Operating Mesh-Survivable WDM Transport Networks

Murari Sridharan, Murti V. Salapaka, Arun K. Somani

Dependable Computing & Networking Laboratory
Department of Electrical & Computer Engineering
Iowa State University, Ames, IA 50011

ABSTRACT

All-optical networks with wavelength-division multiplexing (WDM) are considered to be a promising technology for next generation transport networks, as they can satisfy the growing bandwidth demand caused primarily due to an explosive growth of web-related services over the Internet. As the traffic demand increases, survivability becomes an indispensable requirement in WDM transport networks. This motivates the need for addressing failure restoration as an integral part of optical network design and operation. To date, the design problems have considered a static traffic demand aimed at optimizing the network capacity and cost, assuming various cost and survivability models. In this paper, we formulate three operational phases viz., initial call setup, medium-term reconfiguration when connections are blocked, and long-term reconfiguration to optimize resource utilization for the existing traffic, as a single Integer Linear Programming (ILP) optimization problem. This integrated framework is an attractive formulation that captures both capacity optimization and service disruption aspect in the problem formulation.

Keywords: WDM, Optical Layer Protection and Restoration, Survivability, Optimization, ILP

1. INTRODUCTION

All-optical networks with wavelength-division multiplexing (WDM) are considered to be a promising technology for next generation transport networks, as they can satisfy the growing demand for bandwidth caused primarily due to the explosive growth of web-related services offered over the Internet. With ultra-high capacity fibers and optical cross-connects, the issue of minimizing service disruption due to fiber or equipment failure becomes significantly important. This motivates the need for restoration to be addressed as an integral part of the network design and operation.

Today's Internet is dominated by applications and services based on the ubiquitous Internet Protocol (IP). The trend is likely to continue as IP continues to provide a form of protection and restoration by enabling packets to be dynamically rerouted around link or node failures. With TCP providing a reliable transport service, it is very likely that IP based applications will continue to dominate the Internet traffic for years to come. It is therefore evident that the WDM backbone networks be optimized for IP services. Many factors make it attractive to carry fast growing IP traffic directly over an optical network without the intervening SONET/SDH layer. In such cases, the entire network needs a new restoration strategy. SONET has its own protection schemes providing fast recovery (of the order of milliseconds). The relative benefits of providing restoration at either the service or the optical layer will continue to be debated. Restoration at the optical layer has several advantages a) recovery mechanisms will be much faster b) optical layer can better optimize resources such as wavelengths c) provides protection to higher layer protocols which do not have their own recovery mechanisms.

The challenge is to react quickly to these increasing bandwidth requirements while maintaining reliable service, and to design and operate networks to provide adequate capacity in the geographical areas where demand is growing fastest without over provisioning to the point of reducing the network revenue.

Further author information: (Send correspondence to Murari Sridharan)
Murari Sridharan: E-mail: murari@iastate.edu
Murti V. Salapaka: E-mail: murti@iastate.edu
Arun K. Somani: E-mail: arun@iastate.edu

1.1. Related Work

To date, design problems in mesh-survivable WDM networks have been studied in.[1–6] The study in[1] proposes an optimal design scheme for survivable WDM transport networks in which fast restoration can be achieved by using predetermined restoration paths. Integer programming (ILP) based design problems were formulated to optimally determine working and their corresponding restoration paths, the number of fibers in each span, and the optical cross connects in each node. In,[2] ILP and simulated annealing (SA) were used to solve optimization problems for routing, planning of working capacity, rerouting, and planning of spare capacity in WDM networks. The purpose of the study was the design of a fiber topology and optical path layer for WDM Networks, with a fixed channel plan, minimizing the total cost for a given traffic demand. The work in,[3] aims at providing design protection that is well adapted to WDM networks, where many channels share the same fiber. The design protection, however, does not guarantee carrying all the traffic that was carried prior to the failure. Instead, it aims at maintaining connectivity between all pairs of network ports following a single failure and lets the higher level network layers reconfigure itself so as to carry only the high priority traffic. Joint optimization of primary and restoration routes to minimize the network capacity was studied in.[4] Given a network, a set of point-to-point demands, the optimization problem was formulated to find primary and restoration route for each demand so that the network capacity is minimized. The study also tried to determine the best restoration route for each wavelength demand, given the network topology and the capacities and primary routes of all demands. The work in[5] mainly concerns connection provisioning for optical networks. An heuristic algorithm was developed for routing and wavelength assignment for a set of static connections and an adaptation of the algorithm was proposed to handle a set of failures. The study in[6] examines different approaches to protect mesh-based WDM optical networks from single-link failures. ILPs were formulated to determine the capacity requirements for a static traffic demand based on path/link protection/restoration survivability paradigms.

