SURVIVABLE IP OVER WDM: GUARANTEEEING MINIMUM NETWORK BANDWIDTH

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ABSTRACT

A novel survivable IP over WDM network design problem is proposed. The IP network uses lightpath services of the WDM network to implement its IP links. The WDM network can provide unprotected and protected lightpaths, as well as a new lightpath service referred to as *survivable pair*. The IP network must support two traffic matrices, one under normal conditions and the other whenever there is a failure. A *mixed integer linear programming* (MILP) formulation of the problem is presented. An example is given where the survivable pair service can lead to significantly lower costs, sometimes by at least 30%.

KEY WORDS

Optical networks, survivable networks, IP over WDM, overlay networks, network design, mixed integer linear programming.

1. Introduction

We considered designing a survivable IP network where the IP links are realized by subscribing to lightpath services from a WDM network as shown in Figure 1. The IP network is part of some organization, perhaps a commercial Internet Service Provider (ISP) or government entity. We refer to the organization as Company X. The WDM network is part of another organization, which we refer to as Company Y. We refer to Company Y as an *optical transport service provider* (OT-SP).

Company Y provides different grades of lightpath services, where each grade is a type of protection from faults. Two services we consider are *unprotected* and *protected*. *Unprotected* service means that the lightpath can fail, while *protected* service means that the lightpath cannot, i.e., it has back-ups that it can switch to in case of faults. Note that protected service will cost more than unprotected.

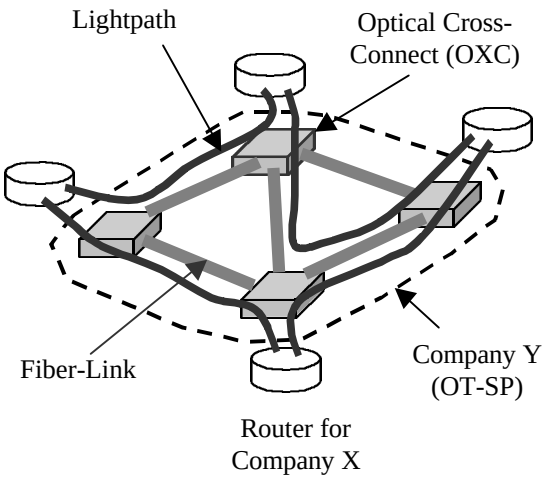

Figure 1. An IP network overlayed over a WDM network.

We assume that Company Y does not reveal its resources such as its fiber-link layout. Thus, the view of the OT-SP by Company X is more like Figure 2 rather than Figure 1. This is realistic because telecommunication companies typically keep their resources secret from competitors and customers. However, they will reveal the type and price of their lightpath services. We consider the following questions:

- *What is an appropriate definition of survivable IP networks over WDM networks?* We assume there are two traffic matrices *T* and *R* that the IP network must support. The IP network is required to carry *T* under normal conditions, i.e., no faults. It is required to carry *R* whenever a fault occurs. Thus, *R* is a survivable (guaranteed) network capacity. Note that *R* will be chosen to balance network costs with survivable performance. Presumably *R* will be significantly smaller than *T* since IP network users are cost sensitive.

- *What kinds of lightpath services will support survivable IP networks over WDM networks?* We

consider unprotected and protected lightpath services. These services are for *individual* lightpaths. We also consider protection for *pairs* of lightpaths that have the same end routers. We refer to such a pair as a *survivable pair*. An example is shown in Figure 3. They are two unprotected lightpaths that are routed so that one of them is guaranteed to survive a fault, i.e., their routes do not have a common point of failure. Note that survivable pair service only makes sense when there can be multiple IP links between routers, i.e., when *link bundling* can be applied.

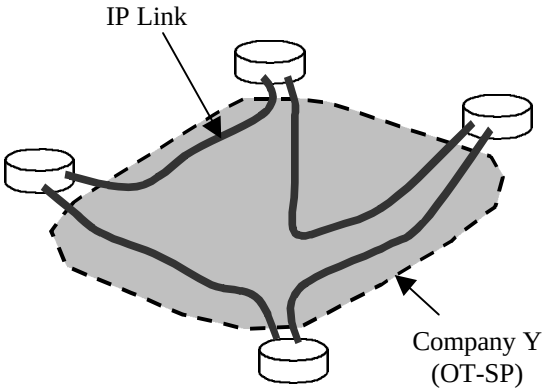

Figure 2. Company X's view of the OT-SP.

