Photon Netw Commun
DOI 10.1007/s11107-014-0452-4

Integrated design of fault localization and survivable mapping in IP over transparent WDM networks

Wenda Ni · Changcheng Huang · Jing Wu

Received: 21 November 2013 / Accepted: 3 June 2014

Abstract Lightpaths play multiple critical roles in cross-layer fault management of IP over transparent optical networks. While the roles of lightpaths have been discussed specifically in fault localization as well as fault recovery phases, these existing works only take a sporadic, piecemeal view of these roles by studying each of them individually as a separate lightpath routing problem. In this paper, we instead take an integrated, systematic view by considering these multiple roles jointly as one single lightpath routing problem. In particular, we propose a new design model to fulfill the lightpath layout requirements in both identifying fiber link failures for fault localization and ensuring IP topology connectivity for fault recovery. With a much smaller formulation size, our new model significantly outperforms the existing counterpart in computational efficiency, scalability, and solution quality.

Keywords IP over transparent optical networks · Cross-layer fault management · Fault detection · Fault localization · Fault recovery · Survivable mapping · Integrated lightpath design

W. Ni (✉) · C. Huang
Department of Systems and Computer Engineering,
Carleton University, Ottawa, ON K1S 5B6, Canada
e-mail: wendani@sce.carleton.ca; wonda.ni@gmail.com

C. Huang
e-mail: huang@sce.carleton.ca

J. Wu
Communications Research Centre Canada,
Ottawa, ON K2H 8S2, Canada
e-mail: jingwu@ieee.org

1 Introduction

Backbone transport networks are evolving into a two-layer architecture of IP over all-optical transparent networks [1, 2]. In such a network, a point-to-point IP link between two routers is laid out as an end-to-end wavelength connection established between the associated optical nodes. The setup and the teardown of a wavelength connection correspond to the creation and the removal of an IP link, respectively. As carrier networks rely on the IP layer to provide survivable services [1,3–5], a wavelength connection takes the form of a single, unprotected lightpath routed over the optical topology [1]. Given the optical and the IP topologies, how each IP link is routed in the form of a lightpath plays key roles in enabling fault manageability, which is an essential concern in network design and real-time operation.

Fault management is generally composed of three subsequent steps: fault detection, fault localization, and fault recovery [2,6]. Fault detection is typically enabled through real-time monitoring techniques. Fault localization identifies the exact failed links or finds the minimum set of likely failed links based on the alarm state raised during the fault detection phase. In all-optical transparent networks, traffic data traverse a lightpath without being electronically processed at the intermediate nodes. While signal transparency offers a cost-effective solution to high-bit-rate data transmission, limited accessibility to digital processing makes the optical performance monitoring a challenging issue to optical-layer network design and operation [6]. To circumvent the difficulty, tier-1 backbone providers employ IP-layer monitoring techniques to detect and localize fiber link failures [7]. Specifically, the symptoms of IP link failures are fed into a centralized localization engine to diagnose the root cause of failures at the optical layer. The health of an IP link (i.e., an optical circuit) is checked continuously through signal

Published online: 26 June 2014

probing of the corresponding lightpath [8–10], which takes immediate advantage of the fact that receiver at the destination node of a lightpath can directly and accurately monitor the accumulated transmission impairments along the entire path. Previous works in [8,9] studied the problem of how many and how lightpaths should be routed in an optimal manner so that the detection of signal loss of several lightpaths can uniquely localize the failed fiber link or largely shrink the set of possible failed links. The work in [10] studied a variant of the problem with given lightpath demands (i.e., given the number of lightpaths to be routed as well as the source and destination node of each lightpath).

During the fault recovery phase, affected traffic flows are detoured to new paths that bypass the failed links. As a fiber link can carry multiple lightpaths with the support of wavelength division multiplexing (WDM) technology, when an IP topology is overlaid on top of an optical topology, the seemingly independent IP links can be intimately related by sharing the same fiber link. Consequently, even a single fiber link failure can lead to the simultaneous failures of multiple IP links and further partition the IP topology. When fault recovery is deployed at the IP layer as carriers' common practice mentioned above, the IP topology connectivity in fiber link failures has to be guaranteed [11,12]. This fundamental requirement was first studied in [13] as the survivable mapping problem: Given the IP and the optical topologies, how each IP link should be mapped in the form of a lightpath such that the IP topology remains connected in the event of any single fiber link failure. Solution methods for survivable mapping were proposed in [13–15].

