Optimum Logical Topology Routing in an IP-over-WDM Optical Network and Physical Link Failure Localization: An Integrated Approach

Tachun Lin
Dept. of Computing and Technology
Cameron University
Lawton, Oklahoma 73505
Email: tlin@cameron.edu

Zhili Zhou
IBM Research Collaboratory
Singapore
Email: zhili@sg.ibm.com

Krishnaiyan Thulasiraman
University of Oklahoma
Norman, Oklahoma 73019
Email: thulasi@ou.edu

Guoliang Xue
Arizona State University
Tempe, Arizona
Email: xue@asu.edu

***Abstract*—The survivable logical topology routing problem for a given IP-over-WDM network is to map each logical link into a lightpath in the physical network which guarantees connectivity of the IP network after any physical link failure. Such a survivable routing is said to protect the logical network against all single physical link failures. But, it is possible that a logical topology may not admit a survivable routing. In view of this, we define a logical topology routing to be optimum if this routing maximizes the number of single physical link failures that do not disconnect the logical topology. First, we give a mixed integer linear programming formulation to determine an optimum logical topology routing. The failure localization problem is to localize the single physical link failures which disconnect the logical network under a given optimum routing. Given a set of monitoring trails and the lightpath routings in an optimum routing, we give a mixed integer linear programming formulation to determine an optimum routing and the corresponding failure localization. We also propose a heuristic approach for these problems to handle large scale IP-over-WDM networks.**

***Index Terms*—Optical communication, IP-over-WDM network, optimal routing, failure localization, graph theory.**

I. INTRODUCTION

IP-over-WDM network is a two-layered network where an IP (logical) network is embedded onto a WDM (physical) network. IP routers and OXCs correspond to the logical and physical nodes. Links connecting the nodes in a logical network are called the logical links, and the physical links are realized via optical fibers. The logical nodes are commonly assumed to have corresponding nodes in the physical network. On the other hand, not all physical nodes may exist in the logical network. A router-to-router link is implemented through a wavelength on a path between two end nodes in a WDM network bypassing opto-electro-optic (O-E-O) conversions on intermediate nodes along the path. This path is called a lightpath. Each optical fiber may carry multiple lightpaths, hence a failure on an optical fiber may have a cascading effect causing failures on multiple logical links, resulting in a huge amount of data traffic (terabytes/sec) loss.

Previous research works to address optical fiber failures are mainly along two directions: (1) survivable logical topology routing in the IP-over-WDM network, and (2) failure localization in the optical network. Survivable logical topology routing in an IP-over-WDM optical network is a mechanism which guarantees the connectivity of the logical network and hence maintains continuous flow and operability after a network facility (link or node) failure. The survivable routing problem has been intensively studied. The research works related to failure localization focus on the optical network. They combine detection sensors and their corresponding monitor trails (m-trail, monitor cycle, and monitor path) to provide a unique signal to identify optical fiber failures. Previous works in the literature considered augmentation of the logical topology with additional links to guarantee the existence of a survivable routing.

The likelihood that a logical topology may not admit a survivable mapping and the need for optical failure localization motivate the study in this paper. We provide an integrated approach to survivable IP-over-WDM routing and optical network failure localization problems. We aim to generate the optimum routing (to be defined later) within the current network structure, which guarantees the connectivity of the logical network under most scenarios of optical link failure without any extra logical network augmentation. Meanwhile, the failure of the optical links would disrupt the communication between logical node pairs, and the corresponding broken lightpaths could help to detect the optical fiber failure through loss of signal or communication. Therefore, the lightpaths have the functionality of the monitoring paths [1][2]. Compared with monitoring paths in the optical network, lightpaths would not involve extra monitoring cost. If appropriately designed, most physical link failures would not cause disconnection of the logical network. So, for failure localization we concentrate on optical links which would disconnect IP communication under a given optimum routing.

On the other hand, the number of lightpaths is equal to the number of logical links. They may not be sufficient to provide a unique detective signal for a physical link failure. Hence, we would still involve monitoring sensors and their corresponding possible monitoring trails in the optical network to localize the

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physical link failure which could disconnect communication in the IP network.

Summarizing, in this paper, we address a new problem which aims to utilize facilities in the current IP-over-WDM network to provide an optimum routing for IP demands which keeps connectivity in the IP layer under most scenarios of the physical link failure, and localize all physical links whose failures cause the disconnection in the IP network. The paper is organized as follows. In section II we review the current literature relating to survivable logical topology routing and physical link failure localization problems. In section III we define the concept of optimum logical topology routing and related concepts. We illustrate the concepts with examples. In section IV we present ILP formulations for three optimization problems. The first is to determine an optimum logical topology routing. Given an optimum logical topology routing and a set of monitoring trails, the second problem is to determine the minimum number of monitoring trails (along with the lightpaths in the routing) required for physical link failure localization. The third problem is to determine a joint routing and corresponding failure localization minimizing an objective that is a weighted sum of the objectives of the previous two problems. In section V a heuristic approach for the joint routing and failure localization problem is given, along with preliminary computational results.

II. LITERATURE REVIEW

In this section, we provide a review of literature on the topics related to the research in this paper, namely, survivable logical topology routing in an IP-over-WDM network, and failure localization in an optical network.

A. Survivable Logical Topology Routing

A survivable logical topology mapping can be achieved if the lightpaths in the physical topology corresponding to this mapping are all link-disjoint. Since finding disjoint paths between pairs of nodes is NP-complete [3], determining a survivable routing of the logical topology in an IP-over-WDM network is also an NP-complete problem. Modiano and Narula-Tam [4] proved a necessary and sufficient condition for survivable routing under a single physical link failure in IP-over-WDM networks and formulated the problem as an Integer Linear Program (ILP). Todimala and Ramamurthy [5] adapted the concept of Shared Risk Link Group introduced in [6] and also computed the routing through an ILP formulation. Other related works are in [7][8][9][10].

