A Novel Restoration Scheme for Optical WDM Networks

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Abstract: The study of restoration schemes so that all-optical WDM networks have fault-tolerancy is a critical issue. Here we study the maximum restoration problem in all-optical WDM networks where, given a physical network with point-to-point working lightpaths and some spare wavelength channels for backup purposes, the goal is to find backup routes for as many working lightpaths as possible under the edge capacity constraints. We propose a scheme that consideres the possibility of using not only sharing of free wavelength channels, but also sharing of existing working lightpaths, to construct a backup route for a working lightpath, as long as they together form a ring and are edge-disjoint. The maximum restoration problem using this approach and the well known shared approach, that just consideres the sharing of free wavelength channels, are both formulated and a distributed algorithm is implemented to analyse the restoration capacity of both approaches.

1 Introduction

In the short term fast circuit-switched optical WDM networks will provide the core network to transmit high data throughputs. While WDM networks may carry large volumes of traffic between users, they also have some potential problems. The most serious is the network *survivability*, that is, the capacity of the network to provide continuous service in the presence of failures. With the ultra-high-capacity fiber cables and optical cross connects, fiber cuts or cross-connect failures can be catastrophic, causing severe service loss, unless rapid restoration of service is an integral part of the network design and operations strategies. Therefore designing survivable WDM networks becames a critical issue [1, 2]. Here we focus on the maximum restoration problem that tries to find a backup route for as many working lightpaths as possible. We propose an approach, called primary-shared path-based, that tries to find backup routes using if necessary existing working lightpaths that, together with the available wavelength channels of some links, form a ring. A distributed algorithm is used to evaluate the performance of this approach.

2 Survivability Concepts

A network with fault-tolerance capacity is called a *survivable network*. The process of reestablishing communication of a failed lightpath, through an alternative link and/or node disjoint lightpath, is known as *restoration*. A lightpath that carries traffic during normal operation is known as *primary lightpath*. The alternative lightpath established in case of failure is known as *backup lightpath*. Designing a network to survive any type of failure, including several elements at the same time, is very costly. Since single failures are more likely to happen than multiple failures at the same time, operators generally consider just a restricted set of realistic failure scenarios that include single link and node failures.

Survivability schemes can be classified into *protection* and *dynamic restoration*. Protection refers to the fact that recovery from network failures is based on preplanned schemes and it relies on dedicated resources. In dynamic restoration the resources used for recovery are not reserved at the time of connection establishment but are choosen from available resources when the failure occurs. When compared to predesigned protection, dynamic restoration makes a more efficient use of the capacity and provides resilience against different kinds of failures but, on the other hand, these are more complex and the restoration time is longer than predesigned protection schemes. Also, full recovery is not guaranteed because sufficient spare capacity may not be available at the time of failure. Since restoration speed is a key concern in optical networks, due to the large traffic carried, most of today optical networks use protection rather than dynamic restoration schemes [3].

The protection and dynamic restoration schemes proposed for mesh networks can be *link-based* or *path-based*. Link-based restoration methods reroute disrupted traffic around the failed link, while path-based rerouting replaces the whole path between the two endpoints of the demand. Path-based approaches may use less capacity than link-based approaches and allows restoration in the event of a node failure [2]. Both link-based and path-based protection can be classified into *dedicated* and *shared*. In dedicated protection the wavelength channels on the links used by a backup lightpath are reserved for a specific primary lightpath meaning that two overlapping backup lightpaths must use different wavelengths channels even if their primary lightpaths do not overlap. This scheme has the ability to recover from not only single-link failures, but also some multilink failures. In shared protection two backup lightpaths may use both a wavelength channel if the corresponding primary lightpaths are link-disjoint (both backup lightpaths will not be activated at the same time in a single-link failure scenario). Therefore, the capacity is used more efficiently while achieving 100 percent recovery from single-link failures only [1]. A path-based restoration method can also be *failure-dependent* or *failure-independent*. In the first case there is a backup lightpath associated with each link of the primary lightpath that might fail and in the second one a single backup lightpath is associated with every link and is activated if any failure occurs [3]. We are considering in this work a failure-independent, shared path-based protection approach. A different kind of sharing was used, called primary-sharing, that will be described later. Single-link failure is also assumed.

