Path Protection Routing with SRLG Constraints to Support IPTV in WDM Mesh Networks

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***Abstract*— The distribution of broadcast TV across large provider networks has become a highly topical subject as satellite distribution capacity exhausts and competitive pressures increase. In a typical IPTV architecture, broadcast TV is distributed from two sources (for redundancy) to multiple destinations. The aim of this paper is to examine how IPTV can be reliably and cost effectively supported in wavelength division multiplexed (WDM) networks. WDM networks have evolved to mesh topologies and recently to support multicast, which is particularly valuable in reducing the network cost in broadcast TV applications.**

Our goal is to find two trees with a minimal total cost such that we have two physically (or Shared Risk Link Group (SRLG)) diverse paths to each of the destinations – one from each of the sources. Any two links that belong to a common SRLG are subject to a single point of failure, be it a channel or wavelength failure, a fiber cut, or a complete conduit cut. We first show that our path protection routing problem is *NP*-complete. We then propose an Integer Programming (IP) formulation for this problem. Using real network topology data, we show that the real networks are amenable to the IP problem formulation and yield optimal solutions.

I. Introduction and Motivation

Modern wavelength-division multiplexing (WDM) optical transport networks have evolved from traditional point-to-point and ring connectivity to a mesh structure. These optical mesh networks are composed of optical cross-connects/switches (OXCs) interconnected via WDM links to form arbitrary topologies. An OXC can be either all-optical or electronic switching, where in either case, we assume that the OXC can switch any input wavelength/fiber to any output wavelength/fiber. If the OXC is electronic, then it may also support time-division multiplexing (TDM) [6]. New optical switching technologies have the potential to support multicast (or one-to-many) communication [12]. These technological advances make optical mesh networks a potentially attractive and economical solution for directly deploying new emerging services such as Internet Protocol TV (IPTV) [7].

In this study, we consider a network provider supporting an application that requires steady and high bandwidth loads simultaneously distributed to multiple end locations. Our work is motivated specifically by the distribution of broadcast TV over national terrestrial networks, a pressing new application for traditional network providers due to today's satellite capacity exhaust and competitive pressures. In this application, IPTV streams are sourced from two geographically diverse *Super Head-Ends*, or *SHEs*. The two SHEs provide redundancy to ensure reliable video transmission, even in the face of catastrophic failure of one of the SHEs. We assume that both SHEs are always active to ensure rapid recovery in the event of a SHE failure. Video streams transmitted from the SHEs are received at the *Video Hub Offices*, or *VHOs*, where the video streams may be further processed (e.g., advertisement insertion) and then transmitted out towards the customers. Service architecture for IPTV is discussed in [1].

When designing the backbone segment of the service architecture (i.e., the network that connects SHEs and VHOs), rapid failure recovery becomes critical since it has to match the availability of traditional always-on broadcast TV that consumers are used to. This necessitates that the network carrying the video streams must employ mechanisms for rapid recovery against network failures. There are two basic classes of rapid failure recovery, namely protection and restoration. Protection mechanisms pre-establish (including cross-connect) the backup routes in advance to guard against failures, whilst we define restoration as requiring signaling after a failure to establish the backup path. Note that in many restoration schemes, the backup routes are also adaptively identified based on the failure and the state of the network at the time of a failure [6]. Protection mechanisms typically provide faster failure recovery than restoration mechanisms [10], and thus we assume end-to-end protection is required here. Specifically, we assume that OXCs directly connected to each VHO receive two signals from each of the SHEs and locally select between the better of the two signals. Because the switching is made locally at OXCs, failure recovery can be faster than that of mesh based restoration. However, this requires that the video signals from the two SHEs follow physically diverse paths to each of the VHOs so that no VHO will lose connectivity from both of the SHEs as a result of a single network failure (even when there is a major fiber cut).

Optical fibers interconnecting OXCs are placed into conduits, which are buried along right of ways (ROWs). As a result, two seemingly diverse fiber links at the OXC layer (e.g., interconnecting different pairs of OXCs) may be routed within a common conduit and are thus subject to a single point of failure. The concept of a *Shared Risk Link Group (SRLG)* is used to represent a group of links that are subject to a common risk, such as a conduit cut [11]. Therefore, for path protection, it is important to find SRLG-diverse paths. SRLGs represent a generic set of risks, including individual link, wavelength, conduit, node or port failures. Note that a single link between adjacent OXCs may be related to multiple SRLGs.