While lightpaths play different roles at different steps of the fault management process, all of the above works, however, take a piecemeal approach to study lightpath design problems, which only target a single, specific fault management purpose, i.e., either for fault localization or for fault recovery. Motivated by the above fact of the existing works, we, instead, take a systematic approach to route lightpaths that are capable of fulfilling multiple roles through the entire fault management process. Specifically, we propose a new lightpath design problem of laying out lightpaths for a given IP topology such that in any single fiber link failure, the lightpath layout can accurately identify the failed fiber link or deliver the smallest set of potentially failed links while maintaining the IP topology connectivity. The joint problem of fault localization and survivable mapping is formulated as a complete integer linear programming (ILP) model, which provides a unified framework to look at the lighpath routing problem in terms of the cross-layer fault management requirements. Compared to a combined design in [17], which uses span-protecting *p*-cycles to serve as *monitoring*-cycles for self-fault detection and localization in single-layer transparent networks, our design focuses on the integration of lightpath-based survivable mapping and fault localization in two-layer IP over transparent optical networks. With a much smaller model size, our model improves the previous one in [20] by significantly accelerating the integrated lightpath design and, subsequently, improving the quality of the design solution. Moreover, we improve the flexibility of fault localization formulation in [18,19] by allowing a set of fiber links to share the same IP-layer failure symptoms. In doing so, our ILP model is generally applicable to any topology inputs with two-link connectivity. Note that recent work in [21] discussed an integrated design problem similar to ours. However, the formulation for the fault localization requirement follows the similar approach as in [20], over which we propose improvement in this paper.

The remainder of the paper is organized as follows. Section 2 presents the new ILP model for integrated lightpath routing. Section 3 provides numerical comparisons. Section 4 concludes the paper.

2 Mathematical formulation

We model the optical topology as an undirected graph $G_l = (\mathscr{N}_l, \mathscr{L}_l)$, where $\mathscr{N}_l$ is the node set, and $\mathscr{L}_l$ is the link set. The links are numbered from 1 to $|\mathscr{L}_l|$. The IP topology is modeled as $G_u = (\mathscr{N}_u, \mathscr{L}_u)$ in the similar fashion. We assume as in [13] that each optical node hosts no more than one IP node from the IP topology. Thus, the number of nodes in the IP topology should be no greater than that in the optical topology, i.e., $|\mathscr{N}_u| \leq |\mathscr{N}_l|$.

Each IP link r ($r \in \mathscr{L}_u$) is laid out as a lightpath, which is represented by binary row vector $\boldsymbol{a}_r = \{a_{ri}\}_{1\times|\mathscr{L}_l|}$. Binary element a_{ri} equals one if IP link r uses fiber link i and equals zero otherwise. Thus, the complete lightpath layout information can be captured by the interlayer link mapping matrix $\boldsymbol{A} = \{\boldsymbol{a}_r\}_{|\mathscr{L}_u|\times 1} = \{a_{ri}\}_{|\mathscr{L}_u|\times|\mathscr{L}_l|}$, which is formed by the collection of these vectors in ascending order of index r. Matrix $\boldsymbol{A}$ is what we want to find through our design model. For illustration purpose, an example of matrix $\boldsymbol{A}$ is given in (1), which corresponds to the two-layer network topology shown in Fig. 1. The second row in (1), for instance, denotes the lightpath routing for IP link 2, which traverses fiber links

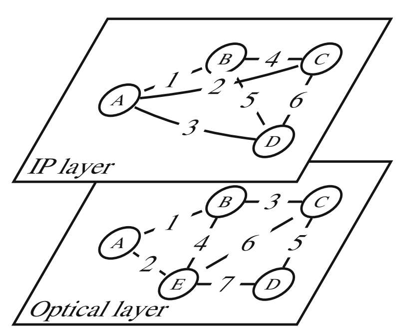

Fig. 1 Net 0 ($|\mathscr{N}_l| = 5, |\mathscr{L}_l| = 7, |\mathscr{N}_u| = 4, |\mathscr{L}_u| = 6$)

2 and 6. We assume that sufficient wavelengths are available to ignore the wavelength continuity constraint and focus only on the routing problem.

$$A = \begin{array}{c} \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \end{matrix} \\ \begin{matrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{matrix} \quad \end{array} \tag{1}$$