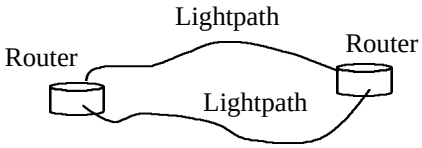

Figure 3. A survivable pair.

In Section 2, we present a *mixed integer linear programming* (MILP) problem formulation of designing an IP network that can support the traffic matrix *T* under normal conditions, and support traffic matrix *R* whenever a fault occurs. The problem assumes that unprotected, protected, and survivable pair lightpath services are available. Note that designing a survivable IP network over a WDM network has been considered before in [1][2][3] However, in these works the design problem is different in a number of ways. First, the input to the problem is an IP topology rather than traffic matrices. Second, only unprotected lightpath service is available rather than a variety of protection types. Third, part of their design problem is to route the unprotected lightpaths, while we do not consider lightpath routing. Finally, their idea of a survivable IP network is different. They only require that the IP network remain connected after a fault. Thus, they have very minimal surviving network bandwidth requirements. This may be insufficient for networks with many users that need quality of service. On the other hand, our problem requires that a prescribed network traffic *R* be supported by the network even after a fault.

In Section 3, we show that the survivable pair lightpath service can reduce costs considerably by giving an example. The costs can be reduced by as much as 30% for a 50 node network. Our final remarks are given in Section 4.

2. Network Design Problem

The following is the IP network design problem we consider. The network designer is given a collection of IP routers, where we denote their number by *n*. The IP routers are labeled 1, 2, ..., *n*. The designer is given a traffic matrix *T*, where for each pair of routers $\{i,j\}$, $T(i,j)$ denotes the rate of traffic from *i* to *j*. The designer is also given another traffic matrix *R*. We assume that *R* is no greater than *T*, i.e., for all pairs of routers $\{i,j\}$, $R(i, j) \le T(i, j)$. Note that the traffic matrices may be asymmetric.

The IP network designer must set up IP links between the routers to create an IP network, that in turn supports traffic matrix *T*. The traffic may be routed over multiple hops and bifurcated. This can be accomplished by MPLS traffic engineering. In addition, the network is survivable in the following sense. For any fault, the surviving IP network must support traffic matrix *R*, where rerouting of traffic is allowed.

The designer leases lightpaths from Company Y (i.e., the OT-SP) and uses them as the IP links. The lightpaths are assumed to be full duplex and have unit capacity. Company Y is able to provide any number of lightpaths to connect any pair of routers. In addition, Company Y provides different types of lightpaths which corresponds to different protection. The protection types are as follows:

- *Unprotected:* An unprotected lightpath is an ordinary one. If a failure occurs along its path then it goes down. We denote the cost of leasing an unprotected lightpath between routers $\{i,j\}$ by $uCost(i,j)$. Note that since the IP network designer does not know how the lightpaths are routed in the WDM network, she must assume that a single fault may bring down *all* unprotected lightpaths.

- *Protected*: A protected lightpath has back-ups. When the lightpath fails, its signal is switched over to a back-up. Thus, the IP network designer may assume that a protected lightpath will never fail. We denote the cost of leasing a protected lightpath between routers $\{i,j\}$ by $pCost(i,j)$.

- *Survivable Pair*: Survivable pairs service is for a pair of IP links between the same routers. The lightpaths

are unprotected, i.e., they may fail individually. However, at least one lightpath will survive any failure. We denote the cost of leasing a survivable pair between routers $\{i,j\}$ by $sCost(i,j)$.

The design problem for the IP network designer is to choose the number of lightpaths between the routers and their protection types to support T and R. In addition, there may be IP router port constraints at each router u, which is denoted by $D(u)$. This is an upper bound on the number of IP links that may terminate at the router u.