In this paper, we investigate the efficient and reliable distribution of traffic from two sources to multiple end locations in WDM mesh networks. This is a generalized problem of the single-source one-to-many or one-to-one communication case studied in [3], [4], [10], [13]. Our goal is to create two trees with a minimum total cost connecting each of the sources with all of the destinations such that the network survives any single SRLG failure. Although we find that the problem is *NP*-complete in general, we present an optimal off-line Integer Programming (IP) model, for which solutions are available even when the network is reasonably large. We demonstrate the effectiveness of our solution using two candidate network infrastructures from a tier-1 network provider as an example.

The rest of the paper is organized as follows. We introduce some background on this work in §II. In §III, we propose the new problem of path protection routing from dual sources to multiple destinations, demonstrate *NP*-completeness, and present an off-line IP model. We then apply our model to a real-world example of operational backbone networks in §IV. We conclude and discuss issues for further work in §V.

II. Preliminaries

We start out by discussing multicast capabilities in WDM mesh networks, the concept of a SRLG, and existing path protection schemes.

A. Multicast Capabilities in WDM Mesh Networks

In scenarios where identical content is to be distributed to multiple distributions, multicasting reduces the communication cost (e.g., bandwidth consumed). While multicast in IP networks has been addressed thoroughly within the research community, multicast in optical networks is a relatively new concept [12]. To support multicast, OXCs must employ the ability to *split* or *replicate* an incoming signal to multiple output ports [3]. A network may support *limited splitting* (i.e., where a node is only able to replicate traffic to a limited number of output ports) or *sparse splitting* (i.e., where only a fraction of the network nodes have splitting capabilities). Here, we assume that all of the OXCs are fully multicast-capable. While multicast appears a natural choice for carrying broadcast TV traffic, supporting such highly sensitive traffic on a new technology can be risky. However, significant economic benefits of multicast in optical networks have been demonstrated in situations where the number of destinations in the multicast tree is relatively large [1], [8].

In contrast to IP networks that utilize routing protocols based on shortest path routing (e.g., OSPF, IS-IS), multicast trees in optical networks are centrally routed and thus may be flexibly chosen using any routing scheme (that is, they do not have to be routed along the shortest path). This is important for ensuring SRLG-diversity of the paths to each VHO. Such routing is possible because optical networks typically employ explicit routing to establish connections, as opposed to shortest path forwarding. In terms of routing protocol, generalized multi-protocol label switching (GMPLS) may be employed [9].

B. Shared Risk Link Group (SRLG)

Fig. 1 illustrates the layering employed in real networks. In this scenario, the biggest cylinder represents a conduit. A conduit typically carries large numbers of fibers (e.g., 256 fibers), where each fiber cable, in turn, carries multiple channels (or wavelengths). This optical channel is so-called a link or a logical connection in transport network. Due to the layered architecture, optical channels connecting two distinct pairs of nodes may traverse the same conduit in physical networks, and may become subject to a single point of failure. A SRLG is a set of links that can potentially fail due to a single cause [11]. For example, all the optical channels in a single fiber form a SRLG, so do all the optical channels traversing the same conduit. Since a fiber may run through several conduits, an optical channel may belong to several SRLGs.

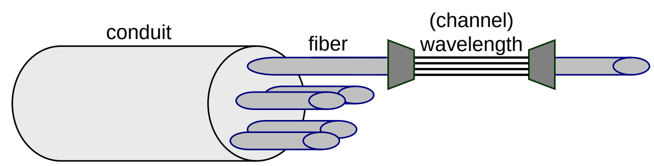

Fig. 1. Risk hierarchy of a SRLG

Fig. 2 shows an example where optical channels connecting two distinct pairs of nodes belong to a common SRLG. For the two links AB and CD, physical routes share the common optical segment of XY. If XY fails, both channels are affected [11]. Routing in WDM mesh networks may exploit physical diversity so that after any SRLG failure, there is always at least one viable route remaining for recovery. Next, we introduce how such physical level path diversity is incorporated in path protection schemes.

