Approaches for Capacity and Revenue Optimization in Survivable WDM Networks

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Abstract

In this paper, we consider two important objectives of network operation: (i) capacity minimization and (ii) revenue maximization. For capacity minimization, we formulate three operational phases in survivable WDM network operation viz., initial call set up, short/medium-term reconfiguration, and long-term reconfiguration. All three phases are derived from a single integer linear programming (ILP) formulation. This common framework incorporates service disruption.

We modify the framework for revenue maximization that includes a service differentiation model based on lightpath protection. We propose a multistage solution methodology to solve individual service classes sequentially and combine them to obtain a feasible solution. We provide cost comparisons in terms of increase in revenue obtained by various service classes with the base case of accepting demands without any protection. Results are provided to demonstrate the effectiveness of our framework.

Keywords

WDM, Protection, Restoration, Survivability, Service Differentiation, Revenue, Optimization, ILP

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I. Introduction

An explosion in the growth of web-related services offered over the Internet is creating a growing demand for bandwidth. The challenge is to react quickly to these increasing bandwidth requirements while maintaining reliable service. The networks should be designed and operated so as to provide adequate capacity in geographical areas where demand is growing fastest, without over-provisioning to a point where network revenue is compromised. All-optical networks employing dense wavelength division multiplexing (DWDM) have fundamentally changed the economics of transport networking, as they can effectively satisfy the growing demand for bandwidth. In WDM networks, the huge bandwidth available on an optical fiber is divided into multiple channels. Each channel can carry bandwidth upto several gigabits per second. A minimum unit of resource allocation is an optical channel, that consists of a route and a wavelength assigned on each link along the route. If wavelength translation is performed in optical switching, then each channel may be assigned different wavelengths on each link along the route; otherwise the same wavelength has to be assigned on all links along the route.

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). Restoration at the optical layer has several advantages like faster recovery mechanisms, better utilization of resources such as wavelengths and protection for higher layer protocols which do not have their own recovery mechanisms is provided. The key-enabling element in the optical layer is the design restoration strategies that provide sub-second restoration for mesh based optical networks.

A. Related Work

To date, design problems in mesh-survivable WDM networks have been studied in [1], [2], [3], [4], [5], [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. The study in [2] 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. Integer programming based design problems were formulated to optimally determine working paths together with their corresponding restoration paths, the number of fibers in each span, and the optical cross connects in each node. In [3], 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 to design 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 [4] 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 [5]. Given a network, a set of point-to-point demands, find a primary and a restoration route for each demand, such that the network capacity is minimized. The study also tried to determine the best restoration route for each wavelength demand, given the network topology, the capacities, and primary routes of all demands. The work in [6] 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.

B. Network Operation

To date, design problems in optical networks 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 in most 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. In this section, we present two important objectives of network operation, capacity minimization and revenue maximization.

B.1 Capacity Minimization

For capacity minimization we decompose network operation into three phases, a) initial call setup b) short/medium term reconfiguration and c) long term reconfiguration. The initial call setup phase is a static optimization problem where the network capacity is optimized, given the topology and a traffic matrix to be provisioned on the network. Once demands arrive dynamically, they are admitted based on a routing and wavelength assignment algorithm. The network cannot afford to run optimization procedures to route every call that arrives dynamically. As a result, the utilization of the network capacity slowly degrades to a point where calls may get blocked. This triggers various reconfigurations stages, which try to better utilize the network capacity. In short/medium term reconfiguration, the goal is to optimize resource consumption for backup paths while not disturbing the primary paths of the currently working connections. Backup paths are used only when the primary path fails, so reconfiguring backups causes no hit in service. If further optimization is required, a long term reconfiguration is triggered.

The long term reconfiguration problem can be treated as a static formulation by allowing re-routing of all working connections and optimizing the network capacity for the complete demand set, comprising of both the current working demands and the new demands. On the other hand, we could avoid disrupting any of the currently working demands (by removing the capacity used by the current working demands) and optimizing the network capacity for the new demands. The former treatment provides the best capacity optimization. However, it is possible that all the current connections may be disrupted, which may not be acceptable. The latter case avoids disruption to the current working paths, which may result in poor capacity utilization. To address this tradeoff in the long term reconfiguration problem, we capture service disruption by adding a penalty term for disrupting existing connections as explained in Section III. To the best of our knowledge, none of the existing formulations include the service disruption aspect into the problem formulation. Although the need for different stages in network operation 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 different reconfiguration stages. We use the terms demands and connections interchangeably in the paper.