1.2. Network Operation

So far the design problems in optical network design and restoration have considered a static traffic demand and tried to optimize the network cost assuming various cost models and survivability paradigms. Fast restoration has been a key feature addressed on all of the designs. Once the network is provisioned, the critical issue is how to operate the network in such a way that the network performance is optimized under dynamic traffic. A problem of practical importance at this stage is to provision the network, given a traffic demand matrix. This can be posed as a static optimization problem, as there are no working connections in the network. Once the network is provisioned, every connection request arriving dynamically between a given source-destination (s-d) pair is satisfied by establishing a primary lightpath and a backup lightpath. We decompose the operational phase into three stages: a) short term reconfiguration b) medium term reconfiguration and c) long term reconfiguration. In short term reconfiguration, if a connection is blocked or a fault occurs, resources are readjusted locally in an attempt to accept or restore the connection. In medium term reconfiguration, the goal is to optimize resource consumption for restoration paths while not disturbing the primary paths of the currently working connections. The problem can be formally stated as follows. Given the current demands in the network, optimize the resource consumption for backup paths, without disturbing the primary paths of the working connections. Recently, in,[8] a heuristic algorithm has been proposed for online reconfiguration of a lightpath network, taking service disruption as a performance metric. If further optimization is required, a long term reconfiguration is triggered. We formulate an ILP to address the following long term optimization problem. This formulation provides a common framework which can be applied at all stages of reconfiguration.

Given the current demands and the new set of demands to be provisioned, optimize the network capacity, while trying to avoid service disruption to the current working paths. We use the terms demands and connections interchangeably in the paper. This optimization problem can be treated as a static formulation by removing all current connections and optimizing the network capacity for the complete demand set which includes the current working and the new demands. On the other hand, we could avoid disrupting any of the current working demands (by removing the links used by the current working demands) and optimizing the network capacity for the new demands. The former treatment provides the best capacity optimization, but all the current paths are disrupted which may not be acceptable. The latter case avoids disruption to the current working paths and tries to optimize on the remaining capacity which may not yield the best solution. To the best of our knowledge, none of the existing formulations capture the service disruption aspect into the problem formulation.

Although the need for different stages in the operational phase and their corresponding triggering mechanisms are of research importance, we do not address them in this paper. We assume that the network control and management monitors the network dynamics and triggers the various reconfiguration stages.

The rest of the paper is organized as follows. Section 2 introduces the network model and explores the choices for a restoration architecture, the optimization problem is formulated in Section 3, Section 4 discusses techniques for problem size reduction, Section 5 discusses the results and Section 6 concludes the paper.

2. RESTORATION ARCHITECTURE

In this section, we discuss the network model and motivate the restoration architecture adapted for our formulation.

The optical layer model (shown in Figure 1) consists of nodes interconnected by links which can accommodate multiple fibers. In our formulation, we assume a single fiber model. Each fiber can carry multiple wavelengths. The number of wavelengths which can be carried on a fiber is a technological constraint, which is expected to increase from a few tens to a few hundreds in the coming years. A connection request between nodes is satisfied by establishing a lightpath from the source node to the destination node. A lightpath is an all optical channel which is assigned the same wavelength on all links along the route, to provide a circuit switched connection between the nodes. Each node consists of an optical cross-connect (OXC) and optical terminating equipment. This may not always be the case as some nodes may act as through nodes where optical channels are in transit. An optical channel passing through the optical cross-connect may be routed from an input fiber to an output fiber without undergoing O-E-O conversions. In our model we assume that the same wavelength is assigned on all links along the route. So no wavelength translation function is performed in the OXC, all cross-connects are wavelength-selective. An optical channel is terminated by optical terminating equipment such as Wavelength Add/Drop Multiplexers (WADMs). WADMs are used to add or drop selected wavelengths to and from the fiber. So any node can be a source or destination to a connection.