To handle the drawback of ILP approaches Kurant and Thiran [11] proposed the Survivable Mapping by Ring Trimming (SMART) framework. Another approach proposed by Lee et al. [12] utilized the concept of ear-decomposition on bi-connected topologies. One can show that this is, in fact, a special variant of the framework given in [11], though it was developed independently. Javed et al. obtained improved heuristics based on SMART [13] [14]. Using duality theory in graphs, a generalized theory of logical topology survivability was given by Thulasiraman et al. [15] [16]. Thulasiraman et al. [17] considered the problem of augmenting the logical graph with additional links to guarantee the existence of a survivable mapping. An earlier work that discussed augmentation is in [18].

B. Physical Link Failure Localization

The single-link failure detection in optical-level mechanism has been studied in [19] and [20]. In [20], the optical failure detection scheme utilizes monitors. Due to the adoption of expensive monitors, the scalability and cost efficiency of this scheme is not ideal. “Probing” (lightpath) fault diagnosis were proposed in [21] and [22]. Monitoring trail (m-trial) has been introduced in [23], [24] and [25] for localizing link failures. A monitoring trail is a non-simple lightpath that is associated with a monitor at a receiver. After identifying a link failure, an alarm would be triggered by a monitor. A control platform would receive the alarm pattern to uniquely localize the link failure detected by a unique combination of m-trails with the alarms. Other related works are in [26] and [27].

Failure localization in IP-over-WDM networks can be achieved by adding monitoring equipments in optical networks which can monitor the power of optical signals, measure the spectrum of the optical signal, detect transmission disruption, and send out the alarm when a failure is detected [28]. Meanwhile, routers in IP networks can also be considered as monitoring devices which retransmit the packets under failure [29]. Mas and Thiran [30] studied the properties of alarms due to failures and proposed an algorithm to locate failures in the WDM network. The m-trail and m-cycle concepts rely on the unique combination of pre-determined light-trails and cycles to locate the physical link failure, which consumes extra wavelengths for monitoring purpose. In this paper, we would like to consider adding monitors to some user lightpaths instead of supervisory lightpaths, which was first introduced in [27]. The difference between our approach and the one in [27] is that we consider a layered network instead of a single optical network. This design requires an integrated control plane which is capable of dealing with both layers routing information.

III. PROBLEM DESCRIPTION

We let $G_P = (V_P, E_P)$ and $G_L = (V_L, E_L)$ represent the physical and logical networks, respectively. The relationship between G_P and G_L is that $V_L \subseteq V_P$. We let e, f, g represent physical edges and u, v represent logical edges. We let i, j denote physical nodes and s, t the logical nodes. The terms edges and links as well as nodes and vertices will be used interchangeably. We assume that both the physical and logical networks are at least two-edge connected.

Without loss of generality, we keep the indices of logical nodes same as their corresponding physical nodes. For a logical edge u we find a path p in the physical topology whose start and end nodes are the two corresponding nodes of u. We call p^u the **lightpath** of u.

We let $i(u)$ and $j(u)$ be the physical nodes of logical edge u and $s(e)$ and $t(e)$ be the logical nodes of physical edge

e. If u connects $s(u)$ and $t(u)$, then, $(s(u), t(u)) = u$. The lightpath provides the routing for a logical edge. The failure of any physical edge in p^u disconnects the lightpath of u and its corresponding logical edge.

In contrast to survivable routing, we define optimum logical topology routing in an IP-over-WDM network as follows.

Definition 1: A logical topology routing is an optimum routing in a given IP-over-WDM network, if lightpath routings for all logical links in the logical network maintain the connectivity of the logical network for the largest number of single physical link failures. In other words, under an optimum routing, the logical network is protected for the largest number of physical link failures. We denote an optimum routing in a given IP-over-WDM network as $\mathcal{P}^*$, where $\mathcal{P}^* = \{p^*(s,t) : (s,t) \in E_L\}$.

Definition 2: Given a logical topology routing, we define $\mathcal{OL}_{p^*}$, the set of physical links each of whose failure disconnects at least one logical cutset, as $\mathcal{OL}_{p^*} = \{(i,j) : \exists\, CS(S, V_L \backslash S),\ s.t.\ (i,j) \in p^*(s,t)$ and $(s,t) \in CS(S, V_L \backslash S), S \subseteq V_L\}$.

Proposition 1: If a given IP-over-WDM network is survivable, then the optimum routing $\mathcal{P}^*$ is a survivable routing and the corresponding $\mathcal{OL} = \emptyset$.

In this paper we we study three optimizations and develop their ILP formulations. Specifically, the first problem is to determine an optimum logical topology routing. Given an optimum logical topology routing and a set of monitoring trails, the second problem is to determine the minimum number of monitoring trails (along with the lightpaths in the routing) required for physical link failure location. The third problem is to determine a joint routing and corresponding failure localization minimizing an objective that is a weighted sum of the objectives of the previous two problems.

If a given IP-over-WDM network is unsurvivable, instead of augmenting the logical network to guarantee a survivable routing, we invoke, after the generation of a optimum $\mathcal{P}^*$, the existing monitoring trails in the optical network coupled with lightpath routings $\mathcal{P}^*$ to localize failures of the physical links in $\mathcal{OL}$.

Now, we demonstrate all above definitions in the following examples.