B.2 Revenue Maximization

Network service providers can offer varying classes of services based on the choice of protection which can vary from full protection to no protection [7], [8], [9]. Based on the service classes, we divide the traffic in the network into one of the three classes viz., full protection, no protection and best-effort. The first class comprises of high priority traffic which require full protection in the optical layer. Many carriers may have already invested hugely in their networks and their equipment may not support protection and such applications have to rely on the optical layer for protection. The second class comprises of high priority traffic which require no protection in the optical layer, as they may already be protected by higher layers such as SONET. The best-effort class tries to provide protection for the connections based on the resources available. These may include IP traffic which have their own protection mechanisms that are slower, and as a result optical layer protection may be beneficial. Also, traffic which does not have any stringent protection requirements, but can pay for protection if the network has enough resources available. The network typically relies on the best-effort traffic for maximizing revenue. We modify the framework for revenue maximization, which includes a service differentiation model based on lightpath protection. We consider two variations on the best-effort class, variation 1) every demand is assigned a primary path. A backup path is assigned if resources are available 2) Accept as many demands as possible with or without backup. The objective is to maximize revenue. Since the network typically relies on best-effort traffic for revenue, we compare the increase in revenue obtained by the two variations of the best-effort class with the case of accepting demands without any protection.

One of the difficulties in adapting the above formulation for online reconfiguration in larger and more practical networks arises due to the combinatorial nature of the optimization problem. These problems typically take hours to solve for a few hundred demands in small networks with few tens of wavelengths. This is still acceptable in the present scenario, as it takes a few weeks to provision a new connection. We present techniques to prune the size of the ILPs for problem size reduction. Several heuristics and decomposition techniques [5], [10], [11], [12], [13] are being explored to significantly reduce the computational complexity of the original problem.

Part of the work in this paper is based on earlier work published in [14], [15]. The rest of the paper is organized as follows. Section II introduces the network model and explores the choices for a restoration architecture, the optimization problems are formulated in Section III, Section IV discusses techniques for problem size reduction, in Section V, we present a solution methodology for solving the combined problem for all classes of demands, Section VI discusses the results and Section VII concludes the paper.

II. 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 that 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 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 an optical cross-connect may be routed from an input fiber to an output fiber without undergoing optical-electronic-optical (O-E-O) conversions. In our model we assume that the same wavelength is assigned on all links along the route. Thus 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.

A connection request between a source-destination (s-d) pair is provided a primary lightpath and a backup lightpath. We assume that, each lightpath, primary or backup, always accommodates an OAM (operation, administration, and maintenance) channel terminated by the same s-d pair as the lightpath. The restoration model is shown in Figure 2. We assume wavelength continuous paths and wavelength continuity constraint must be satisfied on all links along the route. When a primary lightpath fails, an alarm indication signal is generated by the node that detects the link failure, and is transferred over the OAM channel. When the source receives the alarm signal in its OAM channel, it prepares to setup the precomputed backup lightpath and sends messages to the controllers along the backup path to configure the ports accordingly. Since the backup is dedicated for a given primary, 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 the backup 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 costs are assumed to be negligible.

Several survivability paradigms have been explored for surviving single link failures in mesh-based networks [1], [2], [5], [9], [16]. 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 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 its ends and makes restoration more difficult when node failures happen. The choice of restoration paths is limited, and thus may use more capacity than required. 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 paths are pre-computed, while the latter approach is slow, as the alternate path 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 paths 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 run 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 therefore 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 problem 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 called the backup multiplexing technique [9]. 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.

A. Restoration Model

We consider 100% restoration guarantee for any single node or link failure for protected connections. This means that primary and restoration paths of protected connections are allocated the same capacity, and are node and link disjoint. We employ backup multiplexing technique to improve the wavelength utilization. This technique allows many restoration paths, belonging to demands of different node pairs, to share a wavelength λ on link l if and only if their corresponding primary paths are link and node disjoint. It should be noted that, although every primary lightpath, has a corresponding backup lightpath dedicated to it, wavelengths on a link can be shared by restoration paths belonging to demands of different node pairs, as long as their primary paths do not share any common links. This improves wavelength utilization, while providing 100% guarantee under the single fault assumption. This is due to the fact that no single failure will cause two primary paths to contend for the same backup capacity. We have the following constraints in our restoration model.

- Number of connections (lightpath) on each link is bounded
- Levels of protection
  - Full protection: Every demand is assigned a primary and a backup path
  - No protection: Every demand is assigned only a primary path
  - Best-effort protection: (i) Every demand is assigned a primary path. A backup path is assigned if resources are available (ii) Accept as many demands as possible with or without backup.
- No backups are admitted without a primary i.e., for every node pair, the number of primaries accepted is equal to or greater than the number of backups.
- 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
- Restoration path wavelength restrictions: Many restoration paths can share a wavelength λ on link l if and only if their corresponding primary paths are link and node disjoint
- Primary and backup paths for a given demand should be node and link disjoint.

III. Formulation of the Optimization Problem

In this section, we present the ILPs for network capacity minimization and adapt the formulation to include service differentiation based on lightpath protection, for revenue maximization in wavelength routed optical networks.