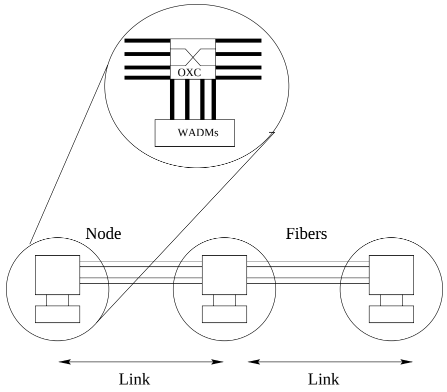

Figure 1. Optical Layer Model

A connection request between a s-d pair is provided a primary route and a backup route. We assume that each path, primary or backup, always accommodates an OAM (operation, administration, and maintenance) channel terminated by the same s-d pair as the path. The restoration model is shown in Figure 2. When a primary path fails, an alarm indication signal is generated by the node which detects the link failure and is transferred over this OAM channel. When the source receives the alarm signal in its OAM channel, it prepares to setup the pre-computed backup path and sends messages to the controllers along the backup path to configure the ports accordingly. Since the backup is dedicated, the capacity is assumed to be reserved, so no run time link capacity search needs to be performed. Once the backup path is setup, the destination prepares to receive on that path. There is no restriction in our model for the choice of wavelength on the backup path. It may or may not be the same as the primary path. The tuning time and the associated cost is assumed to be negligible.

Several survivability paradigms have been explored for surviving single link failures in mesh-based networks.[1,4,6,7,9] They can be classified based on their route computation and execution mechanisms as centralized/distributed, by their re-routing as path/link based, by their computation timing as pre-computed/real time, and their capacity

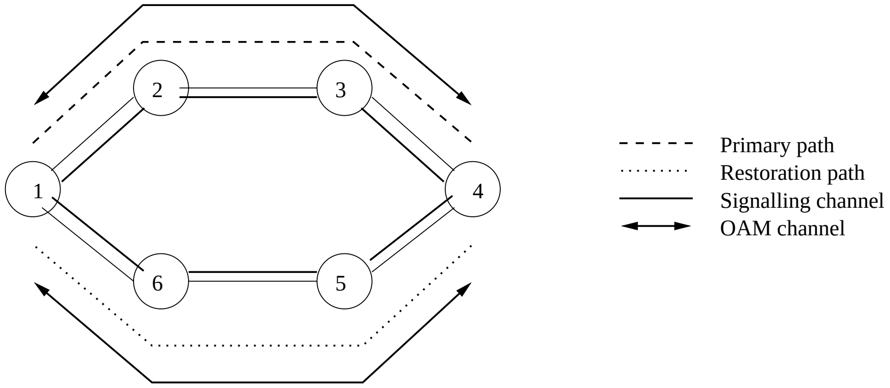

Figure 2. Restoration Model

sharing as dedicated/shared. Link based restoration methods re-route disrupted traffic around the failed link, while path based re-routing replaces the whole path between the source and destination of a demand. Link based approach requires the ability to identify a failed link at both ends and makes restoration more difficult when node failures happen. The choice of restoration paths is limited, and thus may use more capacity. The pre-computed approach calculates restoration paths before a failure happens and real time approach does so after the failure occurs. The former approach allows fast restoration as the routes are pre-computed, while the latter approach is slow, as the alternate route is computed after the failure is detected. Centralized restoration methods compute primary and restoration paths for all demands at a central controller where current information is assumed to be available. The routes are then downloaded into each node's route tables. These algorithms are usually path based. They may use pre-computed routes or detect routes at real time. As explained above, since this step needs to identify failure, ascertain the remaining topology and capacity and then find the best alternate route for the affected demands, the procedure is very slow. Given the importance of restoration speed and potential difficulty in fast failure isolation in optical networks, this approach is not very attractive. Centralized schemes which involve pre-computed routes are more conducive for practical implementations. However, maintaining up-to-date information requires frequent communications between the nodes and the central controller. This overhead becomes a potential problems as the network size grows. Distributed methods may involve pre-computed tables of routes, and discovers capacity in real time. Real time capacity discovery is slow and the capacity utilization may be inefficient. Distributed pre-computation of restoration route is an attractive approach. Capacity sharing among the primary and restoration paths can be dedicated or shared. The dedicated technique uses 1:1 protection where each primary path has a corresponding restoration path. In the shared case several primaries can share the same backup path as long as the primaries are node and link disjoint. This scheme is sometimes called backup multiplexing technique.[7] These paradigms serve as a good framework for analyzing the different design methodologies, as each design methodology uses a restoration model which is a combination of the different paradigms just described.