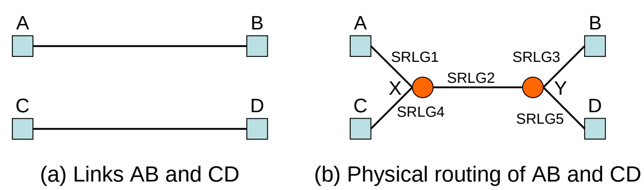

Fig. 2. Links AB and CD belong to the same SRLG.

C. Path Protection Schemes

Generally, there are two categories of protection. One is *path protection*, where a backup path that is disjoint for each "primary" or working path is defined. The other is *link protection*, which usually refers to the replacement of a link by link(s) connecting the two end nodes of the failed link. We assume path protection here, where both sources are always active and two paths from each of the sources are used at the same time to each destination. Those two paths are guarding each other against a single SRLG failure.

Path protection schemes in optical networks have received extensive attention within the research literature, although only limited focus has been put on either multicast networks or SRLG-diversity. Medard *et al.* [10] focus on the problem of identifying two redundant trees from a single source to a set of destinations that can survive any single link failure, i.e., the elimination of any vertex (edge) in the graph leaves each destination vertex connected to the source via at least one of the directed trees. They neglect more general SRLG-diversity requirements and the minimization of network cost. Ellinas *et al.* [3] show that if an arbitrary set of links can belong to a common SRLG, then the problem of finding SRLG-diverse paths between a given source and destination is *NP*-complete for unicast traffic. Zang *et al.* [13] focus on SRLG-diverse path protection in all-optical networks without wavelength converters for one-to-one (unicast) traffic in WDM mesh networks. In contrast to the existing literature, we examine the combined problem of minimizing the network cost of multicast traffic from dual sources to multiple destinations, where we need to ensure SRLG survivability constraints for each receiver.

III. Problem Description

In this section, we formally describe our path protection routing problem with SRLG constraints. This problem can be modeled as a network optimization problem as follows. Let $G = (V, E)$ be an undirected graph representing the WDM mesh network. We denote the set of network (source and destination) nodes by V where OXCs reside, while E is the set of duplex communications links that connect the OXC nodes. In this paper, we consider the problem where there is a set of two source nodes, denoted by $S \subset V$, and there is a set of destination nodes, denoted by $D \subset V$. Each link $(i, j) \in E$ in the graph has an associated communication cost (c_{ij}) and belongs to some groups in SRLGs, denoted by B, in the optical layer topology. In this paper the communication cost c_{ij} reflects the capital expense, which is the sum of the port cost at nodes i and j and the transport cost relative to the distance of link (i, j).

This problem is aimed at designing a network in which data are sent from each source node $s \in S$ to every destination $d \in D$ at a minimum cost such that a network must survive from a single SRLG failure. Conceptually, our aim is to find two paths connecting each of the two source nodes to every destination node $d \in D$ and ensure that these two paths are SRLG-diverse. The SRLG-diverse paths can be defined as: the paths in which every link of the path from one source is not in the same SRLG as that of the path from the other source. In other words, each SRLG can be present in at most one of the two paths to each destination. In short, the objective is to **find two paths connecting the two sources to every destination such that the two paths are SRLG-diverse, while the total cost of the routing trees is minimized**.

A. Complexity Issues

In this section, we investigate the complexity of our path protection routing problem with SRLG constraints. We show that this problem is *NP*-hard by using a reduction from the SRLG-diverse path problem [3].

Definition *1:* The PPRPSC (Path Protection Routing Problem with SRLG Constraints) is defined as follows. Given a mesh network topology with arbitrary SRLGs with two source nodes $s \in S$ and a set of destination nodes $d \in D$, are there feasible SRLG-diverse paths linking each destination d with the two sources s?

It is worth noting that the PPRPSC is a generalization of the problem of finding SRLG-diverse paths between a source and a destination in a given graph (SRG Diverse Routing) proposed in the paper by Ellinas *et al.* [3]. The SRG Diverse Routing problem is shown to be *NP*-complete. We can extend the result from that paper to our case as in the following proposition.