We enumerate all cut-sets of the IP topology to formulate survivable mapping [13]. A cut-set of IP topology $G_u = (\mathscr{N}_u, \mathscr{L}_u)$ is a set of links that straddle a bipartition of node set $\mathscr{N}_u$. Specifically, let two node subsets $\mathscr{S}_u \subset \mathscr{N}_u$ ($\mathscr{S}_u \neq \emptyset$) and $\mathscr{T}_u = \mathscr{N}_u \setminus \mathscr{S}_u$ denote a bipartition of node set $\mathscr{N}_u$. Then, a link in cut-set has one end node in $\mathscr{S}_u$, and the other end node in $\mathscr{T}_u$. For illustration of a cut-set, consider a bipartition of IP topology in Fig. 1 with $\mathscr{S}_u = \{A, B\}$ and $\mathscr{T}_u = \{C, D\}$. The corresponding cut-set is IP link set $\{2, 3, 4, 5\}$. Considering all possible combinations of node set bipartitions, the total number of cut-sets in graph G_u is $2^{|\mathscr{N}_u|-1} - 1$. We number these cut-sets from 1 to $2^{|\mathscr{N}_u|-1} - 1$.

Our design model is described as follows:

Sets:

– $\mathscr{P}^r$ is the pre-calculated candidate lightpath set for IP link r ($r \in \mathscr{L}_u$). The lightpaths are numbered from 1 to $|\mathscr{P}^r|$.

Parameters:

– $\boldsymbol{\alpha}^{r,p} = \{\alpha_i^{r,p}\}_{1\times|\mathscr{L}_l|}$ is a $1 \times |\mathscr{L}_l|$ binary row vector denoting the p-th lightpath in set $\mathscr{P}^r$ ($r \in \mathscr{L}_u$). Element $\alpha_i^{r,p}$ equals one if lightpath p traverses fiber link i ($i \in \mathscr{L}_l$) and equals zero otherwise. Table 1 gives an example of $\boldsymbol{\alpha}^{r,p}$ for Net 0 shown in Fig 1. In this example, we have $|\mathscr{P}^r| = 2$ for all IP links. Note that in general, lightpath sets are not required to be of the same size.

– $\boldsymbol{c}_k = \{c_{k,r}\}_{1\times|\mathscr{L}_u|}$ is a $1 \times |\mathscr{L}_u|$ binary row vector denoting the k-th cut-set of IP topology G_u. Element $c_{k,r}$ equals one if cut-set k contains IP link r ($r \in \mathscr{L}_u$) and equals zero otherwise.

Variables:

– $x^{r,p}$ is a binary variable which equals one if IP link r ($r \in \mathscr{L}_u$) is mapped to lightpath p in set $\mathscr{P}^r$ and equals zero otherwise.

– g_i is a binary variable which equals one if fiber link i carries at least one lightpath and equals zero otherwise.

Table 1 Routing of candidate lightpaths for each IP link on Net 0

r	p	i						
		1	2	3	4	5	6	7
1	1	1	0	0	0	0	0	0
	2	0	1	0	1	0	0	0
2	1	1	0	1	0	0	0	0
	2	0	1	0	0	0	1	0
3	1	0	1	0	0	0	0	1
	2	1	0	1	0	1	0	0
4	1	0	0	1	0	0	0	0
	2	0	0	0	1	0	1	0
5	1	0	0	1	0	1	0	0
	2	0	0	0	1	0	0	1
6	1	0	0	0	0	1	0	0
	2	0	0	0	0	0	1	1

– $h_{i,i'}$ is a binary variable which equals one if fiber link i and i' ($i' > i$) carry different sets of lightpaths and equals zero otherwise.

Objective:

$$\max \zeta \sum\nolimits_{i=1}^{|\mathscr{L}_l|} g_i + \xi \sum\nolimits_{i,i':\,1\le i,i'\le|\mathscr{L}_l|,\,i<i'} h_{i,i'} - \sum\nolimits_{i=1}^{|\mathscr{L}_l|} \sum\nolimits_{r=1}^{|\mathscr{L}_u|} \sum\nolimits_{p=1}^{|\mathscr{P}^r|} x^{r,p} \alpha_i^{r,p} \tag{2}$$