2.1. Restoration Model

We consider a centralized, pre-computed, shared restoration model, with 100% restoration guarantee against any single node or link failure. This means that primary and restoration paths are allocated the same capacity, and are node and link disjoint. We employ backup multiplexing to increase the wavelength utilization. We have the following constraints in our restoration model.

- Number of connections (lightpath) on each link is bounded
- Demand constraints
- Restoration path wavelength usage indicator to identify if a wavelength λ is used by some restoration route (i, r) traversing link l

- Primary path wavelength restrictions: Only one primary path can use a wavelength λ on link l, no restoration path can use the same λ on link l
- Backup multiplexing constraint: Many restoration paths can share a wavelength λ on link l iff their corresponding primary paths are link and node disjoint
- Primary and backup paths for a given demand should be node and link disjoint

3. FORMULATION OF THE OPTIMIZATION PROBLEM

In this section, we develop the ILP formulation for optimizing network capacity, while trying to avoid service disruption to the current working paths.

The following information is assumed to be given: the network topology, a demand matrix consisting of the new connections to be established for each class, and the set of current working connections. We also assume that a set of alternate routes between each node-pair is pre-computed and given. Each route between every s-d pair is viewed as W wavelength continuous paths, one path corresponding to every wavelength and therefore, we do not have an explicit constraint for wavelength continuity. Information regarding whether any two given paths are link and node disjoint (except the source and destination nodes) are also assumed to be given. The ILP solution determines the primary and backup paths for the demand set and hence the routing and wavelength assignment.

3.1. Notation

The network topology is represented as a directed graph $G(N, L)$ with N nodes and L links with W wavelengths on each link. We also assume that two alternate paths, which are node and link disjoint, for each s-d pair, are used to provide survivability. It has been shown in[10] that two alternate paths are generally sufficient to achieve good performance. The following notations are used.

- $n = 1, 2 \ldots, N$: Number assigned to each node in the network
- $l = 1, 2 \ldots, L$: Number assigned to each link in the network
- $\lambda = 1, 2 \ldots, W$: Number assigned to each wavelength
- $i, j = 1, 2 \ldots, N(N-1)$: Number assigned to each s-d pair
- K = Number of alternate routes ($K = 2$)
- $p, r = 1, 2, \ldots, KW$: Number assigned to a path for each s-d pair. The first $1 \leq p, r \leq W$ paths belong to route 1 and $W + 1 \leq p, r \leq 2W$ paths belong to route 2
- $\bar{p}, \bar{r} = 1, 2, \ldots, KW$: if $1 \leq p, r \leq W$ (route 1), then $W + 1 \leq \bar{p}, \bar{r} \leq 2W$ (route 2) and vice versa
- (i, p) : Refers to the pth path for s-d pair i

The following cost parameters are employed.

- C_l: Cost of using a link l (data)
- C_w: Cost of disrupting a currently working path (data)

Information regarding whether two given paths are link and node disjoint

- $I_{(i,p),(j,r)}$ takes a value one if paths (i, p) and (j, r) have at least one link in common, zero otherwise. if $i = j$ then $p \neq q$ (data).

The following notations are used for path related information

- $\delta^{i,p}$: Path indicator which takes a value one if (i, p) is chosen as a primary path, zero otherwise (binary variable)

- $\nu^{i,r}$: Path indicator which takes a value one if (i,r) is chosen as a restoration path, zero otherwise (binary variable)
- $\delta_l^{i,p}$: Link indicator which takes a value one if link l is used in path (i,p), zero otherwise (data)
- $\psi_\lambda^{i,p}$: Wavelength indicator which takes a value one if wavelength λ is used by the path (i,p), zero otherwise (data)
- $\Gamma^{i,p}$: Cost of the path (i,p)

$$\Gamma^{i,p} = \sum_{l=1}^{L} \delta_l^{i,p} C_l$$

- $g_{l,\lambda}$ takes a value one if wavelength λ is used by some restoration route (i,r) that traverses link l (binary variable)

The following notations are used for current working (primary) path related information. We are only interested in the primary route of the current working connection as the restoration paths can be re-assigned.