Proposition *1:* The PPRPSC is *NP*-complete.
This problem is clearly in *NP*. Given two pairs of diverse paths from the two sources to all the destinations, we can ensure that their links do not share any SRLGs. Then we can apply the SRG Diverse Routing problem expression [3] to the PPRPSC as follows: Let us add two nodes ($|S|$) in the graph and two links connecting each of the two new nodes with the source. Assume that the two new links do not share any SRLGs. We then add $|D|$ nodes and $2 * |D|$ edges. Each of these nodes is connected to the destination node by 2 edges that do not share any SRLGs. The new SRG Diverse Routing problem is equivalent to the PPRPSC. In addition, the problem of finding minimum cost trees for a certain source and a set of destinations (Seiner tree problem) is *NP*-hard [5]. For this reason, the problem considered in this paper is *NP*-hard.

B. Integer Programming (IP) Formulation

In this subsection, we propose an Integer Programming (IP) formulation for our problem, in which the decision variables are defined as follows:

- $Y^s_{i,j}$ indicates whether link $(i, j) \in E$ is used by multicast tree rooted at source node $s \in S$. $Y^s_{i,j} = 1$, if and only if link (i, j) is used by the multicast tree rooted at source node t, and $Y^t_{i,j} = 0$, otherwise.
- $X^s_{i,j,d}$ indicates whether link $(i, j) \in E$ is used by a multicast tree rooted at source node $s \in S$ in order to carry traffic to destination $d \in D$. The variable $X^s_{i,j,d} = 1$, if and only if link (i, j) is used by multicast tree rooted at source node s to reach destination d, and $X^s_{i,j,d} = 0$, otherwise.
- $Z^s_{b,d}$ indicates whether a SRLG $b \in B$ is used from source $s \in S$ to reach destination $d \in D$.

The IP formulation for PPRPSC is given by

$$\min \quad \sum_{s\in S}\sum_{(i,j)\in E} Y^s_{i,j} c_{i,j} \quad (1)$$

$$\text{s.t.} \quad Y^s_{i,j} \geq X^s_{i,j,d}, \quad \forall (i,j) \in E, \forall s \in S, \forall d \in D \quad (2)$$

$$\sum_{\{j|(i,j)\in E\}} X^s_{i,j,d} - \sum_{\{j|(i,j)\in E\}} X^s_{j,i,d} = \sigma^s_{i,d}, \quad \forall s \in S, \forall d \in D \quad (3)$$

$$Z^s_{b,d} \geq X^s_{i,j,d}, \quad \forall (i,j) \in b, \forall d \in D \quad (4)$$

$$\sum_{s\in S} Z^s_{b,d} \leq 1, \quad \forall b \in B, \forall d \in D \quad (5)$$

$$X^s_{i,j,d} \in \{0,1\}, Y^s_{i,j} \in \{0,1\}, Z^s_{b,d} \in \{0,1\}, \quad \forall s \in S, \forall d \in D, \forall (i,j) \in E, \forall b \in B \quad (6)$$

where
$$\sigma_{i,d}^{s} = \begin{cases} 1 & \text{if } i = s \\ -1 & \text{if } i = d \\ 0 & \text{otherwise.} \end{cases} \quad (7)$$

The objective function in *Eq.* (1) is to minimize the sum of the total cost of two trees connecting each of the sources with all the destinations. The constraints in *Eq.* (2) ensure that an edge must be selected to be in the multicast tree when it is used by any of the two trees to carry traffic. The flow constraints in *Eq.* (3) ensure the flow conservation at each node allowing each destination to have a flow path from (connected to) the sources. More precisely, $\sigma_{i,d}^{s}$ is the net flow capacity, which has the value of 1 if node i is the source (where the flow is originated), -1 if node i is the destination (acting as a sink), and 0 otherwise (as the net in-flow and net out-flow should be equal for intermediate nodes). The constraints in *Eqs.* (4) and (5) ensure that paths from the two sources to each destination are SRLG-diverse. In other words, each SRLG can be present in at most one of the two paths to each destination. To validate that these constraints are *valid inequalities* for SRLG-diverse, we have the following proposition.

PROPOSITION *2:* Two paths in multicast trees are SRLG-diverse *iff* the constraints in *Eqs.* (4) and (5) are satisfied.

Proof: The proof can be shown by contradiction.