Subject to:

$$\sum\nolimits_{p=1}^{|\mathscr{P}^r|} x^{r,p} = 1, \qquad \forall\, 1 \le r \le |\mathscr{L}_u| \tag{3}$$

$$\sum\nolimits_{r=1}^{|\mathscr{L}_u|} \sum\nolimits_{p=1}^{|\mathscr{P}^r|} x^{r,p} \alpha_i^{r,p} \ge g_i, \qquad \forall\, 1 \le i \le |\mathscr{L}_l| \tag{4}$$

$$\sum\nolimits_{r=1}^{|\mathscr{L}_u|} \sum\nolimits_{p=1}^{|\mathscr{P}^r|} x^{r,p} \left(\alpha_i^{r,p} \oplus \alpha_{i'}^{r,p}\right) \ge h_{i,i'}, \quad \forall\, 1 \le i, i' \le |\mathscr{L}_l|\,,\ i < i' \tag{5}$$

$$\sum\nolimits_{r=1}^{|\mathscr{L}_u|} c_{k,r} \sum\nolimits_{p=1}^{|\mathscr{P}^r|} x^{r,p} \alpha_i^{r,p} < \sum\nolimits_{r=1}^{|\mathscr{L}_u|} c_{k,r}, \quad \forall\, 1 \le k \le 2^{|\mathscr{N}_u|-1} - 1,\ 1 \le i \le |\mathscr{L}_l| \tag{6}$$

Our objective in (2) has three parts: 1) (primary objective) maximizes the total number of fiber links carrying lightpaths or, more intuitively, maximizes the total number of fiber link failures that can be detected; 2) (secondary objective) maximizes the total number of fiber link pairs carrying different sets of lightpaths so that in a single fiber link failure, the potential of unique fault localization is maximized, or more generally, the size of likely failed link set is minimized; and 3) (tertiary objective) minimizes the total number of wavelength channels used to route IP links. The optimization priority is enabled by setting weight parameter $(\zeta \gg \xi \gg 1) \wedge (\zeta > \xi\, |\mathscr{L}_l|\, (|\mathscr{L}_l| - 1)\,/2)$, where the second part ensures the primary objective to be dominant. For Net 0 and the lightpath sets in Table 1, the objective can be instantiated as

$$\max \zeta \left(g_1 + g_2 + \cdots + g_7\right) + \xi \big(h_{1,1} + h_{1,2} + \cdots + h_{1,7} \;\; + h_{2,3} + h_{2,4} + \cdots + h_{2,7} + h_{3,4} + h_{3,5} \cdots + h_{3,7} \;\; + h_{4,5} + h_{4,6} + h_{4,7} + h_{5,6} + h_{5,7} \;\; + h_{6,7}\big) - \big(x^{1,1} + 2x^{1,2} + 2x^{2,1} + 2x^{2,2} + 2x^{3,1} + 3x^{3,2} + x^{4,1} + 2x^{4,2} + 2x^{5,1} + 2x^{5,2} + x^{6,1} + 2x^{6,2}\big).$$

Constraint (3) maps each IP link to one lightpath. For an instance of this constraint, consider Net 0 and the lightpath sets in Table 1. The constraint for IP link 1 is given by

$$x^{1,1} + x^{1,2} = 1.$$

Constraint (4) together with the primary objective finds variable g_i. Specifically, the left side of the constraint computes the number of lightpaths that traverses fiber link i. If no lightpaths use link i, variable g_i equals zero. On the other hand, if at least one lightpath uses link i, variable g_i has the flexibility of being one or zero. However, to maximize the primary objective, variable g_i is bound to be one. An instance of this constraint can be expressed as

$$x^{2,1} + x^{3,2} + x^{4,1} + x^{5,1} \geq g_3,$$

which is for fiber link 3 in Net 0 based on the lightpath sets shown in Table 1. When g_i is one, column i in matrix $\boldsymbol{A}$ has at least one element equal to one. Matrix $\boldsymbol{A}$ in (1) gives an example that all columns have at least one element of being value one. In such case, each fiber link carries at least one lightpath, which further means that all fiber link failures can be detected. Similarly, constraint (5) together with the secondary objective finds variable $h_{i,i'}$. The following inequality gives an instance of this constraint, which is for fiber links 3 and 4 on Net 0 using the lightpath sets in Table 1:

$$x^{1,2} + x^{2,1} + x^{3,2} + x^{4,1} + x^{4,2} + x^{5,1} + x^{5,2} \geq h_{3,4}.$$

When $h_{i,i'}$ is one, column i in matrix $\boldsymbol{A}$ has at least one element whose value is different from that of the corresponding element in column i'. For the example matrix in (1), this holds for any two columns. In such case, any two fiber links carry different sets of lightpaths, which indicates that all single fiber link failures can be uniquely localized. Note that the binary logic XOR operation in (5) is implemented as a linear operation:

$$\alpha_i^{r,p} \oplus \alpha_{i'}^{r,p} = \alpha_i^{r,p}\left(1 - \alpha_{i'}^{r,p}\right) + \left(1 - \alpha_i^{r,p}\right)\alpha_{i'}^{r,p}, \quad \forall 1 \leq p \leq \left|\mathscr{P}^r\right|, 1 \leq r \leq |\mathscr{L}_u|, 1 \leq i, i' \leq |\mathscr{L}_l|, i \neq i'. \tag{7}$$