- $\chi^{i,p}$: Path indicator which takes a value one if (i,p) is a currently working primary path, zero otherwise (data)

The following notation is used to denote the demand in terms of lightpath requests for every node pair

- d_i: Demand for node pair i, in terms of number of lightpath request. Each request is assigned a primary and restoration route.

3.2. Problem Formulations

Objective: The objective is to minimize the network capacity. The first term in objective function denotes the capacity consumed by primary paths, and the second term denotes the capacity consumed by backup paths. The last term indicates that if a currently working connection ($\chi^{i,p} = 1$) is not picked in the final solution ($\delta^{i,p} = 0$), then the objective value is penalized by adding a cost C_w to it.

Minimize

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \sum_{l=1}^{L} \delta_l^{i,p} C_l + \sum_{l=1}^{L} \sum_{\lambda=1}^{W} g_{l,\lambda} C_l + \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \chi^{i,p} (1 - \delta^{i,p}) C_w \tag{1}$$

Restoration path wavelength usage indicator constraint: $g_{l,\lambda}$ takes a value one if wavelength λ is used by some restoration route (i,r) that traverses link l

$$X_{l,\lambda} = \sum_{i=1}^{N(N-1)} \sum_{r=1}^{KW} \nu^{i,r} \delta_l^{i,r} \psi_\lambda^{i,r} \tag{2}$$

$$g_{l,\lambda} \le X_{l,\lambda} \tag{3}$$

$$N(N-1)WK g_{l,\lambda} \ge X_{l,\lambda} \tag{4}$$

$$1 \le l \le L, 1 \le \lambda \le W, X_{l,\lambda} \ge 0$$

Link capacity constraint:

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p}\delta_l^{i,p} + \sum_{\lambda=1}^{W} g_{l,\lambda} \leq W \qquad 1 \leq l \leq L \tag{5}$$

Demand constraints for each node pair

$$\sum_{p=1}^{KW} \delta^{i,p} = d_i \qquad 1 \leq i \leq N(N-1) \tag{6}$$

$$\sum_{r=1}^{KW} \nu^{i,r} = d_i \qquad 1 \leq i \leq N(N-1) \tag{7}$$

Primary path wavelength usage constraint: Only one primary path can use a wavelength λ on link l, no restoration path can use the same λ on link l.

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p}\delta_l^{i,p}\psi_\lambda^{i,p} + g_{l,\lambda} \leq 1 \tag{8}$$

$$1 \leq l \leq L, 1 \leq \lambda \leq W$$

Backup multiplexing constraint: If $I_{(i,p),(j,r)}$ is one, then only one of the restoration paths can use a wavelength as backup among the primaries contending for backup

$$(\nu^{i,p}\delta_l^{i,p}\psi_\lambda^{i,p} + \nu^{j,r}\delta_l^{j,r}\psi_\lambda^{j,r}) I_{(i,\bar{p}),(j,\bar{r})} \leq 1 \tag{9}$$

$$1 \leq i, j \leq N(N-1), 1 \leq p, \bar{p}, r, \bar{r} \leq KW$$

Constraint for topological diversity of primary and backup paths: Primary and restoration paths of a given demand should be node and link disjoint

$$\sum_{p=1}^{W} \delta^{i,p} = \sum_{r=W+1}^{KW} \nu^{i,r} \qquad 1 \leq i \leq N(N-1) \tag{10}$$

$$\sum_{p=W+1}^{KW} \delta^{i,p} = \sum_{r=1}^{W} \nu^{i,r} \qquad 1 \leq i \leq N(N-1) \tag{11}$$

The number of variables $\delta^{i,p}$ and $\nu^{i,p}$ grow rapidly with network size. This effect is more pronounced with an increase in the number of wavelengths. For a network of size $N = 14$, $W = 32$ and $K = 2$, there are $K * W = 2 * 32$ instances of each variable for every node pair. Since there are $N * (N - 1) = 182$ node pairs, we have 11,648 $\delta^{i,p}$ variables and 11,648 $\nu^{i,p}$ variables. The number of equations will be roughly 125 million $(11,648^2)$. Thus the problem is complex even for small networks.

4. ILP PROBLEM SIZE REDUCTION

In this section, we discuss techniques for ILP problem size reduction.