Necessity: Assume that multicast trees do not satisfy *Eqs.* (4) and (5), and two paths are SRLG-diverse. As such paths are SRLG-diverse, it implies that each SRLG can be present in at most one of the two paths to each destination. The variable $Z_{b,d}^{s}$ is equal to 1, when a SRLG $b \in B$ is present in the path from source $s \in S$ to reach destination $d \in D$. Therefore, the summation of $Z_{b,d}^{s}$ over the two sources in *Eq.* (5) must be less than or equal to 1. This concludes that *Eqs.* (4) and (5) hold and contradicts our initial assumption.

Sufficiency: Assume that multicast trees satisfy *Eqs.* (4) and (5), but two paths are not SRLG-diverse. As such trees satisfy *Eqs.* (4) and (5), it implies that each SRLG can be present in at most one of the two paths to each destination. This concludes that such paths are SRLG-diverse and contradicts our initial assumption. ■

In this study, we model the above-mentioned IP formulation with GAMS[1] and use CPLEX[2] as an IP solver. CPLEX Mixed Integer Optimizer (MIO) utilizes state-of-the art algorithms and techniques, including cuts, heuristics, and a variety of branching and node selection strategies. Multiple types of cutting planes such as geometry fractional, flow covers, mixed integer rounding, flow paths, cliques, covers have been implemented in CPLEX MIO. Several heuristics are used to quickly find the upper bound and prove the optimality.

IV. CASE STUDY

In this section, we perform a case study applying our IP model as a network provider supporting IPTV services on its backbone network, and compare the capital expense of our design with other candidate designs. We consider two network topologies, each consisting of two SHEs and 40 VHO locations across the US. Table I summarizes the network topologies considered in our evaluation. We use realistic fiber spans to identify SRLGs and model all SRLGs associated with ports, links and fiber spans [11]. Note that we do not include node-diverse paths in our design.

TABLE I
NETWORK TOPOLOGIES CONSIDERED IN EVALUATION

topology	nodes#	links#	SRLG#	run-time	iterations#
Net1	219	504	212	816 sec	61,511
Net2	79	150	45	3 sec	4,011

Here, we model the cost of a link by computing the capital expenditure associated with the ports at the two ends of the link and the transport cost relative to the link distance. Since we assume a WDM optical network with electronic OXCs and time-division multiplexing capabilities, the total cost will increase roughly linearly with the IPTV bandwidth requirements. We thus simply assume that the traffic from SHEs to VHOs is 1Gb/s and calculate the capital expenditure for that setting.

Our IP formulation is modeled and run using CPLEX solver. Although not always guaranteed, the solver finished with an optimal solution for both of our network topologies. Table I reports the run-time and the number of iterations required for the program on a desktop environment with a 2.8GHz Intel Pentium 4 processor and 1GB memory. We refer to the solution identified by solving our IP problem as SRLG-Div.

We compare our approach with a heuristic approach, namely Active Path First (APF), introduced in [2], [4]. The idea behind APF is to construct two minimum-cost multicast trees from each of the sources independently[3]. Among the two trees, the one with the smaller cost is selected as the first tree. All links that share any SRLG with the first tree are then removed from the graph. A secondary tree from the other source is constructed using the remaining links. Note that it is possible to have the destination become disconnected from the second source in the reduced graph. Thus, this approach does not always guarantee a solution. Search solutions have been developed to enhance the basic APF procedure to reduce the risk of not identifying any solution [2]. Fortunately, we do not encounter such a problem with our network topologies.

To understand the inefficiency (as increase in the overall cost) due to the SRLG survivability constraint, we also compare our design with two other designs with relaxed survivability constraint. The first one, which we will refer to as Src-Div, is derived by simply constructing two minimum cost multicast trees from each of the sources independently. In the second design, refered to as Link-Div, two multicast trees are constructed from each of the sources simultaneously, while the routing paths are constrained to be link-diverse and the total cost is minimized. The IP formulation resembles that of our SRLG-diverse paths, except that *Eqs.* (4) and (5) are replaced by, $\sum_{s \in S} X_{i,j,d}^{s} \leq 1, \forall (i,j) \in E, \forall d \in D$.

[1]GAMS, http://www.gams.com/
[2]ILOG Inc., CPLEX, http://www.ilog.com/.

[3]The IP formulation is trivial and omitted. We may modify the one in §III by simply setting $|S| = 1$ and removing all SRLG-constraints.