Constraint (6) ensures that links in one cut-set do not all map onto the same fiber link to fulfill the survivable mapping requirement. Note that this constraint must hold for all fiber links under any cut-set. As an instance, we give constraints under cut-set {2, 3, 4, 5} on Net 0. Using the lightpath sets in Table 1, constraints for fiber links 1 to 7 can be written, respectively, as

$$x^{2,1} + x^{3,2} < 4,$$
$$x^{2,2} + x^{3,1} < 4,$$
$$x^{2,1} + x^{3,2} + x^{4,1} + x^{5,1} < 4,$$
$$x^{4,2} + x^{5,2} < 4,$$
$$x^{3,2} + x^{5,1} < 4,$$
$$x^{2,2} + x^{4,2} < 4,$$

and

$$x^{3,1} + x^{5,2} < 4.$$

Our model uses a flexible objective of fault localization, extended from identifying a single failed fiber link to identifying a minimal set of likely failed fiber links. This is because in practical networks, it may be impossible or too costly to identify an exact failed fiber link from failure symptoms at the IP layer. For example, to uniquely localize any single fiber link failure, it is required that every degree-two optical node in $\mathscr{N}_l$ (such as node M in Fig. 3) must have its corresponding IP node present in the IP topology. Otherwise, as lightpaths traversing one fiber link incident to a degree-two optical node also pass through the other link incident to it, these two fiber links carry the same set of lightpaths (IP links) and thus share the same IP-layer failure symptom. A similar issue was discussed in fault detection and localization with limited monitoring node locations [18]. Our model allows identifying a set of likely failed fiber links, which makes our model generic to any topology inputs satisfying two-link connectivity. In other words, models for unique fault localization, such as [17,18], are special cases of our general model.

A feasible lightpath routing solution to our model determines the interlayer link mapping matrix $\boldsymbol{A}$, whose element a_{ri} can be obtained as

$$a_{ri} = \sum_{p=1}^{|\mathscr{P}^r|} x^{r,p}\alpha_i^{r,p}, \quad \forall 1 \leq r \leq |\mathscr{L}_u|, \; 1 \leq i \leq |\mathscr{L}_l|. \tag{8}$$

With the lightpath sets in Table 1, a feasible routing solution to Net 0 can be written as $x^{1,1} = 1, x^{1,2} = 0, x^{2,1} = 0, x^{2,2} = 1, x^{3,1} = 1, x^{3,2} = 0, x^{4,1} = 1, x^{4,2} = 0, x^{5,1} = 0, x^{5,2} = 1, x^{6,1} = 1$, and $x^{6,2} = 0$. This solution yields the matrix given in (1).

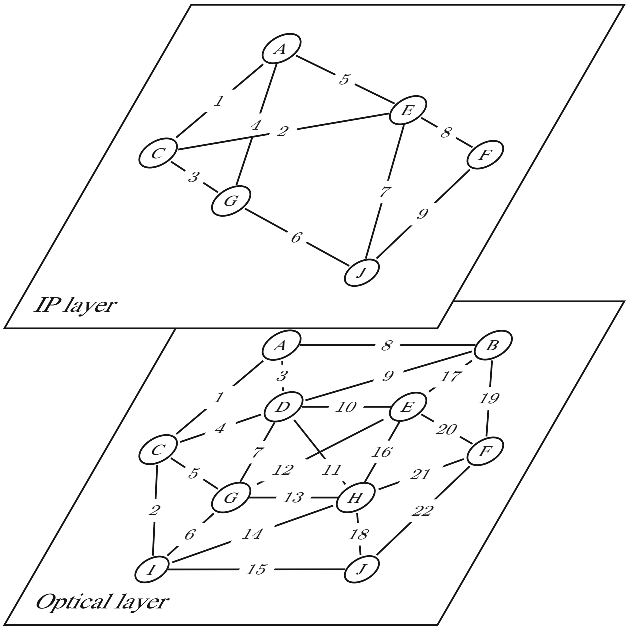

Fig. 2 Net 1 ($|\mathscr{N}_l| = 10$, $|\mathscr{L}_l| = 22$, $|\mathscr{N}_u| = 6$, $|\mathscr{L}_u| = 9$)