4.1. Pruning the Variables

As explained in the previous section, the number of variables $\delta^{i,p}$ and $\nu^{i,p}$ grow rapidly with network size. A smarter solution would be to consider only variables that are relevant to the problem at hand. This implies that variables which are zero are removed. If a node pair does not have any demands to be routed between them, then all the variables relating to that node pair are removed.

For a network of size $N = 14$, $W = 32$ and $K = 2$, there are $K * W = 2 * 32$ instances of each variable for every node pair and there are $N * (N - 1) = 182$ such node pairs. For every node pair that does not have demands to be routed between them, we get a reduction of $K * W = 2 * 32$ instances of each variable. We also get a reduction of $K * W = 2 * 32$ equations for each of the constraints (1),(2),(5)-(11) and so if only 10 node pairs have demands to be routed between them, we have to deal with 1320^2 instead of $11,648^2$ equations!

Further reductions are possible by considering only links that affect the specific instance of demands to be provisioned. For each link not considered, we get a reduction of 248^2 equations. The above discussions suggest that it is necessary to carefully enumerate the constraints.

4.2. Demand Normalization Technique

Another procedure which results in significant problem size reductions is the demand normalization technique. Since we deal with wavelength continuous request chunks between node pairs and since all demands between every node pair source and sink at the same nodes, we do not distinguish between each of those requests.

In order to reduce the solution space, we treat each chunk of requests between every demand pair as one entity. Since the whole network should have a consistent view of each entity, we normalize the demand sets by finding the least common denominator(LCM) for all the demand requests, and dividing each demand set by that factor. The capacity on all links are also normalized. This results in a scaled down version of the original problem which is less difficult to solve.

Since the capacity on each link is normalized, the number of wavelengths W reduces by a factor of m, where m is the LCM of the demand sets. Considering the network with $N = 14$, $W = 32$ and $K = 2$, and if m is say 2, the number of variables reduces by a factor of 2 and we are left with 660^2 equations which is a $1/m^2$ reduction. This technique can yield considerable reduction if m were to be comparable to W. An appropriate procedure that can be adopted here is to adjust demand requests to get a m comparable to W and solution be adjusted accordingly. If more demands than required were solved for, then resources may be reclaimed. If fewer demands were given, then the ILP can be solved again with the solution from the previous stage fed in as currently working connections. Such approaches may deviate from the optimal value, but a feasible solution can be obtained.

5. RESULTS

We use CPLEX Linear Optimizer 5.0.1[11] to solve the ILPs. The combined routing and wavelength assignment problem is known to be NP-Complete[12] and the problem addressed in this paper is expected to be NP-Complete as well. The major difficulty in using the above formulation for larger and more practical networks arises due to the combinatorial nature of the ILP. Although several algorithmic approaches exist for solving ILP problems, it should be observed that as the number of 0-1 variables increases, the computational complexity grows exponentially. The ILP problem has been shown to belong to the class of NP-complete problems.[13] Various decomposition techniques, based on lagrangean relaxation[4,14] and LP relaxation techniques,[13,15] can be employed to reduce the computational complexity of the original problem . We demonstrate the effectiveness of our formulation on the 14 node 21 link NSFNET topology (shown in Figure 3) with one fiber per link and 10 wavelengths per fiber.

Static optimization: Consider a set of 25 demands distributed uniformly across 5 node pairs as shown in Table 1. In the static optimization stage, there are no current working connections and hence the demand matrix is to be provisioned by providing a primary and backup connection for each demand. The resulting routing and wavelength assignment is shown in Table 1. The resulting objective for the ILP is 95.

Long term reconfiguration: To understand the working of the ILP for long term reconfiguration, consider the node pairs, their alternate routes, and an instance of the primary paths of the currently working connections on their routes, as shown in Table 2. The ILP will try to avoid service disruption to the primary paths of the working connections. These paths are input to the formulation through the $\chi i, p$ variable. The ILP was solved for node pairs shown in Table 2 with $C_l = 1$ and $C_w = 4$. The effect of the solution depends on the value of C_w, the higher the value, more the guarantee that the path will remain unaffected. This value is set to be some β times the cost of primary paths. Typically the value of β is set to 3 or 4. For every connection that is disturbed, the objective value is penalized by a factor C_w.

Let node pairs 1,32,110,167 request 5 connections each and node pair 27 require 6 connections. The total number of connections requested between each node pair include those which are currently working. The resulting route and wavelength assignments for the demands are shown in Table 3. The objective for the ILP is 53.

