightpaths \( \mathcal{L} \) that can potentially become part of the virtual topology include one lightpath for each node pair using the shortest path.

**Figure 2. The 6-node network used in simulations.**

Since working IP LSPs and protection must be computed to all IP LSPs, the value of \( W \) used in the simulations must be a value for which a feasible solution is possible, otherwise the problem becomes impossible to be solved. The following table include the values of the ILPs obtained for \( h = 1 \) (single-hop) and \( h \geq 2 \) (multihop), for different values of \( W \). The results obtained for \( h = 2, 3, \ldots, \infty \) were the same. The cells with a bar mean that no feasible solution can be obtained for the corresponding value of \( W \).
Tables 1 and 2 show the total number of input and output grooming ports (F1) and maximum number of input/output optical grooming ports at nodes (F2) necessary to provide protection to all traffic. The values show that the IP LSP protection scheme requires much more ports for both cost functions. This is because there are no backup lightpaths and only active lightpaths exist to carry the backup and working IP LSPs. However, this scheme is more bandwidth efficient than lightpath protection since it is able to carry all the IP LSPs using a smaller number of wavelengths. The number of grooming ports used by the lightpath protection scheme is the smallest number of grooming ports possible.

In what concerns to the number of wavelengths, one extra wavelength is enough to achieve the best number of grooming ports in table 1. The values in 2 do not change with the number of wavelengths available for both single-hop and multihop traffic delivery. For the single-hop case this happens because no routing alternatives exist. For the multihop case the values do not change because of the nature of this objective function. That is, this objective function imposes an upper limit and does not count for the exact number of grooming ports.

When comparing the single-hop and multihop cases we can also conclude that, as expected, multihop traffic delivery requires fewer number of wavelengths because the bandwidth of lightpaths is better utilized. The difference of performance between the two cost functions is also smaller in this case.

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6 Conclusions

In this work the cost effectiveness of IP LSP and lightpath protection schemes, operating at the IP and WDM layers respectively, has been compared. Two cost functions were used to capture the transceiver and electronic switching costs, considered to be the most relevant costs in traffic grooming studies: i) total number of lightpaths and ii) maximum number of lightpaths terminating/originating at a node. The results show that the IP LSP protection approach is the one consuming more grooming ports although being more bandwidth efficient.

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References