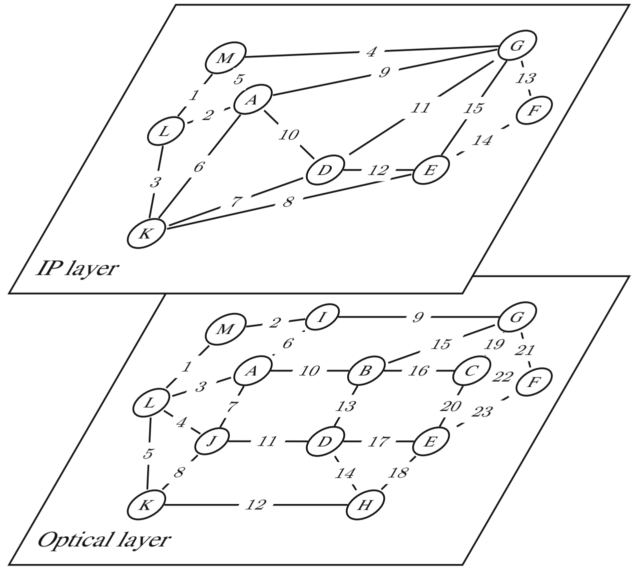

Fig. 3 Net 2 ($|\mathscr{N}_l| = 13$, $|\mathscr{L}_l| = 23$, $|\mathscr{N}_u| = 8$, $|\mathscr{L}_u| = 15$)

3 Numerical results

Our model is evaluated in terms of its fault localization capability, model complexity and scalability, and resource usage efficiency. The performance comparison between the integrated lightpath design and the traditional survivable lightpath routing (i.e., survivable mapping in [13]) has been discussed in [20]. Our main finding is that compared with the traditional survivable lightpath routing, the integrated lightpath design achieves accurate or near-accurate fault localization at the cost of high computational complexity and longer lightpath lengths. Hence, in this paper, we mainly focus on the integrated lightpath design to compare the performance between different modeling methods. Yet, results from the model in [13] are still provided for comparison. Figs. 2 and 3 show the example networks we use for study, which are taken from [12]. Considering the transparent reach limit of an optical signal, we choose moderate-sized networks as the underlying optical networks. For each IP link, up to 20 lightpaths are pre-computed by using the K-shortest path algorithm with the cost of each fiber link set to 1.

Fault detection of fiber links is performed by continuously monitoring the health of all IP links. If a fiber link does not carry any IP link, its failure cannot be detected. For fiber links that carry one or more IP links, upon detection of IP link failures, an IP-layer alarm code can be generated as

$$w = \sum_{r=1}^{|\mathscr{L}_u|} 2^{r-1} v_r, \tag{9}$$

where v_r equals one if IP link r fails and equals zero otherwise. The real-time generated alarm code w is compared with all fiber-link alarm codes, which are pre-defined in contrast. Alarm code for fiber link i ($1 \leq i \leq |\mathscr{L}_l|$) is calculated as

$$u_i = \sum_{r=1}^{|\mathscr{L}_u|} 2^{r-1} a_{ri} = \sum_{r=1}^{|\mathscr{L}_u|} 2^{r-1} \sum_{p=1}^{|\mathscr{P}^r|} x^{r,p} \alpha_i^{r,p},$$
$$\forall\, 1 \leq i \leq |\mathscr{L}_l|, \tag{10}$$

where the second equality follows from (8). If a single match is found, failed fiber link is uniquely identified. If no match is found, an unknown failure occurs. If multiple matches are found, failure is among the links with code match, but the exact failed one cannot be further identified. Note that once the lightpath design is made, alarm codes for all fiber links are determined and fixed. For fiber links whose failures cannot be detected, the corresponding fiber-link alarm codes equal zero. Also, note that we introduce the notion of alarm codes only for the purpose of representing IP-layer failure symptoms in an intuitive way. Such failure symptom information is essentially grounded in and thus fully captured by the interlayer link mapping matrix $\boldsymbol{A}$, where the i-th column gives the set of IP link failures when fiber link i fails. In other words, in practical implementation, the identification of failed fiber links should be solely based on the interlayer link mapping matrix without the need of introducing any alarm coding mechanism.