3 The Maximum Restoration Problem

The problem considered here is known as *Maximum Restoration* (MR) problem and is defined as follows: *Given an all-optical WDM physical network $\mathcal{G}(\mathcal{N},\mathcal{A})$, where $\mathcal{N}$ is the set of nodes and $\mathcal{A}$ is the set of links, a set of point-to-point demands $\mathcal{C}$, where $\mathcal{R}(c)$ denotes the primary lightpath of demand $c \in \mathcal{C}$, and spare capacity on each link, find backup lightpaths for as many demands as possible under the link capacity constraints.*

This problem is considered in [2] where it is shown to be NP-complete. This applies to a scenario in which the network is already carrying demands and, while it is not possible to change the routes of their primary lightpaths, backup lightpaths can be recomputed to get better capacity utilization because these are not in use in the absence of a failure. Some shared path-based schemes have been proposed in the literature (see for example, [2, 4]) to solve this problem. In a realistic scenario where wavelength channels are limited, some primary lightpaths may not have a backup lightpath. Here we propose a novel approach to solve the MR problem that, when searching a route for backup, it consideres the possibility of using not only available channels but also existing primary lightpaths if necessary, thus increasing backup possibilities. When using this approach two backup routes may use both a wavelength channel or a primary lightpath if the corresponding primary lightpaths are link-disjoint. The reasons why we propose this scheme are: *i*) Working primary lightpaths may be destroyed by operators if considered to be useless. If this happens, wavelength channels released by these primary lightpaths can be rapidly added to the backup routes using it; *ii*) Since a primary lightpath is only used by two backup routes if their corresponding primary lightpaths are link-disjoint, meaning that both backup routes will never be activated at the same time in a single-failure scenario, the increase of congestion for primary lightpaths used by backup routes is low since they will have to deliver traffic from at most one extra pair of nodes.

4 MR Problem Formulation

The network consists of physical edges connecting nodes equipped with wavelength division multiplexers (WDMs) and wavelength cross connects (WXCs). It is assumed that each physical edge contains two optical fibers for transmission on both directions and that an edge failure will affect both optical fibers in it. The term link and optical fiber will be used interchangeably. We considere WXC with wavelength conversion functionality.

Let $\mathcal{G}(\mathcal{N},\mathcal{A})$ be an all-optical WDM physical network, where $\mathcal{N}$ is the set of nodes and $\mathcal{A}$ is the set of links, and let $N = |\mathcal{N}|$ and $L = |\mathcal{A}|$ denote the number of nodes and links in the network respectively. The set of wavelengths on each fiber is represented by $\mathcal{W}$, where $W = |\mathcal{W}|$ and $w = 1, ..., W$ indexes the set of wavelengths available on each fiber.

Define $\mathcal{Z}$ as the set of existing primary lightpaths where $z \in \mathcal{Z}$ uses a connected series of links, written $z : s(z) \rightarrow d(z)$, from the source node $s(z)$ to the destination node $d(z)$. Define also $\forall z \in \mathcal{Z}$ and $\forall l \in \mathcal{A}$, $\delta_l^z = 1$ if l is a link used by z, $\delta_l^z = 0$ otherwise. The available capacity on each link is $\forall l \in \mathcal{A}$, $c(l) = W - \sum_{z \in \mathcal{Z}} \delta_l^z$. Naturally, it is assumed that no two already established primary lightpaths use the same wavelength channel on a link. Let also $\mathcal{F}$ be the set of all physical edges, possible faults in our case, where the physical edge $f \in \mathcal{F}$ connecting nodes i and j includes both links (i, j) and $(j, i) \in \mathcal{A}$. Then, $\forall f \in \mathcal{F}$, $\mathcal{P}_f = \{z \mid \exists l \in f, \delta_l^z = 1\}$ is the set of all primary lightpaths affected by the fault f.