Example 1: We demonstrate the concept of optimum routing for a given un-survivable IP-over-WDM network in Figs. 1 and 2. In Figure 1, the routings for all logical edges are $\mathcal{P}^1 = \{p^1_{12}, p^1_{14}, p^1_{25}, p^1_{45}\}$ with $p^1_{12} = \{(1,2)\}$, $p^1_{14} = \{(1,2),(2,3),(3,4)\}$, $p^1_{25} = \{(2,5)\}$, and $p^1_{54} = \{(4,5)\}$. In Figure 2, the routings for all logical edges are $\mathcal{P}^2 = \{p^2_{12}, p^2_{14}, p^2_{25}, p^2_{24}\}$ with $p^2_{12} = \{(1,2)\}$, $p^2_{14} = \{(1,6),(6,5),(5,4)\}$, $p^2_{25} = \{(2,5)\}$, and $p^2_{45} = \{(4,5)\}$. After the failure of $(1,2)$, the logical network in Figure 1 is disconnected, and after other failures the logical network in Figure 1 remains connected. So, $\mathcal{OL}_{p^1} = \{(1,2)\}$. After $(4,5)$ fails, the logical network in Figure 2 is disconnected, i.e. $\mathcal{OL}_{p^2} = \{(4,5)\}$. Both $\mathcal{P}^1$ and $\mathcal{P}^2$ are optimum routings for the given IP-over-WDM network.

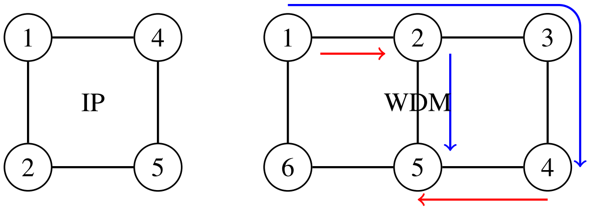

Fig. 1. The example of optimum routing for IP-over-WDM network: $\mathcal{P}^1$

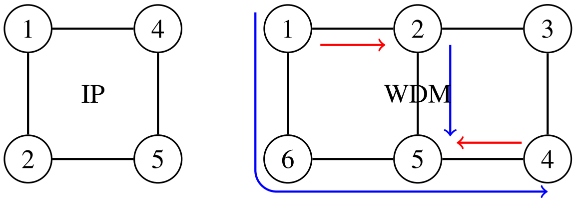

Fig. 2. The example of optimum routing for IP-over-WDM network: $\mathcal{P}^2$

Example 2: Based on the optimum routing solutions $\mathcal{P}^1$ and $\mathcal{P}^2$, we build the link-path/trail matrix in Table I and Table II. It is obvious that both $\mathcal{P}^1$ and $\mathcal{P}^2$ provide the unique combination to identify $\mathcal{OL}_{p^1}$ and $\mathcal{OL}_{p^2}$. For $\mathcal{P}^1$, p^1_{12} and p^1_{14} identify $(1,2)$. For $\mathcal{P}^2$, p^2_{14} and p^2_{45} identify $(4,5)$. Note here that $\{(1,2),(1,4)\}$ and $\{(1,4),(4,5)\}$, respectively, are the two cutsets in the given logical network disconnected under the routings $\mathcal{P}^1$ and $\mathcal{P}^2$.

	p^1_{12}	p^1_{14}	p^1_{25}	p^1_{45}
(1,2)	1	1	0	0
(2,3)	0	1	0	0
(3,4)	0	1	0	0
(2,5)	0	0	1	0
(4,5)	0	0	0	1
(5,6)	0	0	0	0
(1,6)	0	0	0	0

TABLE I
THE OPTIMUM LINK-PATH/TRAIL MATRIX FOR FIGURE 1

	p^2_{12}	p^2_{14}	p^2_{25}	p^2_{45}
(1,2)	1	0	0	0
(2,3)	0	0	0	0
(3,4)	0	0	0	0
(2,5)	0	0	1	0
(4,5)	0	1	0	1
(5,6)	0	1	0	0
(1,6)	0	1	0	0

TABLE II
THE OPTIMUM LINK-PATH/TRAIL MATRIX FOR FIGURE 2

Observation 1: Based on Example 1, there exists multiple solutions for the optimum routing problem in a given IP-over-WDM network.

Observation 2: Based on Example 2, the lightpaths alone could identify the failure of $\mathcal{OL}$.

Example 3: We now demonstrate the need for monitoring trails for failure localization. Consider the IP-over-WDM network in Fig. 3, the routing $\mathcal{P}^* = \{p^*_{13}, p^*_{14}, p^*_{36}, p^*_{46}\}$ with $p^*_{13} = \{(1,2),(2,3)\}$, $p^*_{14} = \{(1,2),(2,3),(3,4)\}$, $p^*_{36} = \{(3,4),(4,5),(5,6)\}$, and $p^*_{46} = \{(4,5),(5,6)\}$ is an optimum routing. The corresponding $\mathcal{OL}_{p^*} = \{(1,2),(2,3),(4,5),(5,6)\}$. Let $\mathcal{MP} = \{m^*_1\}$ with monitoring trail $m^*_1 = \{(1,2),(2,5),(5,6),(6,1)\}$. The link-path/trail matrix is in Table 3. The combination of $\mathcal{P}^*$ and $\mathcal{MP}$ provides the unique combination required to identify each link in $\mathcal{OL}$

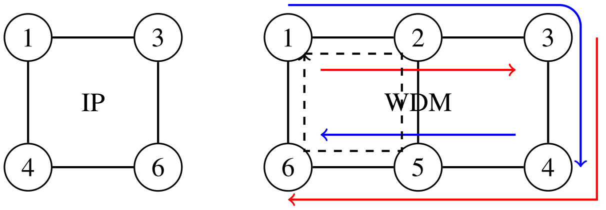

Fig. 3. The example of optimum routing for IP-over-WDM network: Solution 2

based on row information in Table 3. Row vectors in the link-path/trail matrix for physical links $(1,2)$ and $(2,3)$, and for $(4,5)$ and $(5,6)$ are the same. m-trails are necessary to identify them. The reason to select m-trail m_1^* is that a monitoring trail which routes through $(1,2)$ and $(5,6)$, but does not route through $(2,3)$ and $(4,5)$, could identify $(1,2)$ and $(2,3)$, $(4,5)$ and $(5,6)$.