Tables 2 and 3 show the fiber-link alarm codes obtained from different design models for Net 1 and Net 2, respectively. We observe that our model achieves unique localization of all single fiber link failures for both instances. In contrast, the model in [20] only delivers the same solution quality on Net 1. For Net 2, failures on fiber links 12 and 20 cannot be distinguished. As expected, the model in [13] can-

Table 2 Fiber-link alarm codes for Net 1

i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
u_i of model in [13]	9	**0**	**0**	**2**	12	**0**	**0**	**16**	**0**	**2**	**0**	**0**	**32**	**0**	**0**	**0**	**16**	**32**	**0**	192	**0**	320
u_i of model in [20]	12	8	16	17	18	10	4	5	132	65	192	272	288	66	64	2	128	256	1	257	160	32
u_i of our model	16	12	8	24	3	10	48	1	33	257	256	17	4	258	260	2	128	68	160	320	64	32

Table 3 Fiber-link alarm codes for Net 2

i	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
u_i of model in [13]	1	24	34	**0**	36	272	**0**	**0**	264	512	**0**	192	1536	64	1024	**0**	2048	128	**0**	**0**	20480	**0**	24576
u_i of model in [20]	9	16	8	4	2	512	258	6	528	56	256	**224**	1984	128	1792	248	2048	96	4120	**224**	16384	4096	24576
u_i of our model	1	24	2	36	32	16	544	4	8	256	512	192	1024	64	4352	5120	2048	128	9216	8192	24576	4096	16384

Table 4 Comparisons of model complexity and scalability

	Net 1			Net 2		
	Model in [13]	Model in [20]	Our model	Model in [13]	Model in [20]	Our model
No. of variables	180	11975	433	300	786749	576
No. of constraints	666	1244	919	2902	35739	3178
Run time	0.02 s to obtain optimal solution	Terminate after 5 days	22.15 min to obtain optimal solution	0.16 s to obtain optimal solution	Terminate after 14 days	2.38 s to obtain optimal solution

not identify or uniquely identify failures of a large number of links.

Table 4 compares the complexity and scalability of our model and the models in [13] and [20] in terms of number of variables, number of constraints, and computation time. Optimization models are solved using CPLEX 11.0, running on a computer with an Intel QuadCore processor (3.00 GHz) and 8 GB RAM. We see that our new formulation reduces the model size greatly for both design instances. Specifically, our model contains much fewer variables and constraints than that in [20]. The complexity of our model is quite close to the model in [13] despite its extra capability of fault localization. The explicit benefit follows is that the branch-and-cut algorithm of the solver runs dramatically faster for our model than that in [20]. In particular, on both design instances, the branch-and-cut algorithm finds optimal solutions to our model within reasonable time, that is, 22.15 minutes for Net 1 and 2.38 seconds for Net 2. In contrast, the solver terminates at the preset run-time limit without finding the optimal solutions or proving the solution optimality to the model in [20]. The best solutions reported are recorded instead, as shown in Tables 2 and 3.

Table 5 compares the total number of wavelength channels used to lay out the IP topology. We observe that on Net 1,

Table 5 Total number of wavelength channels required for lightpath routing

	Model in [13]	Model in [20]	Our model
Net 1	14	35	35
Net 2	23	47	31

our model uses the same number of wavelength resources as the model in [20], while on Net 2, the solution to our model uses much fewer wavelengths than that in [20]. This is because our model outperforms the model in [20] in terms of scalability, and thus, the branch-and-cut algorithm finds better solutions within the run-time limit as the network size increases from Net 1 to Net 2. It is also interesting to find that the solution to the model in [20] on Net 1 is actually an optimal one. However, the branch-and-cut algorithm cannot prove the optimality of the solution within the run-time limit due to the much larger size of the model.

4 Conclusions

We proposed a new lightpath design model that incorporates both fault localization and survivable mapping in IP over transparent optical networks. In particular, we formulated the fault localization requirement by proposing a model with a much smaller size. Numerical results show that our new modeling method is far more efficient and scalable than the existing one, resulting in a significantly accelerated lightpath finding process, and more importantly, an improved solution quality. Future work includes enhancing the integrated design in the context of multiple fiber link failures.