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 assume that a two alternate routes between each node-pair is precomputed and given. Each route between every s-d pair is viewed as W wavelength continuous paths (lightpaths), one for each wavelength and therefore, we do not have an explicit constraint for wavelength continuity. Information regarding whether any two given routes are link and node disjoint are also assumed to be given. The ILP solution determines the primary and backup lightpaths for the demand set and hence determines the routing and wavelength assignment.

A. 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 [17] that two alternate paths are usually sufficient to achieve good performance. The following notation is 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
- $K = 2$ alternate routes between every s-d pair
- $p, r = 1, 2, \ldots, KW$: Number assigned to a path for each s-d pair. A path has an associated wavelength (lightpath). Each route between every s-d pair has W wavelength continuous paths. 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
- d_i: Demand for node pair i, in terms of number of lightpath request. Each request is assigned a primary and restoration route.

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)

- C_{ND}: Cost of a primary path (data)
- C_D: Cost of a backup 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 two routes share a link, then all lightpaths using those routes have the corresponding I value set to 1, else 0. (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)
- $\epsilon_l^{i,p}$: 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)
- $g_{l,\lambda}$ takes a value one if wavelength λ is used by some restoration route that traverses link l (binary variable)
- $\chi^{i,p}$: Path indicator which takes a value one if (i,p) is a currently working primary path, zero otherwise (data). We are only interested in the primary paths of the current working connection as the restoration paths can be re-assigned

B. *Problem Formulations*

B.1 Capacity Minimization

Objective: The objective is to minimize the network capacity. The first term in objective function (Equation (1)) denotes the capacity consumed by primary paths, and the second term denotes the capacity consumed by backup paths. The last term is a penalty term. If a currently working connection ($\chi^{i,p} = 1$) is re-assigned in the final solution ($\delta^{i,p} = 0$), then the objective value is penalized by adding a cost C_w to it.

Minimize

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

$$+\sum_{i=1}^{N(N-1)}\sum_{p=1}^{KW}\chi^{i,p}(1-\delta^{i,p})C_w \tag{1}$$

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. Constraints (3) and (4) set $g_{l,\lambda}=1$, if $X_{l,\lambda}\geq 1$

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

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

$$N(N-1)WKg_{l,\lambda}\geq X_{l,\lambda} \tag{4}$$

$$1\leq l\leq L, 1\leq\lambda\leq W, X_{l,\lambda}\geq 0$$

Link capacity constraint:

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

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.

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

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

Backup multiplexing constraint: If $I_{(i,\bar{p}),(j,\bar{r})}$ is one, then only one of the restoration paths can use a wavelength λ on a link l as backup, since the primary paths share link(s) on their route

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

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

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

$$\sum_{p=1}^{W} \delta^{i,p} = \sum_{r=W+1}^{KW} \nu^{i,r} \tag{10}$$

$$\sum_{p=W+1}^{KW} \delta^{i,p} = \sum_{r=1}^{W} \nu^{i,r} \tag{11}$$

The ILP can be used in different phases of network operation by appropriately setting the C_w value. For example, in the initial call setup phase, all $\chi^{i,p}s$ are zero as there are no working connections. Hence the third term in Equation (1) is zero. The higher the value of C_w, more the guarantee that primary paths of the working connections will remain unaffected. In the short/medium reconfiguration phase, the cost of C_w is typically set very high for the primary paths of the working connections. It is to be noted here that a high value of C_w does not guarantee that the primary path will not be re-routed in the final solution. Hence to avoid disruption to primary paths of working connections, the capacity consumed by them should be removed and the backup capacity consumption can be optimized. In the long term reconfiguration phase, an intermediate value of C_w is chosen to capture the tradeoff between possibly disrupting all connections and avoid disrupting any connection.

B.2 Revenue Maximization

Objective: The objective is to maximize the revenue. Each demand translates into a primary path and a backup path for full protection class, or only primary path for no protection class, and either only primary or both primary and backup path for best-effort class depending on the capacity available. The first term in Equation (12), denotes the revenue generated from primary paths, and the second term denotes the revenue from backup paths. The last term indicates that if a currently working connection ($\chi^{i,p} = 1$) is re-assigned in the final solution ($\delta^{i,p} = 0$), then the objective value is penalized by subtracting a cost C_w from it.