	p_{13}^*	p_{14}^*	p_{36}^*	p_{46}^*	m_1^*
(1,2)	1	1	0	0	1
(2,3)	1	1	0	0	0
(3,4)	0	1	1	0	0
(2,5)	0	0	0	0	1
(4,5)	0	0	1	1	0
(5,6)	0	0	1	1	1
(1,6)	0	0	0	0	1

TABLE III
THE OPTIMUM LINK-PATH/TRAIL MATRIX FOR FIGURE 3

IV. OPTIMUM ROUTING, FAILURE LOCALIZATION, AND ILP FORMULATION

In this section, we develop integer linear programming (ILP) formulations, which provide an exact solution approach for optimum routing generation and optimum routing generation with physical link failure localization. Note here that we let term route m represent routes in the physical network, such as m-trails and lightpaths. We assume that a set of m-trails is given and each node in the network can convert the wavelengths. If $m \in \mathcal{MP}$, then m stands for an m-trail. If $m \in P$, then, m stands for a lightpath.

M : parameter. A big number.

f_m^{ij}: parameter. If a route m routes through physical link (i,j), $f_m^{ij} = 1$; otherwise, $f_m^{ij} = 0$.

ξ_{st}^{β}: parameter. If (s,t) is in cutset β, if yes, $\xi_{st}^{\beta} = 1$; otherwise, $\xi_{st}^{\beta} = 0$.

y_{ij}^{st} : binary indicator. If lightpath of (s,t) routes through physical link (i,j), $y_{ij}^{st} = 1$; otherwise, $y_{ij}^{st} = 0$.

z_{ij} : binary indicator. If with optimum routing in the given IP-over-WDM network, $(i,j) \in \mathcal{OL}$, $z_{ij} = 1$; otherwise, $z_{ij} = 0$.

λ_m: binary indicator. If a route $m \in \mathcal{MP} \cup \mathcal{P}^*$ is selected, $\lambda_m = 1$; otherwise, $\lambda_m = 0$.

α_β: binary indicator. If cutset β is selected for failure localization or not, if yes. $\alpha_\beta = 1$; otherwise, $\alpha_\beta = 0$.

c_{ij} : the alarm code for physical link (i,j)

c_{ij}^{β} : partial alarm code for physical link (i,j) with respect to cutset β

h_{ij}^{uv} : binary indicator, whether c_{ij} is greater than c_{uv}

$h_{ij}^{\beta uv}$: binary indicator, whether c_{ij}^{β} is greater than c_{uv}^{β}

η_{ij}^{β} : binary indicator. If physical link (i,j) failure disconnects logical cutset β, $\eta_{ij}^{\beta} = 1$; otherwise, $\eta_{ij}^{\beta} = 0$.

A. ILP Formulation for Optimum Logical Topology Routing

We first discuss the ILP formulation for the optimum routing problem in a given IP-over-WDM network.

To generate the optimum routing in the given IP-over-WDM network, flow conservation constraints still hold and are formulated as follows.

$$\sum_{(i,j)\in E_P} y_{ij}^{st} - \sum_{(i,j)\in E_P} y_{ji}^{st} = 1, \quad \text{if } i = s, (s,t) \in E_L \quad (1)$$

$$\sum_{(i,j)\in E_P} y_{ij}^{st} - \sum_{(i,j)\in E_P} y_{ji}^{st} = -1, \quad \text{if } i = t, (s,t) \in E_L \quad (2)$$

$$\sum_{(i,j)\in E_P} y_{ij}^{st} - \sum_{(i,j)\in E_P} y_{ji}^{st} = 0, \quad \text{otherwise}, (s,t) \in E_L. \quad (3)$$

Proposition 2: Given the routing information, (4) and (5) identify $\mathcal{OL}$.

$$\sum_{(s,t)\in CS(S,V_L\setminus S)} y_{ij}^{st} - (|CS(S,V_L\setminus S)| - 1) \le z_{ij}, \qquad (i,j) \in E_P, S \subseteq V_L \quad (4)$$

$$\sum_{(s,t)\in CS(S,V_L\setminus S)} y_{ij}^{st} \ge |CS(S,V_L\setminus S)| z_{ij}, \qquad (i,j) \in E_P, S \subseteq V_L. \quad (5)$$

Proof: We consider two cases and show that (i,j) is in $\mathcal{OL}$ if and only if $z_{ij} = 1$.

(1) If physical link (i,j) disconnects cutset $CS(S, V_L \setminus S)$, then, all links in the cutset are disconnected, i.e., $\sum_{(s,t)\in CS(S,V_L\setminus S)} y_{ij}^{st} - |CS(S,V_L\setminus S)| = 0$. Hence, by equation (4) $z_{ij} = 1$ and (i,j) is in $\mathcal{OL}$.

(2) If (i,j) fails, the number of logical links whose lightpath are disrupted is less than the cardinality of cutset, i.e., $\sum_{(s,t)\in CS(S,V_L\setminus S)} y_{ij}^{st} < |CS(S,V_L\setminus S)|$. Hence, by equation (5) $z_{ij} = 0$ and (i,j) is not in $\mathcal{OL}$.

■

ILP for Optimum Routing:

$$\min \sum_{(i,j)\in E_P} z_{ij}, \quad (6)$$

subject to:(1) to (5)

The above ILP achieves a logical topology routing under which the number of physical links each of whose failure disconnects G_L is minimum.

B. Logical Topology Routing and Physical Links Failure Localization

Given an optimum routing, in this section we develop an ILP formulation to minimize the number of m-trails (besides the lightpaths in the optimum routing) to be selected for physical link failure localization. Recall that, given a logical topology routing, $\mathcal{OL}$ is the set of physical links each of whose failure disconnects the logical topology. For failure localization we need to localize the failures of only those physical links in $\mathcal{OL}$ because the failures of other physical links would not disconnect the logical topology.