The connections which were disturbed are denoted in Table 2 by an asterisk(*). The currently working connections were deliberately chosen to demonstrate the working of the ILP. The connections that are disturbed are the ones

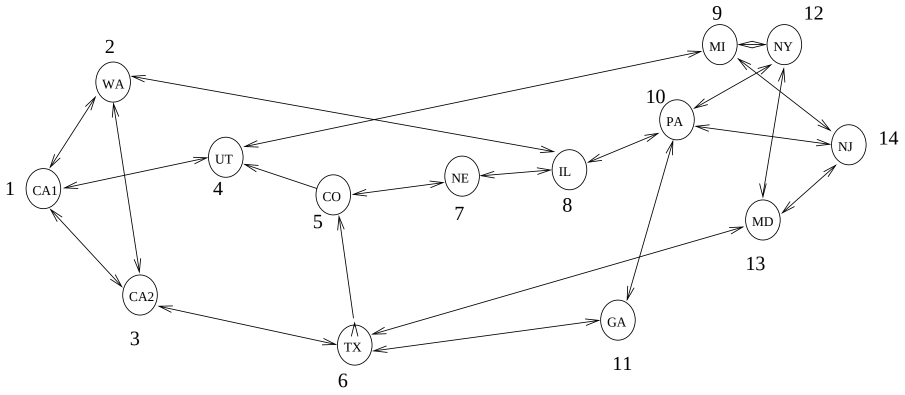

Figure 3. The 14 node 21 link NSFNET

Node pair	Alternate routes	Primary paths	Backup paths
1	1 2	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$	-
	1 3 2	-	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$
27	3 1	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$	-
	3 2 1	-	$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$
110	9 4 5 6	$\lambda_1, \lambda_2, \lambda_4, \lambda_8, \lambda_9$	-
	9 12 13 6	-	$\lambda_1, \lambda_2, \lambda_4, \lambda_8, \lambda_9$
142	11 6 13	$\lambda_1, \lambda_2, \lambda_4, \lambda_8, \lambda_9$	-
	11 10 12 13	-	$\lambda_1, \lambda_2, \lambda_4, \lambda_8, \lambda_9$
167	13 6 11	-	$\lambda_1, \lambda_2, \lambda_4, \lambda_8, \lambda_9$
	13 12 10 11	$\lambda_1, \lambda_2, \lambda_4, \lambda_8, \lambda_9$	-

Table 1. Static optimization stage

which use links where backups can be multiplexed. To understand this better, take the case of node pairs 1 and 27. They share a link $(3-2)$ on one of their routes. Since both the node pairs have atleast one disjoint route, the routes corresponding to link $3-2$ could be used for multiplexing the backup paths. Thus the primary paths of connections using wavelength λ_5 on route $1-3-2$, and λ_1, λ_2 on route $3-2-1$, were reassigned to routes $1-2$ and $3-1$ respectively.

In medium reconfiguration stage, the goal is to optimize resource consumption for backup paths. In order to ensure that the primary paths of the current working connections are never disturbed, the ILP can be solved with a very high value of C_w. This would have a similar effect as removing the currently working connections and solving

Node pair	Alternate routes	Primary paths of working connections (wavelengths)
1	1 2	λ_1, λ_2
	1 3 2	λ_5 *
27	3 1	$\lambda_1, \lambda_2, \lambda_3$
	3 2 1	*λ_1, λ_2*
110	9 4 5 6	λ_7, λ_8
	9 12 13 6	λ_5
167	13 6 11	λ_5*,λ_8*,λ_{10}*
	13 12 10 11	λ_3
32	3 6 5 7	λ_1, λ_2
	3 2 8 7	*λ_3, λ_4

Table 2. Long term reconfiguration stage

Node pair	Alternate routes	Primaries	Backups
1	1 2	$\lambda_1, \lambda_2, \lambda_3, \lambda_6, \lambda_{10}$	-
	1 3 2	-	$\lambda_1, \lambda_2, \lambda_3, \lambda_6, \lambda_{10}$
27	3 1	$\lambda_1, \lambda_2, \lambda_3, \lambda_6, \lambda_{10}$	λ_9
	3 2 1	λ_9	$\lambda_1, \lambda_2, \lambda_3, \lambda_6, \lambda_{10}$
110	9 4 5 6	$\lambda_3, \lambda_6, \lambda_7, \lambda_8$	λ_5
	9 12 13 6	λ_5	$\lambda_3, \lambda_6, \lambda_7, \lambda_8$
167	13 6 11	-	$\lambda_3, \lambda_6, \lambda_7, \lambda_8, \lambda_{10}$
	13 12 10 11	$\lambda_1\lambda_3, \lambda_6, \lambda_7, \lambda_8$	-
32	3 6 5 7	$\lambda_1, \lambda_2, \lambda_3, \lambda_{10}$	λ_4
	3 2 8 7	λ_4	$\lambda_1, \lambda_2, \lambda_3, \lambda_{10}$