The variables necessary to build the backup routes are ϕ^z, ϵ_l^z and $\varphi_{z'}^z$, where $\phi^z = 1$ indicates that a backup route has been found for the primary lightpath z, 0 otherwise, $\epsilon_l^z = 1$ indicates that the backup route of the primary lightpath z uses link l, 0 otherwise, and $\varphi_{z'}^z = 1$ indicates that the backup route of

z includes the primary lightpath z'. Finally note that a link $l \in \mathcal{A}$ and a lightpath $z \in \mathcal{Z}$ may also be denoted by (i,j) if we need to specify the two end nodes. The place where (i,j) is used will indicate if it is a link or a lightpath.

4.1 Shared Path-Based Approach

The problem of finding backup routes for as many primary lightpaths as possible is formulated next.

$$Maximize \sum_{z \in \mathcal{Z}} \phi^z \tag{1}$$

$$\sum_{j \in \mathcal{N}} \epsilon^z_{(i,j)} - \sum_{j \in \mathcal{N}} \epsilon^z_{(j,i)} = \begin{cases} \phi^z, & if\ s(z) = i \\ -\phi^z, & if\ d(z) = i \\ 0, & otherwise \end{cases} \quad , \forall z \in \mathcal{Z}, \forall i \in \mathcal{N} \tag{2}$$

$$\sum_{z \in \mathcal{P}_f} \epsilon^z_l \le c(l) \quad , \forall l \in \mathcal{A}, \forall f \in \mathcal{F} \tag{3}$$

$$\epsilon^z_{(i,j)} + \epsilon^z_{(j,i)} + \delta^z_{(i,j)} \le 1 \quad , \forall i,j \in \mathcal{N}, \forall z \in \mathcal{Z} \tag{4}$$

Constraint 2 guarantees flow conservation for the backup route of every primary lightpath z. For some edge failure, the affected lightpaths can not use shared protection since they need to activate their backup routes. The necessary wavelength channels to accomodate their backup routes can not, however, exceed the number of wavelength channels available on links, and this is what constraint 3 ensures (f represents an edge that might fail while l represents a link used for backup). Naturally, this is not necessary for non overlapping primary lightpaths since they may use shared protection. Constraint 4 guarantees that a primary lightpath and its backup route are edge disjoint.

4.2 Primary-Shared Path-Based Approach

Backup routes for as many primary lightpaths as possible must be found using, if necessary, existing primary lightpaths. The second term of the objective function is used to ensure that the use of existing primary lightpaths to build backup routes is the smallest possible. The value of α should be small so that the second term never reaches the value one. If this condition is not verified, building a backup route for a primary path using existing primary lightpaths could be prefered to using available wavelength channels. The value of α could be $\frac{1}{|Z|^2 - |Z|}$, for example, a hypothetic situation where each primary lightpath uses every other primary lightpath in its backup route.

$$Maximize \sum_{z \in \mathcal{Z}} \phi^z - \alpha \sum_{z' \in \mathcal{Z}} \sum_{z \in \mathcal{Z}} \varphi^z_{z'} \tag{5}$$

$$\sum_{j \in \mathcal{N}} (\epsilon^z_{(i,j)} + \varphi^z_{(i,j)}) - \sum_{j \in \mathcal{N}} (\epsilon^z_{(j,i)} + \varphi^z_{(j,i)}) = \begin{cases} \phi^z, & if\ s(z) = i \\ -\phi^z, & if\ d(z) = i \\ 0, & otherwise \end{cases} \quad , \forall z \in \mathcal{Z}, \forall i \in \mathcal{N} \tag{6}$$

$$\sum_{z \in \mathcal{P}_f} \varphi^z_{z'} \le 1 \quad , \forall z' \in \mathcal{Z}, \forall f \in \mathcal{F} \tag{7}$$