Suppose we are given a set $\mathcal{MP}$ of monitoring trails and a set $\mathcal{P}^*$ of lightpaths used in the logical topology routing. Let $\mathcal{LR}$ be the physical link-routing matrix which has one row for each physical link and one column for each path/trail in $\mathcal{MP} \bigcup \mathcal{P}^*$ and has one in position (k, ℓ) whenever link k is in path/trail ℓ. To localize the links in $\mathcal{OL}$ we have to select a subset $S_{\mathcal{MP}}$ of m-trails in $\mathcal{MP}$ such that, for any two physical links, the corresponding rows in the submatrix formed by $\mathcal{OL}$ and $\mathcal{P}^* \bigcup S_{\mathcal{MP}}$ are distinct.

In the following when we say that a logical cutset identifies (localizes) (i, j) we mean that the set of lightpaths mapping the logical links in this cutset are selected for localization of a failure of (i, j). The following proposition contains a key idea for failure localization.

Proposition 3: Given a routing and the corresponding set $\mathcal{P}^*$ of lightpaths. Suppose, under this routing, a logical cutset $CS(S, V_L \backslash S)$ is disconnected when a physical link fails. Then

(1) If $|\mathcal{F}(CS(S, V_L \setminus S))| = 1$, then, $(i, j) \in \mathcal{F}(CS(S, V_L \setminus S))$ failure is identified by cutset $CS(S, V_L \setminus S)$. In other words, in this case no monitoring trail needs to be included for identifying (i, j). NOTE: Recall that $\mathcal{F}(CS(S, V_L \setminus S))$ is the set of physical links each of whose failure disconnects the cutset $CS(S, V_L \setminus S)$.

(2) If $|\mathcal{F}(CS(S, V_L \setminus S))| \geq 2$, then at most $|\mathcal{F}(CS(S, V_L \setminus S))| - 1$ m-trails, in addition to the cutset, are needed to to identify (i, j).

With a given optimum routing $\mathcal{P}^*$, we let $S_{\mathcal{CS}}$ be a subset of logical cutsets which is disrupted by physical link failures. We let β be the index of a cutset.

Proposition 4: Suppose S_{CS} be a subset of cutsets such that all these cutsets are disconnected because of the failure of one or more physical links. Then

(1) If $| \cap_{\{\beta \in S_{\mathcal{CS}}\}} \mathcal{F}(\beta)| = 1$, then the only link causing the failure of all the cutsets in $\mathcal{S}_{CS}$ can be identified by $\cup_{\{\beta \in S_{\mathcal{CS}}\}} \beta$.

(2) If $| \cap_{\{\beta \in S_{\mathcal{CS}}\}} \mathcal{F}(\beta)| \geq 2$, the links each of whose failure causes the failures of all the cutsets in $S_{\mathcal{CS}}$ can be identified by $\cup_{\{\beta \in S_{\mathcal{CS}}\}} \beta$ and possibly a maximum of $|\cap_{\{\beta \in S_{\mathcal{CS}}\} \mathcal{F}(\beta)}| - 1$ m-trails.

If, for the scenario in (2) in proposition 4, the m-trails are not available to generate the combinations of paths/trails in $\mathcal{MP} \bigcup \mathcal{P}^*$, then additional m-trails need to be introduced.

Now we proceed to generate the different constraints in our ILP formulation to determine an optimum logical topology routing along with the unique combinations of lightpaths/m-trails for localization of faults in physical links in $\mathcal{OL}$. First we modify constraints (4) and (5) to provide the connection between physical link (i, j) and a cutset.

$$\sum_{(s,t) \in \beta} y_{ij}^{st*} - (|\beta| - 1) \leq \eta_{ij}^{\beta}, \quad \beta \in \mathcal{CS}, (i, j) \in \mathcal{OL} \quad (7)$$

$$\sum_{(s,t) \in \beta} y_{ij}^{st*} \geq |\beta| \eta_{ij}^{\beta}, \quad \beta \in \mathcal{CS}, (i, j) \in \mathcal{OL}. \quad (8)$$

Constraints (7) and (8) ensure that $\eta_{ij}^{\beta} = 1$ if and only if the failure of physical link (i, j) disconnects cutset β in the logical topology. Constraints (9) and (10) guarantee that $\alpha_\beta = 1$ if and only if for some physical link (i, j), $\eta_{ij}^{\beta} = 1$ (that is if and only if (i, j) failure disconnects cutset β.)

$$\alpha_\beta \leq \sum_{(i,j) \in E_P} \eta_{ij}^{\beta}, \quad \beta \in \mathcal{CS} \quad (9)$$

$$\sum_{\beta \in \mathcal{CS}} \eta_{ij}^{\beta} \alpha_\beta \geq \eta_{ij}^{\beta}, \quad (i, j) \in E_P, \beta \in \mathcal{CS} \quad (10)$$

Code Assignment for Failure Localization

To localize the failure in a physical link (i, j) we associate with (i, j) a combination of lightpaths and m-trails. This combination is captured by a code c_{ij} which is basically the integer value derived from the combination that is given by the link-path/trail matrix. Since, each cutset β disconnected by the failure of (i, j) is to be included in the combination we exclude the links of β in calculating the value of the code. This partial code will be denoted by c_{ij}^{β}. So, we have

$$c_{ij}^{\beta} = \sum_{m \in \mathcal{MP} \cup (\mathcal{P}^* \backslash \{p_{st}^* : (s,t) \in \beta\})} 2^m (f_m^{ij} + f_m^{ji}) \gamma_{ijm}^{\beta} \quad (11)$$

, where γ_{ijm}^{β} is a binary variable used to select/deselect trail m for each (i, j) cutting of the same β.