Maximize

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} C_{ND} + \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \nu^{i,p} C_D - \sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \chi^{i,p}(1-\delta^{i,p}) C_w \tag{12}$$

Restoration path wavelength usage indicator constraint:

$$X_{l,\lambda} = \sum_{i=1}^{N(N-1)} \sum_{r=1}^{KW} \nu^{i,r} \epsilon_l^{i,r} \psi_\lambda^{i,r} \tag{13}$$

$$g_{l,\lambda} \leq X_{l,\lambda} \tag{14}$$

$$N(N-1)WKg_{l,\lambda} \geq X_{l,\lambda} \tag{15}$$

$$1 \leq l \leq L, 1 \leq \lambda \leq W, X_{l,\lambda} \geq 0$$

Link capacity constraint:

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \epsilon_l^{i,p} + \sum_{\lambda=1}^{W} g_{l,\lambda} \leq W \qquad 1 \leq l \leq L \tag{16}$$

Primary path wavelength usage constraint:

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \epsilon_l^{i,p} \psi_\lambda^{i,p} + g_{l,\lambda} \leq 1 \tag{17}$$

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

Backup multiplexing constraint:

$$(\nu^{i,p} \epsilon_l^{i,p} \psi_\lambda^{i,p} + \nu^{j,r} \epsilon_l^{j,r} \psi_\lambda^{j,r}) I_{(i,\bar{p}),(j,\bar{r})} \leq 1 \tag{18}$$

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

Constraint for topological diversity of primary and backup paths:

$$\sum_{p=1}^{W} \delta^{i,p} = \sum_{r=W+1}^{KW} \nu^{i,r} \qquad 1 \leq i \leq N(N-1) \tag{19}$$

$$\sum_{p=W+1}^{KW} \delta^{i,p} = \sum_{r=1}^{W} \nu^{i,r} \qquad 1 \leq i \leq N(N-1) \tag{20}$$

Demand constraints for each node pair: Only one of the service classes described below is active in the formulation. For solving the combined problem for all classes, we adopt a different procedure as explained in Section V.

- Full protection: Every demand is assigned a primary and a backup path. The number of full protection demands for node pair i is denoted by d_{i1}.

$$\sum_{p=1}^{KW} \delta^{i,p} = d_{i1} \qquad 1 \leq i \leq N(N-1) \tag{21}$$

$$\sum_{r=1}^{KW} \nu^{i,r} = d_{i1} \qquad 1 \leq i \leq N(N-1) \tag{22}$$

- No protection: Every demand is assigned only a primary path. The number of no protection demands for node pair i is denoted by d_{i2}.

$$\sum_{p=1}^{KW} \delta^{i,p} = d_{i2} \qquad 1 \leq i \leq N(N-1) \tag{23}$$

$$\sum_{r=1}^{KW} \nu^{i,r} = 0 \qquad 1 \leq i \leq N(N-1) \tag{24}$$

- Best-effort protection: Only one variation of the best-effort service class can be used in the formulation. This assumption holds when the problem is solved for all classes. (i) Every demand is assigned a primary path. A backup path is assigned, if resources are available. The number of best-effort demands for node pair i is denoted by d_{i3}.

$$\sum_{p=1}^{KW} \delta^{i,p} = d_{i3} \qquad 1 \leq i \leq N(N-1) \tag{25}$$

$$\sum_{r=1}^{KW} \nu^{i,r} \leq d_{i3} \qquad 1 \leq i \leq N(N-1) \tag{26}$$

- Best-effort protection: (ii) Accept as many demands as possible with or without backup. The number of best-effort demands for node pair i is denoted by d_{i3}.

$$\sum_{p=1}^{KW} \delta^{i,p} \leq d_{i3} \qquad 1 \leq i \leq N(N-1) \tag{27}$$

$$\sum_{r=1}^{KW} \nu^{i,r} \leq d_{i3} \qquad 1 \leq i \leq N(N-1) \tag{28}$$

Best-effort class constraints: These constraints are used only when the best-effort class demands are being solved. For best-effort variation 2 class demands (Equations (27) and (28)), no backups are admitted without a primary i.e., for every node pair, the number of primaries accepted is equal to or greater than the backups. This constraint is required to ensure that when best-effort variation 2 class demands are admitted, the ILP does not admit more backups than primaries. The topological diversity constraint has to be modified while solving for best effort class demands. This is because all primaries need not be accepted with backups. Both these constraints can be stated together as follows.

$$\sum_{p=1}^{W} \delta^{i,p} \geq \sum_{r=W+1}^{KW} \nu^{i,r} \qquad 1 \leq i \leq N(N-1) \tag{29}$$

$$\sum_{p=W+1}^{KW} \delta^{i,p} \geq \sum_{r=1}^{W} \nu^{i,r} \qquad 1 \leq i \leq N(N-1) \tag{30}$$

In Equation (12), the last term indicates that if a currently working connection ($\chi^{i,p} = 1$) is re-assigned in the final solution ($\delta^{i,p} = 0$), then the cost C_w is subtracted from the objective and since the objective is to maximize, it ensures that service is not disrupted unless otherwise to increase revenue. The choice of C_w offers flexibility to the network provider. Although the network would like to avoid service disruption to all connections, there may be some customers who are willing to pay more and do not wish to be disturbed. This can be accommodated by modifying C_w to be path specific ($c_w^{i,p}$) and setting a higher cost for disrupting such connections.