The design problem can be formulated as an MILP problem as follows:

- *Input Parameters*:
  - Matrix T: the traffic that the network must support under normal conditions. We refer to this as the *nominal* traffic.
  - Matrix R: the traffic that the network must support whenever there is a failure. We refer to this as the *surviving* traffic.
  - Vector D: port constraints at each router.
  - *Costs*: for each router pair $\{i,j\}$,
    - $uCost(i,j)$, the cost of an unprotected lightpath between $\{i,j\}$.
    - $pCost(i,j)$, the cost of a protected lightpath between $\{i,j\}$.
    - $sCost(i,j)$, the cost of a survivable pair between $\{i,j\}$.

- *Integer Variables*:
  - Matrix C: for each pair of routers $\{i,j\}$, $C(i,j)$ is the number of unprotected lightpaths (that are not part of survivable pairs) between them.
  - Matrix P: for each pair of routers $\{i,j\}$, $P(i,j)$ is the number of protected lightpaths between them.
  - Matrix S: for each pair of routers $\{i,j\}$, $S(i,j)$ is the number of survivable pairs between them.

- *Continuous Variables*:
  - For all ordered pairs of routers $\{i,j\}$ and destination router d, t_{ij}^d is the amount of nominal traffic that is carried on some IP link between $\{i,j\}$, from i to j, and that is destined for d.
  - For all ordered pairs of routers $\{i,j\}$ and destination router d, r_{ij}^d is the amount of surviving traffic that is carried on some IP link between $\{i,j\}$, from i to j, and that is destined for d.

- *Constraints*:
  - *All variables are nonnegative.*
  - *Lightpaths are full duplex:* Since the lightpaths are full duplex, the matrices C, P, and S are symmetric. Thus, for each pair of routers $\{i, j\}$,
$$C(i, j) = C(j, i),$$
$$P(i, j) = P(j, i),$$
$$S(i, j) = S(j, i).$$
  - *Port constraints*: for each router u,
$$\sum_v \left(C(u,v) + P(u,v) + 2S(u,v)\right) \le D(u).$$
The summation is the number of IP links that are incident to router u. Thus, the inequality insures that there are at most $D(u)$ incident IP links.
  - *Link capacity constraints for* t_{ij}^d: for each router pair $\{i, j\}$,
$$\sum_d t_{ij}^d \le \left(C(i, j) + P(i, j) + 2S(i, j)\right).$$
The summation is the amount of nominal traffic carried on links between routers $\{i, j\}$ from i to j. This cannot exceed the total capacity of the IP links between the routers.
  - *Link capacity constraints for* r_{ij}^d: for each router pair $\{i, j\}$,
$$\sum_d r_{ij}^d \le S(i, j) + P(i, j).$$
The summation is the amount of surviving traffic carried on links between routers $\{i, j\}$ from i to j. This cannot exceed the total capacity of the surviving IP links between the routers. It is assumed that only protected lightpaths and one of every survivable pair will survive failures. This assumption is necessary because the exact routes of the lightpaths are unknown, and so it is unclear which lightpaths will fail together when a physical fault occurs. In addition, the surviving traffic *must* be supported.
  - *Flow conservation constraints for* t_{ij}^d: for each router i and destination router d,
$$\sum_j t_{ij}^d - \sum_j t_{ji}^d = \begin{cases} T(i,d) & \text{if} \quad i \ne d \\ -\sum_{j \ne d} T(j,d) & \text{if} \quad i = d. \end{cases}$$
Note that the left hand side of the equality is the "net flow" of nominal traffic that is destined for d that comes out of router i The right hand side is what the net flow should be for router i. If i is not d then the net flow should be $T(i,d)$, which is the required amount of traffic that router i sources that is destined for d. If i is equal to d then the net flow should be the total amount of traffic that d must sink.

- *Flow conservation constraints for* r_{ij}^d : for each router *i* and destination router *d*,

$$\sum_j r_{ij}^d - \sum_j r_{ji}^d = \begin{cases} R(i,d) & \text{if} \quad i \neq d \\ -\sum_{j \neq d} R(j,d) & \text{if} \quad i = d. \end{cases}$$

This constraint is for surviving traffic, and is similar to the flow conservation constraints for t_{ij}^d described above.