Constraint (12) ensures that the code is assigned to only those physical links in $\mathcal{F}(\beta)$ that satisfies $\mathcal{F}(\beta)$ greater than or equal to 2. Constraint (13) is to guarantee that an m-trail is chosen to localize (i, j) only when cutset β is selected for localization. Constraint (14) is to ensure that c_{ij}^{β} is nonzero only when cutset β is selected for localization. Constraint (15) says that an m-trail is included in the set of paths/trails for localization only if for some cut set β and some physical link (i, j), γ_{ijm}^{β} is nonzero.

Finally, the two constraints (16) and (17) guarantee that the partial codes for two distinct links are different.

Given an optimum logical topology routing $\mathcal{P}^*$, we have the following mathematical programming formulation that minimizes the number of monitors required to localize the failures of the links in $\mathcal{OL}$.

$$\min \sum_{m \in \mathcal{MP}} \lambda_m$$

$$s.t. \quad (7) \text{ to } (11)$$

$$c_{ij}^{\beta} \leq M(\sum_{(u,v) \in E_P} \eta_{uv}^{\beta} \alpha_\beta - 1), \quad (12)$$

$$\gamma_{ijm}^{\beta} \leq \alpha_\beta, \quad (13)$$

$$c_{ij}^{\beta} \leq M \alpha_\beta \eta_{ij}^{\beta} \quad (14)$$

$$\gamma_{ijm}^{\beta} \leq \lambda_m, \quad (15)$$

$$c_{ij}^{\beta} <= c_{uv}^{\beta} - 1 + M h_{ij}^{\beta uv} \quad (16)$$

$$c_{uv}^{\beta} <= c_{ij}^{\beta} - 1 + M(1 - h_{ij}^{\beta uv}) \quad (17)$$

$$\eta_{ij}^{\beta}, \alpha_\beta, f_m^{ij}, h_{ij}^{\beta uv}, \lambda_m, \gamma_{ijm}^{\beta} \in \{0, 1\}, c_{ij}^{\beta} \geq 1,$$

$$\beta \in \mathcal{CS}, m \in \mathcal{MP}, (i, j) \in \mathcal{OL} \quad (18)$$

Once the codes c_{ij}^{β} are obtained then the codes c_{ij} can be obtained by simply adding the value corresponding to the links (or corresponding lightpaths) in the cutset β. Note that in the above formulation (12) is a nonlinear constraint, which can be linearized with an auxiliary variables ξ_{uv}^{β}:

$$\xi_{uv}^{\beta} \leq \eta_{uv}^{\beta}, \qquad (u,v) \in \mathcal{OL}, \beta \in \mathcal{CS} \qquad (19)$$

$$\xi_{uv}^{\beta} \leq \alpha_{\beta}, \qquad (u,v) \in \mathcal{OL}, \beta \in \mathcal{CS} \qquad (20)$$

$$\xi_{uv}^{\beta} \geq \eta_{uv}^{\beta} + \alpha_{\beta} - 1, \qquad (u,v) \in \mathcal{OL}, \beta \in \mathcal{CS} \qquad (21)$$

Constraints (19)-(21) guarantee that the value of ξ_{uv}^{β} equals to $\eta_{uv}^{\beta}\alpha_{\beta}$. Constraints (19) and (20) force $\xi_{uv}^{\beta} = 0$ when $\eta_{uv}^{\beta} = 0$ or $\alpha_{\beta} = 0$. Constraint (21) allows $\eta_{uv}^{\beta} = 1$ if and only if both $\eta_{uv}^{\beta} = 1$ and $\alpha_{\beta} = 1$.

C. Optimum Logical Topology Routing and Minimizing the Number of m-Trails for Failure Localization

In section IV-A we provided an ILP formulation to generate an optimum routing that minimizes the number of physical links each of whose failure disconnects the logical topology. In section IV-B, given an optimum routing we provided an ILP formulation to minimize the number of m-trails needed to localize physical link failures. In this section we provide an integrated approach to optimize a weighted sum of the both the objectives of the problems considered in sections IV-A and IV-B. This integrated formulation is as follows, where θ and ϑ are given weights.

$$\min \theta \sum_{(i,j)\in E_P} z_{ij} + \vartheta \sum_{m\in\mathcal{MP}} \lambda_m$$

$$s.t. \text{ Constraints } (1)-(3),(9)-(11),(13)-(17),(19)-(21)$$

$$\sum_{(s,t)\in\beta} y_{ij}^{st} - (|\beta|-1) \leq \eta_{ij}^{\beta},\ \beta \in \mathcal{CS}, (i,j) \in E_P \qquad (22)$$

$$\sum_{(s,t)\in\beta} y_{ij}^{st} \geq |\beta|\eta_{ij}^{\beta}, \qquad \beta \in \mathcal{CS}, (i,j) \in E_P. \qquad (23)$$

$$z_{ij} \leq \sum_{\beta} \eta_{ij}^{\beta}, \qquad (i,j) \in E_P \qquad (24)$$

$$Mz_{ij} \geq \sum_{\beta} \eta_{ij}^{\beta}, \qquad (i,j) \in E_P \qquad (25)$$

$$y_{ij}^{st}, z_{ij}, \eta_{ij}^{\beta}, \xi_{uv}^{\beta}, h_{ij}^{\beta uv}, \lambda_m, \gamma_{ijm}^{\beta} \in \{0,1\}, c_{ij}^{\beta} \geq 1,$$
$$(i,j) \in \mathcal{OL}, \beta \in \mathcal{CS}, m \in \mathcal{MP} \qquad (26)$$

V. HEURISTIC APPROACH AND SIMULATION RESULTS

We present a heuristic for optimum routing and corresponding failure localization of physical links in two stages. First the optimum routing $\mathcal{P}^*$ for all logical links is generated using the concept of protection spanning tree, which was introduced in [8]. The simulation results in [8] showed that the generated routing cannot guarantee survivability but a routing with high probability of survivability can be achieved. Hence the objective of the heuristic introduced below is two-fold: find a survivable routing when possible; otherwise, provide a mechanism to uniquely identify the physical link failure using lightpaths and minimum number of m-trails.