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.

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

IV. ILP Problem Size Reduction

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

A. 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 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.

B. 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 greatest common divisor 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 greatest common divisor 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 obtain a m comparable to W and solution be adjusted accordingly.

V. Solution Methodology

In this section, we describe the solution methodology for solving the revenue maximization problem for all classes of demands.

Multistage Approach: As explained earlier, the number of variables grow rapidly with the network size. We present a multistage solution methodology to solve the combined problem for all classes of demands. At each stage, the problem is solved for one of the classes, and the result is used in successive stages.

Stage 1: In the first stage, we solve for the primary paths of full protection and no protection classes. The following modified maximization problem is solved at this stage.

Maximize

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} C_{ND} \tag{31}$$

Demand constraint:

$$\sum_{p=1}^{KW} \delta^{i,p} = d_{i1} + d_{i2} \qquad 1 \leq i \leq N(N-1) \tag{32}$$

Link capacity constraint:

$$\sum_{i=1}^{N(N-1)} \sum_{p=1}^{KW} \delta^{i,p} \epsilon_l^{i,p} \leq W \qquad 1 \leq l \leq L \tag{33}$$

The solution to the above ILP is a set of primary paths (chosen paths will have $\delta^{i,p}$ = 1). For the next stage, for every $\delta^{i,p} = 1$, in the Stage 1 solution, the corresponding $\chi^{i,p}$ variables is set to 1 in Stage 2. Thus, the solution from Stage 1 is fed to Stage 2 as working primary paths.

Stage 2: In this stage, we solve the original problem presented in Section III-B.2. The demand constraints for full protection class (Equations (21) and (22)), no protection class (Equations (23) and (24)) and best-effort variation 2 class (Equations (27) and (28)) are modified as follows.

$$\sum_{p=1}^{KW} \delta^{i,p} \geq d_{i1} + d_{i2} \qquad 1 \leq i \leq N(N-1) \tag{34}$$

$$\sum_{p=1}^{KW} \delta^{i,p} \leq d_{i1} + d_{i2} + d_{i3} \qquad 1 \leq i \leq N(N-1) \tag{35}$$

$$\sum_{r=1}^{KW} \nu^{i,r} \geq d_{i1} \qquad 1 \leq i \leq N(N-1) \tag{36}$$

$$\sum_{r=1}^{KW} \nu^{i,r} \leq d_{i1} + d_{i3} \qquad 1 \leq i \leq N(N-1) \tag{37}$$

It is to be noted here that we do not distinguish between demands from different service classes for a given node pair i. When the ILP solves, the result is interpreted as follows. The first $d_{i1} + d_{i2}$, $\delta^{i,p}$ variables which are set to 1, are considered to be the primary paths for the full protection and no protection class. Any feasible solution to the ILP has to satisfy this constraint. Similarly, the first d_{i1}, $\nu^{i,r}$ variables which are set to 1, are considered to be the backup paths for the full protection class. Equation (36) ensures that the backup paths for full protection class demands are chosen in this stage. Any excess primary and backup variables, which are chosen, are considered to belong to the best-effort class.

Effect of C_w: 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. It is to be noted here that a high value of C_w does not guarantee that the primary path will not be re-routed. Typically, this value is set to be some $\beta = 3, 4$ times the cost of primary paths. This implies that the increase in the objective value for choosing β primary paths is lost for disrupting one existing path.

Complexity: We provide some insights into a possible reduction in complexity at each stage of the multi-stage solution methodology. To understand the reduction in complexity at each stage, let us first examine the stage 1 of the solution. Since we are interested only in the primary paths for the full protection and no protection class in the stage 1 (backups will be chosen in the stage 2 of the solution). This is a direct reduction in complexity because, we do not consider the $\nu^{i,p}$ variables in the formulation. The stage 2 complexity depends on the value of C_w. The higher the value of C_w, more the guarantee that the path will remain unaffected in the final solution. Since this stage starts with a initial solution, there may be a decrease in the number of combinations that need to be explored, hence a faster solution can be obtained. However, it should be clearly noted that, a higher value of C_w does not guarantee that the solution will be faster. This is because, the ILP can choose to re-route any or all of the existing connections, in an attempt to maximize the objective. Although, the worst case complexity of stage 2 is same as that of solving the combined problem for all classes of demands, typically the solution is obtained much faster.

VI. RESULTS

We use CPLEX Linear Optimizer 5.0.1 [18] to solve the ILPs. The combined routing and wavelength assignment problem is known to be NP-Complete [19] and the problems addressed in this paper are expected to be NP-Complete as well. As a result, these formulations are not easily adaptable for real-time reconfiguration in larger and more practical networks. We use the techniques discussed in Section IV for problem size reduction. Several heuristics and decomposition techniques [5], [10], [11], [12], [13] are being explored to significantly 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. For comparing the increase in revenue got by two variations of the best-effort class, we show results for various demand sets on the NSFNET topology and the 20 node 32 link ARPANET topology (shown in Figure 4).