- *Objective*: the objective is to minimize

$$\sum_{(u,v):u<v} \big(uCost(u,v) \cdot C(u,v) + pCost(u,v) \cdot P(u,v) + sCost(u,v) \cdot S(u,v) \big).$$

Thus, the objective is to minimize the total cost of leasing lightpaths.

3. Cost Efficiency of Survivable Pairs

In this section, we will discuss whether survivable pairs can reduce cost. A natural approach to illustrate the cost effectiveness is to create instances of traffic matrices *T* and *R* and lightpath costs, and then design IP networks with and without the survivable pair lightpath service. For the case when survivable pair service is available, the design would be accomplished by solving the MILP of Section 2. For the case when survivable pair service is unavailable, the design is accomplished by first modifying the MILP so that the service is unavailable (which is straightforward), and then solving it. The resulting network costs can be compared to determine the effectiveness of the survivable pair service.

However, we found that solving the MILP of Section 2 can be time consuming for even small networks. For example, we solved the MILP for a case of six routers and uniform traffic matrices *T* and *R* using the AMPL and CPLEX software package on a SUN Blade 100 workstation. The run time ("elapsed time") to solve the MILP took approximately 5 minutes and 43 seconds. We also tried an example of seven routers but the run time exceeded a couple of hours, and so we terminated it before completion.

Therefore, we will use another approach to illustrate the cost efficiency of survivable pairs. We will derive two formulas for the cost of IP networks. The first formula will be a lower bound on network cost without survivable pair lightpath service, and the second formula will be an upper bound on cost with the service. Then the formulas will be compared. We will make the following simplifying assumptions.

- *Traffic matrices T and R are uniform*: We assume that there are values τ and ρ such that for all pairs of routers $\{i,j\}$, $T(i,j) = \tau$ and $R(i,j) = \rho$. Note that uniform traffic matrices are commonly used in the research community for performance evaluation. Also note that *R* is a fraction ρ/τ of *T*.

- *No port constraints*: For all routers *u*, the value $D(u)$ is essentially infinite, i.e., it is ignored.

- C*ost of a lightpath is independent of the pair of routers it connects*. We assume the values of $uCost(i,j)$, $pCost(i,j)$, and $sCost(i,j)$ are independent of the pair of routers $\{i,j\}$. This assumption may be false for long-haul lightpath service. Then lightpath costs may depend on distance, which can vary considerably. However, the assumption may be reasonable for metro networks, where lightpath lengths are less variable.

Without loss of generality, we may further assume that for all router pairs $\{i,j\}$, $uCost(i,j) = 1$. In addition, without loss of generality, we may assume that there are constants σ and π such that for all router pairs $\{i,j\}$, $sCost(i,j) = 2 + \sigma$ and $pCost(i,j) = 1 + \pi$.

Note that the value of σ should be nonnegative (i.e., $2 + \sigma$ should be at least 2) because a survivable pair is composed of two lightpaths. In addition, σ can be significant. To illustrate this, consider the following example. Suppose the WDM network is a large ring network. Suppose unprotected lightpaths follow shortest hop paths. Note that, on average, a shortest hop path traverses approximately 1/4 of the fiber-links. However, the lightpaths of a survivable pair must traverse all fiber-links of the ring because the lightpaths must be disjoint. Thus, on average, a survivable pair uses about four times as many fiber-links as an unprotected lightpath. This suggests $\sigma = 2$.