Step 2 in Algorithm 1 finds the physical link utilization for all lightpaths. For each physical link, step 3 identifies a logical link set $\beta, \beta \in \mathcal{CS}$, whose failure disconnects the logical topology. Steps 4 – 8 group the physical links whose failure cut off the same set of logical links. Those groups are denoted as $\mathcal{S}_{\beta_i}$. Steps 9 – 12 generate candidate m-trails, denoted as $\mathcal{MP}_C$, which connect $\mathcal{S}_{\beta_i}$ and $\mathcal{S}_{\beta_j}, i \neq j$. Once the candidate m-trails are generated, step 13 iterates through all $\mathcal{MP}_C$ and finds the minimal number of m-trails whose combination can be used to identify (i,j) failures. Here we only provide the preliminary simulation results for our heuristic due to page limitation. The physical topologies selected are NSF, Nobel-Germany, Norway, Europe, and COST 266 [32]. The corresponding logical topologies are randomly generated with 50% of nodes in the physical topologies and at least two-edge connected. After generating the optimum routing, we apply the heuristic and calculate the number of physical link failures which disconnect the logical topology (denoted as cuts in Table IV.) For all cuts, additional monitoring trails are randomly generated (denoted as m-trails in Table IV.) For optimum routing which is survivable, we also record the percentage of survivability (denoted as Surv% in Table IV.) The simulation results show that the hybrid approach not only guarantees high percentage of survivable route generation, but also provides the minimum number of additional m-trails required in order to uniquely identify all physical link failures.

Graph	nodes	edges	cuts	m-trails	Surv. %
NSF	14	21	6	3	90.12
Nobel-Germany	17	26	4	2	93.58
Norway	27	51	15	6	91.99
Nobel-Europe	28	41	8	4	94.98
COST266	37	57	15	7	96.53

TABLE IV
SIMULATION RESULTS

Algorithm 1 Survivable routing and failure localization with minimum m-trails

```
Require: $G_P = (V_P, E_P), G_L = (V_L, E_L), \mathcal{MP}_C = \emptyset, \mathcal{CS} = \emptyset$
 1: Generate optimum routing $\mathcal{P}^*$ for all logical links
 2: Identify all $f_m^{ij}, m \in \mathcal{P}^*$
 3: Identify all $\mathcal{CS}$ [31]
 4: for all $(i,j) \in E_P$ do
 5:     if $(\cup_{m\in\mathcal{MP}\cup\mathcal{P}^*} f_m^{ij}) = \beta, \beta \in \mathcal{CS}$ then
 6:         $\mathcal{S}_\beta = \mathcal{S}_\beta \cup (i,j)$ {i.e., $\eta_{ij}^{\beta} = 1$}
 7:     end if
 8: end for
 9: for $(i,j) \in \mathcal{S}_{\beta_1}, (k,\ell) \in \mathcal{S}_{\beta_2}$, where $\mathcal{S}_{\beta_1}, \mathcal{S}_{\beta_2} \in \mathcal{S}_\beta$ and $\mathcal{S}_{\beta_1} \neq \mathcal{S}_{\beta_2}$ do
10:     Find a path $m^*$ connecting $(i,j)$ and $(k,\ell)$
11:     $\mathcal{MP}_C = \mathcal{MP}_C \cup m^*$
12: end for
13: Find the minimal cardinality subset of $\mathcal{MP}_C$ which uniquely distinguish all $(i,j) \in \mathcal{S}_{\beta i}, \mathcal{S}_{\beta i} \in \mathcal{S}_\beta$
```

VI. CONCLUSIONS

Recognizing that a survivable logical topology routing in an IP-over-WDM network may not exist, we studied the problem of an optimum routing which minimizes the number of single physical link failures causing disconnection of the logical topology. We provided ILP formulations for three problems. The first is to determine an optimum logical topology routing. Given an optimum logical topology routing and a set of monitoring trails, the second problem is to determine the minimum number of monitoring trails (along with the lightpaths in the routing) required for physical link failure location. The third problem is to determine a joint routing and corresponding failure localization minimizing an objective that is a weighted sum of the objectives of the previous two problems. A heuristic approach for the joint routing and failure localization problem is given, along with preliminary computational results. Summarizing, this paper provided an integrated approach to logical topology routing and physical link failure localization problems, thereby generalizing previous works in these areas. Applying the formulations discussed in our earlier work [7] we can get MILP formulations for all the problems considered in this paper as well as formulations for optimizing several cross-layer metrics. Due to space limitations, details of those formulations are not included.

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REFERENCES

[1] M. Kodialam, T. V. Lakshman, J. Orlin, and S. Sengupta, "Preconfiguring ip-over-optical networks to handle router failures and unpredictable traffic," *IEEE Journal on Selected Areas in Communications*, vol. 25, pp. 934–948, 2007.

[2] C. Ware, C. Lai, D. Brunina, W. Zhang, A. Garg, B. Bathula, and K. Bergman, "Cross-layer reconfigurable optical network: Fast failure recovery in testbed for routing algorithms," in *The 13th International Conference on Transparent Optical Networks (ICTON)*, 2011, pp. 1–4.

[3] R. M. Karp, "Reducibility among combinatorial problems," in *Complexity of Computer Computations*, 1st ed., R. E. Miller and J. W. Thatcher, Eds. Plenum Press, 1972, pp. 85–103.

[4] E. Modiano and A. Narula-Tam, "Survivable routing of logical topologies in WDM networks," in *IEEE INFOCOM*, 2001.