A. Capacity Minimization

Initial call setup: Consider a set of 25 demands distributed uniformly across 5 node pairs as shown in Table I. 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 path for each demand. The resulting routing and wavelength assignment is shown in Table I. The objective value 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 II. 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 II 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 working path will remain unaffected. This value (C_w) is set to be some β times the cost of primary paths (C_{ND}). 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 III. The objective value for the ILP is 53.

The connections which were disturbed are denoted in Table II 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 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 re-assigned to routes $1 - 2$ and $3 - 1$ respectively.

In short/medium reconfiguration stage, the goal is to optimize resource consumption for backup paths. The higher the value of C_w, more the guarantee that primary paths of the working connections will remain unaffected. In the short/medium reconfiguration phase, the cost of C_w is typically set very high for the primary paths of the working connections. It is to be noted here that a high value of C_w does not guarantee that the primary path will not be re-routed in the final solution, hence to avoid disruption to primary paths of working connections, the capacity consumed by them be removed and the backup capacity consumption can be optimized.

B. Revenue Maximization

Consider the following cost relationship between the primary and backup paths. $C_D = \alpha * C_{ND}$, where $0 \leq \alpha \leq 1$. The total revenue is calculated as $(\#totalprimaries * C_{ND} + \#totalbackups * \alpha * C_D)$ costunits (cu). The network relies on the best-effort class to increase revenue. We compare the increase in revenue got by the two variations of the best-effort class with a base case of accepting all connections without any protection. We show results for $C_{ND} = 500$cu and for two values of α = $\{$1,0.5$\}$. The results for various demand sets on NSFNET and ARPANET topologies are shown in Table IV and Table V respectively. For particular instances of demands, we see that the best-effort variation 1 results in a 67% gain in revenue and variation 2 achieves an additional 6% gain, for $\alpha = 1$. The cases are compared to the revenue generated by accepting all demands without protection $(\#primaries * C_{ND})$. For example, consider the case of 48 demands for $\alpha = 1$ in Table IV. The base case accepting all demands without any protection results in $48 * C_{ND} = 24,000$cu. The total revenue for variation 1 is $48 * C_{ND} + 32 * C_D = 40,000$cu, which is a 66.7% gain. The revenue for variation 2 is $44 * C_{ND} + 39 * C_D = 41,500$cu, which is a 72.9% gain. Although, both schemes employ backup multiplexing, the first variation has no choice but to choose all the primary paths and then tries to accommodate backups and so is restricted. The second variation better exploits the backup resource consumption by effectively multiplexing more connections on the same wavelength, thus accepting more connections and generating a slight increase in revenue.

We now demonstrate our multistage solution methodology on the NSFNET topology. We consider a demand set comprising of 48 demands with 12 demands in full protection class, 12 demands in no protection class, and 24 demands in best-effort class, distributed uniformly across four node pairs. The cost values used are $C_{ND} = 500$, $C_D = 500(\alpha = 1)$, $C_w = 500(\beta = 1)$.

In the first stage, the problem is solved for full protection demands. We assume that there are no currently working connections. Thus, the value of $\chi^{i,p}$ for all the node pairs is zero. The ILP determined a feasible solution, which is a set of paths, with a route and wavelength associated with each of them, for all the 12 demands in the full protection class. This set of paths, is fed into the second stage by setting the associated

$\chi^{i,p}$ variables to 1. The problem is then solved for full protection and no protection classes. The 12 paths chosen for full protection class are assumed to be working paths in this stage. The ILP assigned primary paths for all full protection and no protection demands with an objective value of 11,500.

Although, the objective value is of no relevance as long as we know the number of primary and backups selected, it is interesting to see how the ILP handles service disruption. Since the ILP determined a feasible solution for all the full protection and no protection demands, the objective value is expected to be 12,000, but the value got is 11,500 (24*$C_{ND} - 1 * C_w$). This was due to the fact that one of the full protection demand's primary path was re-assigned . The objective value incurred a penalty for disturbing the connection. Thus, by appropriately choosing C_w, as explained in Section V, this aspect of the formulation can be used to try and avoid service disruptions to existing connections in the network.

This set of primary paths is then fed to the third stage. The third stage solves the problem for all classes. The value of C_w is set to 1500 ($\beta = 3$). As explained in Section V, Equation (30) ensures that backups for all demands of the full protection class are chosen. The final solution at the end of the third stage is shown in Table VI. The demands rejected are those belonging to the best-effort class. The total revenue generated for provisioning the complete demand set for all classes is $45 * C_{ND} + 36 * C_D = 58,500$cu.