Note that the value of π depends on the type of protected lightpaths. The two types of protected lightpaths are *dedicated* and *shared*. Dedicated protection means that the back-up lightpath has dedicated, reserved bandwidth, e.g., 1+1 and 1:1 protection. The advantage of dedicated protection is simpler and faster switching to the back-up. Typically, a lightpath has only one back-up. Then the lightpath must be disjoint from its back-up to avoid a common point of failure. Therefore, a protected lightpath and its back-up consumes as much bandwidth as a survivable pair. Hence, for dedicated protection, $1 + \pi = 2 + \sigma$, or equivalently, $\pi = 1 + \sigma$

Shared protection means that the back-ups of lightpaths may share bandwidth. The advantage of shared protection is smaller bandwidth use and lower

cost. Note that if $\pi < \sigma$ then survivable pairs are not cost effective because there will be a cheaper alternative. The alternative to a survivable pair is another pair of lightpaths, one protected and the other unprotected. It has cost $2+\pi$, which is less than the $2+\sigma$ cost of a survivable pair. It also supports the same traffic (2 units of capacity under normal conditions and 1 unit of capacity if there is a failure).

The following is an example of when $\pi < \sigma$. Suppose the WDM network is a ring network. Then $\sigma = 2$, as we have shown earlier. Suppose that the scheme to share protection bandwidth is the same as in a *bi-directional line switched ring* (BLSR). BLSR requires twice as much bandwidth as an unprotected network because half of its bandwidth is for protection. Hence, if cost is dependent on bandwidth then a protected lightpath has twice the cost of an unprotected one. Then $\pi = 1$, and so $\pi < \sigma$.

Now we will derive the lower bound formula for IP network cost *without* survivable pair lightpath service. We will use the following proposition.

Proposition 1. Consider a network with n nodes, full-duplex links with capacity 1, and a traffic matrix T' such that for all pairs of nodes $\{i,j\}$, $T'(i,j) = t$. Let L denote the total number of links. Then

$$L \geq \frac{(n-1)nt}{1+t}$$

Proof. Let a denote the amount of traffic that is routed along one-hop paths, and b the amount of traffic that is routed on multi-hop paths. Since one-hop traffic traverses one link, it consumes a unit amount of link bandwidth per unit of traffic. Since multi-hop traffic traverses two or more links, it consumes at least 2 units of link bandwidth per unit of traffic. Also note that each link is full duplex and can carry a unit of bandwidth in both directions. Therefore, $2L \geq a + 2b$.

Next, note that the total amount of traffic is $2\binom{n}{2}t$. Thus, $b = 2\binom{n}{2}t - a$, which implies $2L \geq a + 2\left(2\binom{n}{2}t - a\right) = 4\binom{n}{2}t - a$. Finally, note that if there are L links then at most $2L$ ordered pairs of nodes will have their traffic routed along one-hop paths. Hence, $a \leq 2Lt$. This implies $2L \geq 4\binom{n}{2}t - 2Lt$. After some algebra, we get the inequality of the proposition. QED

The proposition implies that we need at least $\left\lceil \frac{(n-1)nt}{1+t} \right\rceil$ lightpaths to support T. If survivable pair lightpaths are unavailable, we would need $\left\lceil \frac{(n-1)nr}{1+r} \right\rceil$ protected lightpaths to support R. Thus, to insure we have enough lightpaths to support T, we need least $\left\lceil \frac{(n-1)nt}{1+t} \right\rceil - \left\lceil \frac{(n-1)nr}{1+r} \right\rceil$ unprotected lightpaths. Hence, the cost is at least

$$(1+p)\left\lceil \frac{(n-1)nr}{1+r} \right\rceil + \left(\left\lceil \frac{(n-1)nt}{1+t} \right\rceil - \left\lceil \frac{(n-1)nr}{1+r} \right\rceil \right).$$

This is our lower bound for the cost of an IP network that can support T and R without survivable pair lightpath service. We denote this lower bound by *LB*.

Next we will derive an upper bound on IP network cost when survivable pair lightpaths *are* available. We accomplish this by defining an IP network that can carry traffic matrices T and R, and then evaluate its cost. Since the network can carry the required traffic, its cost is an upper bound.