Fig. 3 shows the relative capital expense across all designs. The y-axis is normalized for proprietary reasons such that the cost of SRLG-Div is 100% for each topology. Note that only SRLG-Div and APF can survive from any single SRLG failure. We make the following observations. First, among the SRLG-diverse designs, SRLG-Div design can be significantly more cost effective than APF. This demonstrates the advantage of our approach by jointly considering two trees from both sources as opposed to constructing one tree at a time (as in APF). The advantage is more evident with the smaller Net2 (with a cost difference by 60%), where the network itself has fewer nodes and links. Second, comparing to non SRLG-diverse designs, SRLG-Div design is only slightly more expensive (less than 5% increase in cost). However, since Src-Div is only resilient to single source failure, and Link-Div is resilient to single source or link failure, the cost increase shown in the SRLG-Div design is in fact the cost for the additional resilience incorporated to handle fiber cuts. For highly sensitive traffic such as IPTV, this is a necessity.

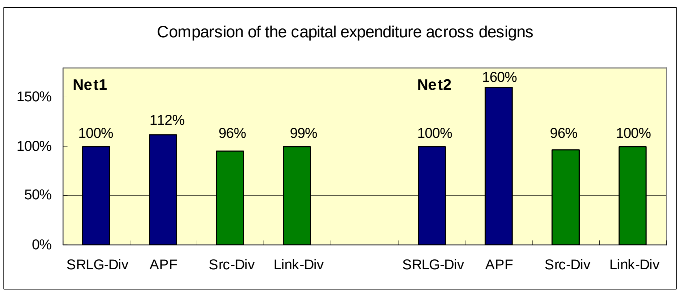

Fig. 3. Comparison of capital expenditure across designs

To evaluate the risk due to single SRLG failures, we report in Table II the number of critical SRLGs whose failure disconnects one or more receiver(s) from both sources in each design. We also report the number of unreliable receivers that are subject to service interruption under a SRLG failure. Recall that there are a total of 40 receivers in both networks, and 212 distinct SRLGs in Net1 and 45 SRLGs in Net2. As expected, the number of critical SRLGs and the number of unreliable receivers are 0 for both SRLG-Div and APF. This means that each destination is always connected to at least one source under any single fiber cut. Src-Div and Link-Div, however, do not have this property. For example in Src-Div design in Net1, there are 31 critical SRLGs whose failure will disconnect at least one receiver from both sources. In Link-Div of Net2, 5 unreliable receivers are subject to the risk of disconnection under certain critical SRLG failures.

TABLE II

RISK ANALYSIS ACROSS DESIGNS UPON SINGLE SRLG FAILURE

	SRLG-Div, APF		Src-Div		Link-Div	
topology	u.rcvr	c.SRLG	u.rcvr	c.SRLG	u.rcvr	c.SRLG
Net1	0	0	29	31	20	7
Net2	0	0	21	12	5	2

Notation: *u.rcvr* denotes unreliable receiver; *c.SRLG* denotes critical SRLGs.

V. CONCLUSION AND FUTURE WORKS

In this paper, we studied the problem of efficient and reliable distribution of steady and high bandwidth loads to multiple end locations in WDM mesh networks. Our problem formulation is driven by realistic application demands and network topologies, with practical considerations including cost minimization and survivability constraint for SRLG failures. We found that the problem is *NP*-complete. However, we are able to cast the problem into an equivalent Integer Programming (IP) problem, for which solutions are available even when the network is reasonably large. Furthermore, we applied our approach to real network scenarios using realistic topologies and SRLG-maps. We found that using our IP model greatly reduces the overall data dissemination cost compared to an existing heuristic approach. Moreover, in comparison to designs that only provide source- or link-diverse paths, our SRLG-diverse design significantly reduces the risk of data stream interruption against failures, while only slightly increasing the dissemination cost.

In our future work, we plan to consider a more sophisticated risk model in which not only do we model the possible failure scenarios, but also the likelihood of those failures. We can thus identify the design that minimizes the overall risk of delivery interruption on the planned data stream. We also plan to further explore the trade-offs between efficiency and reliability through comprehensive simulations. We expect to gain insight on the relationship between the network topology structure, location of sources and destinations, and the robustness of data dissemination trees.

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