VII. Conclusions

In this paper, we considered two important objectives of network operation: (i) capacity minimization and (ii) revenue maximization. We formulated three phases in survivable WDM network operation viz., initial call set up, short/medium-term reconfiguration, and long-term reconfiguration. All three phases are derived from a single integer linear programming formulation. This common framework includes service disruption.

We modified the framework for revenue maximization, which includes a service differentiation model based on lightpath protection. The combined problem for solving demands from various service classes can be quite complex. We proposed a multistage solution methodology to solve individual service classes sequentially and combine them to obtain a feasible solution. We provided cost comparisons in terms of increase in revenue got by various service classes with the base case of accepting demands without any protection. For particular instances of demands, we see that the best-effort variation 1 results in a 67% gain in revenue and variation 2 achieves an additional 6% gain, for $\alpha = 1$. We are currently working on a heuristic algorithm based on the LP relaxation technique, for fast, near optimal, online reconfiguration in large survivable optical networks.

References

[1] Y. Miyao and H. Saito, "Optimal design and evaluation of survivable wdm transport networks," *IEEE Journal of Selected Areas in Communications*, vol. 16, no. 7, pp. 1190–1198, September 1998.

[2] S. Ramamurthy and B. Mukherjee, "Survivable wdm mesh networks, part i - protection," *IEEE INFOCOM*, vol. 2, pp. 744–751, March 1999.

[3] B.V. Caenegem, W.V. Parys, F. De Turck, and P.M. Demeester, "Dimensioning of survivable wdm networks," *IEEE Journal of Selected Areas in Communications*, vol. 16, no. 7, pp. 1146–1157, September 1998.

[4] O. Crochat and J.Y. Boudec, "Design protection for wdm optical networks," *IEEE Journal of Selected Areas in Communications*, vol. 16, no. 7, pp. 1158–1165, September 1998.

[5] B.T. Doshi, S. Dravida, P. Harshavardhana, O. Hauser, and Y. Wang, "Optical network design and restoration," *Bell Labs Technical Journal*, pp. 58–83, January-March 1999.

[6] M. Alanyali and E. Ayanoglu, "Provisioning algorithms for wdm optical networks," *IEEE INFOCOM*, vol. 2, pp. 910–918, March 1998.

[7] T. D. Ndousse and N. Golmie, "Differentiated optical services: Quality of optical service model for wdm networks," *SPIE All Optical Networking: Architecture, Control and Management Issue*, pp. 79–88, September 1999.

[8] O. Gerstel and R. Ramaswami, "Optical layer survivability: A services perspective," *IEEE Communications Magazine*, vol. 38, no. 3, pp. 104–113, March 2000.

[9] G. Mohan and A.K. Somani, "Routing dependable connections with specified failure restoration guarantees in wdm networks," *IEEE INFOCOM*, pp. 1761–1770, March 2000.

[10] M.L. Fischer, "The lagrangean relaxation method for solving integer programming problems," *Management Science*, vol. 27, no. 1, pp. 1–18, 1981.

[11] D. Banerjee and B. Mukherjee, "A practical approach for routing and wavelength assignment in large wavelength-routed optical networks," *IEEE Journal of Selected Areas in Communications*, vol. 14, no. 5, pp. 903–908, June 1996.

[12] C.A. Floudas, *Nonlinear and Mixed-Integer Optimization: Fundamentals and Applications*, Oxford University Press, 1995.

[13] M. Sridharan, M.V. Salapaka, and A.K. Somani, "A practical approach to operating survivable wdm networks," submitted for publication.

[14] M. Sridharan and A.K. Somani, "Revenue maximization in survivable wdm networks," *OptiComm: Optical Networking and Communications*, pp. 291–302, October 2000.

[15] M. Sridharan, M.V. Salapaka, and A.K. Somani, "Operating mesh-survivable wdm transport networks," *SPIE International Symposium on SPIE Terabit Optical Networking: Terabit Optical Networking*, pp. 113–123, November 2000.

[16] T.H. Wu, *Fiber Network Service Survivability*, Norwood, MA: Artech House, 1992.

[17] L. Li and A.K. Somani, "Dynamic wavelength routing using congestion and neighbourhood information," *IEEE/ACM Transactions on Networking*, vol. 7, no. 5, pp. 779–786, October 1999.

[18] http:://www.cplex.com.

[19] 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, pp. 1171–1182, July 1992.