The network has the star topology shown in Figure 4. It has one router designated as the *center*, and all other routers are referred to as *peripheral*. The peripheral routers are directly connected to the center by unprotected and survivable pair lightpaths. The number of survivable pairs between a peripheral router and the center is $\lceil (n-1)r \rceil$ because $(n-1)r$ is the amount of traffic that the peripheral router must source/sink even when there is a failure. The number unprotected lightpaths between a peripheral router and the center is

$$\max\{0, \lceil (n-1)t \rceil - 2\lceil (n-1)r \rceil\}.$$

Then the total number of lightpaths between the peripheral router and the center is at least $\lceil (n-1)t \rceil$. This insures that the lightpaths can carry $(n-1)t$ amount of traffic, which is the amount that the peripheral router must source/sink under normal conditions. Thus, the cost of the lightpaths between the peripheral router and the center is K, where

$$K = (2+s)\lceil (n-1)r \rceil + \max\{0, \lceil (n-1)t \rceil - 2\lceil (n-1)r \rceil\}.$$

Since there are n–1 peripheral routers, the total network cost is (n–1)K. This is our upper bound on the IP network cost if survivable pairs are available, and we denote it by *Star*.

Next, we numerically compare the lower bound *LB* with the upper bound *Star*. For parameter values, we choose τ and ρ so that $\rho = \tau/2$, i.e., the surviving matrix *R* is half of *T*. We choose $\pi = 1 + \sigma$, i.e., the case when protected lightpaths use dedicated protection. We consider $\sigma = 0$ (the minimum value for σ), $\sigma = 1$, and $\sigma = 2$ (the case when the WDM network is a ring).

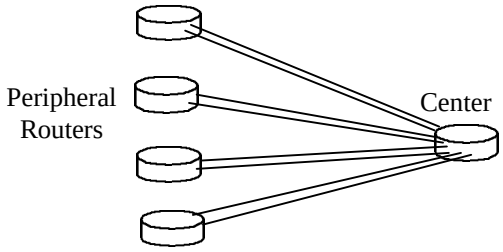

Figure 4. Star topology for an IP network.

Figure 5 shows δ, which is defined to be $100\ \% \times \frac{LB - Star}{LB}$, for $n = 50$. The value δ indicates the percent decrease in cost of using survivable pairs. It is plotted as a function of τ, which ranges from $\frac{2}{n-1}$ to $\frac{8}{n-1}$. Note that for positive values *c*, if $t = \frac{c}{n-1}$ then each peripheral router must have at least *c* lightpaths.

Since *LB* and *Star* are bounds, the actual decrease in cost could be greater than δ. This is why δ is sometimes negative. The figure shows that the decrease in cost can exceed 30%. This occurs when $\sigma = 0$ and $t = \frac{2}{n-1} = 0.041$. Also note that survivable pairs are more cost effective for smaller values of σ, which suggests that they will be more effective in WDM networks with mesh topologies.

4. Conclusions

We have defined a survivable IP over WDM network design problem and formulated it into an MILP. The resulting network guarantees a survivable network throughput. We introduce survivable pairs as a lightpath service and demonstrate that in certain cases, it can achieve a decrease in cost of at least 30%. A future direction for research is to investigate other lightpath services that support survivable network throughput at lower cost.

5. Acknowledgements

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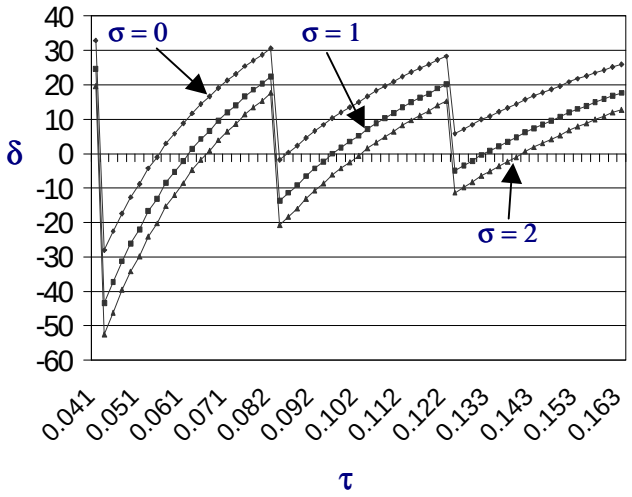

Figure 5. Percentage decrease in cost δ as a function of τ for *n* = 50.

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