Table 3. Route and wavelength assignment

the ILP for only the backup paths.

6. CONCLUSION

In this paper, we formulated three operational phases in survivable WDM networks viz., initial call set up, medium-term reconfiguration when connections are blocked, and long-term reconfiguration to optimize resource utilization for the existing traffic, as a single optimization problem. This integrated framework is an attractive formulation that captures both capacity optimization and service disruption aspect in the problem formulation. Currently, we are extending our formulation to include a service differentiation model based on lightpath protection.[16] We are also working on decomposition techniques based on LP relaxation,[17] to reduce the computation complexity of the problem, and to make it practical for large networks.

ACKNOWLEDGMENTS

This work is funded in part under NSF grant ANI 9973102.

REFERENCES

1. Y. Miyao and H. Saito, "Optimal Design and Evaluation of Survivable WDM Transport Networks," *IEEE JSAC,* Vol. 16, No. 7, September 1998, pp 1190-1198.
2. B.V. Caenegem, W.V. Parys, f. De Turck, and P.M. Demeester, "Dimensioning of Survivable WDM Networks," *IEEE JSAC,* Vol. 16, No. 7, September 1998, pp 1146-1157.
3. O. Crochat and J.Y. Boudec, "Design Protection for WDM Optical Networks ,", *IEEE JSAC,* Vol. 16, No. 7, September 1998, pp 1158-1165.
4. B.T. Doshi, S. Dravida, P. Harshavardhana, O. Hauser, and Y. Wang, "Optical Network Design and Restoration," *Bell Labs Technical Journal,* January-March 1999, pp 58-83.
5. M. Alanyali and E. Ayanoglu, "Provisioning Algorithms for WDM Optical Networks," *IEEE INFOCOM,* 1998.
6. S. Ramamurthy and B. Mukherjee, "Survivable WDM Mesh Networks, Part I - Protection," *IEEE INFOCOM,* 1999, pp 744-751.
7. G. Mohan and A. K. Somani, "Routing Dependable Connections With Specified Failure Restoration Guarantees in WDM Networks," *IEEE INFOCOM,* 2000.
8. G. Sai Kiran Reddy, G. Manimaran, and C. Siva Ram Murthy, "Reconfiguration based failure restoration in wavelength-routed WDM networks," *IEEE Intl. Conf. on Dependable Systems and Networks,* 2000.
9. T.H. Wu, "*Fiber Network Service Survivability,*" Norwood, MA: Artech House, 1992.
10. L. Li and A.K. Somani, "Dynamic Wavelength Routing Using Congestion and Neighbourhood Information," *IEEE/ACM Transactions on Networking,* October 1999.
11. http:://www.cplex.com
12. I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath Communications: An approach to high-bandwidth optical WAN's," *IEEE Transactions on Communications,* Vol. 40, No. 7, July 1992, pp 1171-1182.

13. C.A. Floudas, "*Nonlinear and Mixed-Integer Optimization: Fundamentals and Applications,*" Oxford University Press, 1995
14. M.L. Fischer, "The Lagrangean Relaxation Method for Solving Integer Programming Problems," *Management Science,* Vol. 27, No. 1, 1981, pp 1-18.
15. D. Banerjee and B. Mukherjee, "A Practical Approach for Routing and Wavelength Assignment in Large Wavelength-Routed Optical Networks," *IEEE JSAC,* Vol. 14, No. 5, June 1996, pp 903-908.
16. M. Sridharan and A.K. Somani, "Revenue Maximization in Survivable WDM Networks," accepted for publication in OPTICOMM 2000.
17. M. Sridharan, M.V. Salapaka, and A.K. Somani, "A Practical Approach to Operating Large Mesh-Survivable WDM Transport Networks,", *under preparation.*