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 I

STATIC OPTIMIZATION STAGE

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 II

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 III

ROUTE AND WAVELENGTH ASSIGNMENT

Demand	$\alpha = 1$					$\alpha = 0.5$				
	Best-effort 1		Best-effort 2			Best-effort 1		Best-effort 2		
	Primary	Backups	Primary	Backups	Rejected	Primary	Backups	Primary	Backups	Rejected
12	12	8	12	8	0	12	8	12	8	0
20	20	16	20	16	0	20	16	20	16	0
24	24	12	21	18	3	24	12	21	18	3
32	32	20	28	27	4	32	20	29	26	3
36	36	22	33	28	3	36	22	33	28	3
44	44	30	41	36	3	44	30	41	36	3
48	48	32	44	39	4	48	32	46	36	2

TABLE IV

INCREASE IN REVENUE FOR THE TWO VARIATIONS OF BEST-EFFORT CLASS (NSFNET)

Demand	$\alpha = 1$					$\alpha = 0.5$				
	Best-effort 1		Best-effort 2			Best-effort 1		Best-effort 2		
	Primary	Backups	Primary	Backups	Rejected	Primary	Backups	Primary	Backups	Rejected
12	12	8	12	8	0	12	8	12	8	0
20	20	16	18	18	2	20	16	20	16	0
24	24	12	20	20	4	24	12	20	20	4
32	32	20	28	28	4	32	20	28	28	4
36	36	20	32	28	4	36	20	32	28	4
44	44	28	40	37	4	44	28	41	34	3
48	48	24	40	40	8	48	24	41	38	7

TABLE V

INCREASE IN REVENUE FOR THE TWO VARIATIONS OF BEST-EFFORT CLASS (ARPANET)

Node pair	Class 1	Class 2	Class 3	Primary paths	Backup paths
1	3	3	6	10	10
2	3	3	6	11	10
3	3	3	6	12	8
4	3	3	6	12	8
				45	36

TABLE VI

SOLUTION AT THE END OF THE THIRD STAGE

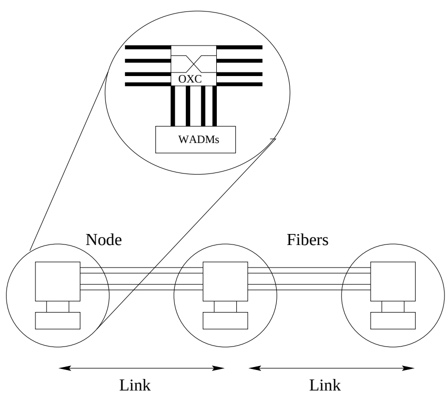

Fig. 1. Optical Layer Model

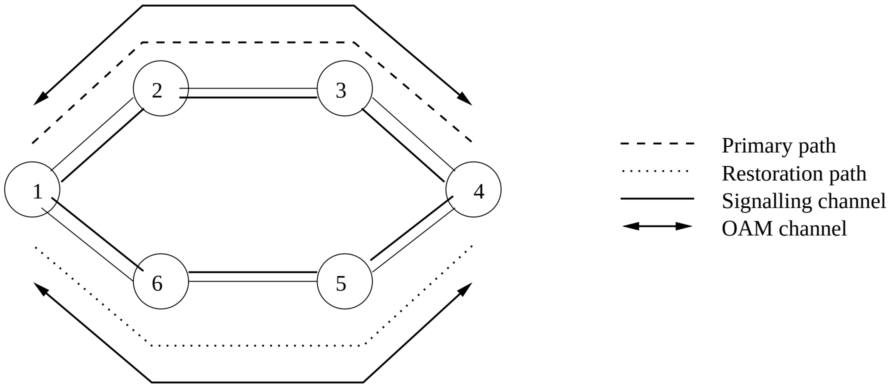

Fig. 2. Restoration Model

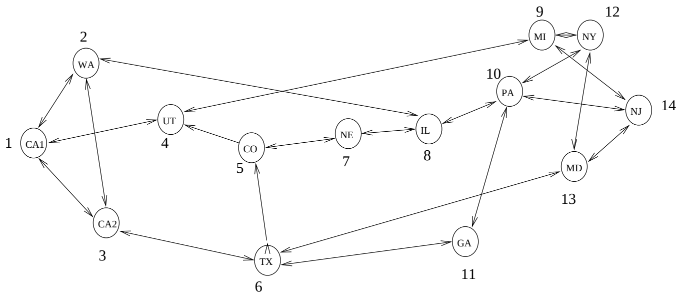

Fig. 3. The 14 node 21 link NSFNET

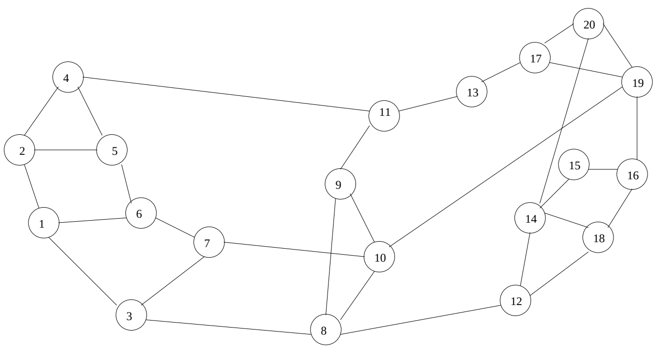

Fig. 4. The 20 node 32 link ARPANET