[5] A. Todimala and B. Ramamurthy, "A scalable approach for survivable virtual topology routing in optical WDM networks," *IEEE Journal on Selected Areas in Communications*, vol. 25, pp. 63–69, 2007.

[6] J. Strand, A. L. Chiu, and R. Tkach, "Issues for routing in the optical layer," *IEEE Communications Magazine*, vol. 39, pp. 81–87, 2001.

[7] T. Lin, Z. Zhou, and K. Thulasiraman, "Logical topology survivability in IP-over-WDM networks: Survivable lightpath routing for maximum logical topology capacity and minimum spare capacity requirements," in *Proc. International Workshop on Design of Reliable Communication Networks (DRCN'11)*, October 2011, pp. 1–8.

[8] Z. Zhou, T. Lin, K. Thulasiraman, G. Xue, and S. Sahni, "Novel survivable routing in IP-over-WDM networks by logical protecting spanning tree set," in *Proc. Reliable Networks Design and Modeling (RNDM)*, October 2012, pp. 3 – 9.

[9] D. D. Kan, A. Narula-Tam, and E. Modiano, "Lightpath routing and capacity assignment for survivable IP-over-WDM networks," in *7th International Workshop on Design of Reliable Communication Networks*, 2009.

[10] K. Lee and E. Modiano, "Cross-layer survivability in WDM-based networks," in *IEEE INFOCOM*, 2009.

[11] M. Kurant and P. Thiran, "On survivable routing of mesh topologies in IP-over-WDM network," in *IEEE INFOCOM*, 2005.

[12] S. Lee, J. Liu, and Y. Chen, "An ear-decomposition based approach for survivable routing in WDM networks," in *19th International Conference on Advanced Information Networking and Applications*, 2005.

[13] M. Javed, K. Thulasiraman, M. A. Gaines, and G. Xue, "Survivability aware routing of logical topologies: On Thiran-Kurant approach, enhancements and evaluation," in *IEEE Global Telecommunications Conference*, 2006.

[14] M. Javed, K. Thulasiraman, and G. Xue, "Lightpaths routing for single link failure survivability in IP-over-WDM networks," *Journal of Communication and Networks*, 2007.

[15] K. Thulasiraman, M. S. Javed, and G. Xue, "Circuits/Cutsets duality and a unified algorithmic framework for survivable logical topology design in IP-over-WDM optical networks," in *IEEE INFOCOM*, 2009.

[16] K. Thulasiraman, M. Javed, and G. Xue, "Primal meets dual: A generalized theory of logical topology survivability in IP-over-WDM optical networks," in *Second International Conference on Communication Systems and Networks*, 2010.

[17] K. Thulasiraman, T. Lin, M. Javed, and G. Xue, "Logical topology augmentation for guaranteed survivability under multiple failures in IP-over-WDM optical networks," *Optical Switching and Networking*, pp. 206–214, 2010.

[18] C. Liu and L. Ruan, "A new survivable mapping problem in IP-over-WDM networks," *IEEE Journal on Selected Areas in Communications*, vol. 25, pp. 25–34, 2007.

[19] C. Assi, Y. Ye, A. Shami, S. Dixit, and M. Ali, "A hybrid distributed fault-management protocol for combating single-fiber failures in mesh-based DWDM optical networks," in *Proc. IEEE GLOBECOM*, Nov 2002, pp. 2676–2680.

[20] Y. Hamazumi, M. Koga, K. Kawai, H. Ichino, and K. Sato, "Optical path fault management in layered networks," in *Proc. IEEE GLOBECOM*, Nov 1998, pp. 2309–2314.

[21] N. Harvey, M. Patrascu, Y. Wen, S. Yekhanin, and V. W. S. Chan, "Optical path fault management in layered networks," in *Proc. IEEE GLOBECOM*, Nov 1998, pp. 2309–2314.

[22] J. Tapolcai, B. Wu, and P. H. Ho, "On monitoring and failure localization in mesh all-optical networks," in *Proc. IEEE INFOCOM*, Apr 2009.

[23] B. Wu, P. H. Ho, and K. L. Yeung, "Monitoring trail: on fast link failure localization in all-optical WDM mesh network," *IEEE/OSA Journal of Lightwave Technology*, vol. 27, pp. 4175–4185, 2009.

[24] S. Ahuja, S. Ramasubramanian, and M. Krunz, "Single link failure detection in all-optical networks using monitoring cycles and paths," *IEEE/ACM Transactions on Networking*, vol. 17, pp. 1080–1093, 2009.

[25] ——, "Srlg failure localization in optical networks," *IEEE/ACM Transactions on Networking*, vol. 19, pp. 989–999, 2011.

[26] J. P. Vasseur, M. Pickavet, and P. Demeester, "Network recovery: Protection and restoration of optical, sonet-sdh, ip, and mpls," in *The Morgan Kaufmann Series in Networking*. Morgan Kaufmann, 2004, vol. 7.

[27] S. Stanic, S. Subramaniam, H. Choi, G. Sahin, and H. Choi, "On monitoring transparent optical networks,," in *Proceeding of International Conference of Parallel Processing*, 2002, pp. 217–223.

[28] M. Sivakumar and K. M. Sivalingam, "On surviving dual-link failures in path protected optical wdm mesh networks," *Optical Switching and Networking*, vol. 3, pp. 71–88, 2006.

[29] K. M. Sivalingam and S. Subramaniam, Eds., *Emerging Optical Network Technologies: Architectures, Protocols and Performance*, 1st ed. Springer, 2005.

[30] C. Mas and J. Thiran, P.; Le Boudec, "Fault localization at the wdm laye," *Photonic Network Communications*, vol. 1, pp. 235–255, 1999.

[31] "An algorithm to enumerate all cutsets of a graph in linear time per cutset," *J. ACM*, vol. 27, no. 4, pp. 619–632, 1980.

[32] "SNDlib," 2006, http://sndlib.zib.de.