$$\sum_{z \in \mathcal{P}_f} \epsilon^z_l \le c(l) \quad , \forall l \in \mathcal{A}, \forall f \in \mathcal{F} \tag{8}$$

$$\epsilon^z_{(i,j)} + \epsilon^z_{(j,i)} + \delta^z_{(i,j)} \le 1 \quad , \forall i,j \in \mathcal{N}, \forall z \in \mathcal{Z} \tag{9}$$

$$\varphi^z_{z'} [\delta^{z'}_{(i,j)} + \delta^{z'}_{(j,i)}] + \delta^z_{(i,j)} \le 1 \quad , \forall i,j \in \mathcal{N}, \forall z, z' \in \mathcal{Z} \tag{10}$$

When building a backup route for a primary lightpath, the flow conservation constraint 6 consideres now the possibility of using other existing primary lightpaths. These should be edge disjoint (constraint 10). Constraint 7 guarantees that a primary lightpath is only used by more than one backup route if their primary lightpaths are edge-disjoint. The reasons why this is assumed were explained in section 3.

5 Results

To evaluate the performance of the proposed approach a distributed asynchronous algorithm was implemented. This algorithm is a modified version of the one proposed in [2] for the shared path-based scheme. Changes were made so that our approach can also be implemented. The performance of both the shared and primary-shared path-based approaches where studied using the distributed algorithm on the European Optical Network (EON) with 19 nodes and 37 links proposed in [5]. The results of simulations for 100 and 200 randomly generated primary lightpaths are shown next. These primary lightpaths are assumed to be working on the network and the goal is to find a backup route for each primary lightpath.

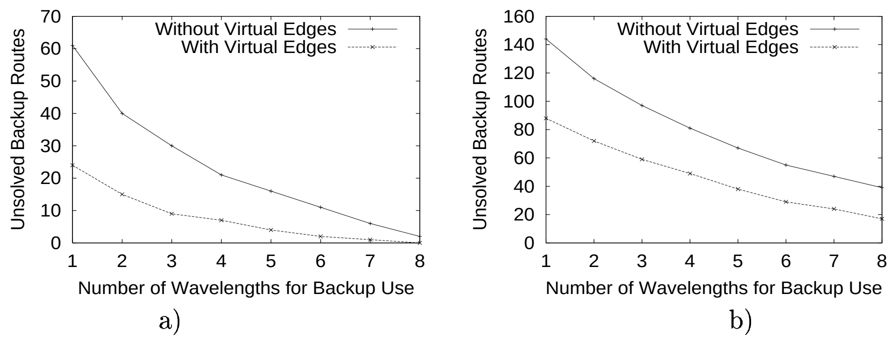

Figure 1: Unsolved backup routes for: a) 100 primary lightpaths; b) 200 primary lightpaths.

The results show that the use of virtual edges by the primary-shared path-based approach to build backup routes greatly reduces the number of unsolved backup routes meaning that the number of wavelength channels necessary to find a backup route for every primary lightpath can be much smaller when compared with the shared path-based approach. Thus, one can greatly reduce the number of wavelength channels that will be unused most of the time waitting for some failure. The performance penalty on congestion will be very small since an existing primary lightpath used by a backup route will carry traffic of just one damaged primary lightpath at a time. The primary-shared path-based approach can therefore be considered as a good solution to build backup routes.

6 Conclusions

This paper studies the maximum restoration problem in all-optical WDM networks. A primary-shared scheme is proposed for backup route construction. The restoration capacity of both shared and primary-shared approaches was compared. Simulations have shown that the proposed primary-shared path-based approach greatly reduces the number of unsolved backup routes when the number of wavelength channels for backup use is not enough to build a backup route for every primary lightpath by the well known shared path-based approach. The performance penalty on congestion is also very small. We can finally conclude that the primary-shared path-based approach can be a very good alternative to the shared path-based approach when the wavelength channels for backup use is small.

References

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