References

[1] Chiu, A.L., et al.: Network design and architectures for highly dynamic next-generation IP-over-optical long distance networks. IEEE/OSA J. Lightw. Technol. **27**(12), 1878–1890 (2009)
[2] Chołda, P., Jajszczyk, A.: Recovery and its quality in multilayer networks. IEEE/OSA J. Lightw. Technol. **28**(4), 372–389 (2010)
[3] Markopoulou, A., Iannaccone, G., Bhattacharyya, S., Chuah, C.-N., Ganjali, Y., Diot, C.: Characterization of failures in an operational IP backbone network. IEEE/ACM Trans. Netw. **16**(4), 749–762 (2008)
[4] Doverspike, R., Cortez, B.: Restoration in carrier networks. In: Proceedings of IEEE Workshop on the design of reliable communication networks (DRCN), pp. 45–54 (2009)
[5] Iannaccone, G., Chuah, C.-N., Bhattacharyya, S., Diot, C.: Feasibility of IP restoration in a tier 1 backbone. IEEE Network **18**(2), 13–19 (2004)
[6] Pinart, C.: A multilayer fault localization framework for IP over all-optical multilayer networks. IEEE Network **23**(3), 4–9 (2009)
[7] Kompella, R.R., Yates, J., Greenberg, A., Snoeren, A.C.: IP fault localization via risk modeling. IEEE Trans. Dependable Secure Comput. 7(4) (2010)
[8] Wen, Y., Chan, V.W.S., Zheng, L.: Efficient fault-diagnosis algorithms for all-optical WDM networks with probabilistic link failures. IEEE J. Lightw. Technol. **23**(10), 3358–3371 (2005)
[9] Harvey, N.J.A., Pătraşcu, M., Wen, Y., Yekhanin, S., Chan, V.W.S.: Non-adaptive fault diagnosis for all-optical networks via combinatorial group testing on graphs. In Proceedings of IEEE INFOCOM (2007)
[10] Khair, M., Kantarci, B., Zheng, J., Mouftah, H.T.: Optimization for fault localization in all-optical networks. IEEE/OSA J. Lightw. Technol. **27**(21), 4832–4840 (2009)
[11] Kan, D.D.-J., Narula-Tam, A., Modiano, E.: Lightpath routing and capacity assignment for survivable IP-over-WDM networks. In Proceedings of IEEE workshop on the design of reliable communication networks (DRCN) (2009)
[12] Liu, Y., Tipper, D., Vajanapoom, K.: Spare capacity allocation in multi-layer networks. IEEE J. Sel. Areas Commun. **25**(5), 974–986 (2007)
[13] Modiano, E., Narula-Tam, A.: Survivable lightpath routing: a new approach to the design of WDM-based networks. IEEE J. Sel. Areas Commun. **20**(4), 800–809 (2002)
[14] Kurant, M., Thiran, P.: On survivable routing of mesh topologies in IP-over-WDM networks. In Proceedings of IEEE INFOCOM (2005)
[15] Thulasiraman, K., Javed, M., Xue, G.: Circuits/cutsets duality and a unified algorithmic framework for survivable logical topology design in IP-over-WDM optical networks. In Proceedings of IEEE INFOCOM (2009)
[16] Wen, Y., Chan, V.W.S., Zheng, L.: Efficient fault detection and localization for all-optical networks. In: Proceedings of IEEE GLOBECOM (2006)
[17] Grover, W.D., Grue, A.: Self-fault isolation in transparent p-cycle networks: p-cycles as their own m-cycles. IEEE Commun. Lett. **11**(12), 1004–1006 (2007)
[18] Ahuja, S.S., Ramasubramanian, S., Krunz, M.M.: Single-link failure detection in all-optical networks using monitoring cycles and paths. IEEE/ACM Trans. Netw. **17**(4), 1080–1093 (2009)
[19] Wu, B., Ho, P.-H., Yeung, K.L.: Monitoring trail: on fast link failure localization in all-optical WDM mesh networks. IEEE/OSA J. Lightw. Technol. **27**(18), 4175–4185 (2009)
[20] Ni, W., Ye, Y., Schlosser, M., Patzak, E., Zhang, H.: Survivable mapping with maximal physical-layer failure-localization potential in IP over transparent optical networks. In Proceedings of IEEE/OSA OFC (2010)
[21] Lin, T., Zhou, Z., Thulasiraman, K., Xue, G.: Optimum logical topology routing in an IP-over-WDM optical network and physical link failure localization: an integrated approach. In Proceedings of IEEE Workshop on Reliable Network Design and Modeling (RNDM), pp. 82–88 (2013)

Wenda Ni (S'07-M'11) received his B.Eng. (with excellence) and PhD degree in electronic engineering from Tsinghua University, Beijing, China, in 2005 and 2010, respectively. He is currently a researcher with the Department of Systems and Computer Engineering, Carleton University, Ottawa, Ontario, Canada. His research interests include reliable network design and analysis, passive optical networks, datacenter networking, and decomposition methods for large-scale network optimization. Dr. Ni was a semifinalist in the 2010 Corning Outstanding Student Paper Competition for his paper "Survivable mapping with maximal physical-layer failure-localization potential in IP over transparent optical networks" (10–12 papers out of over 430 student submissions), and a runner-up of the 2013 Fabio Neri Best Paper Award for his paper "Availability of survivable Valiant load balancing (VLB) networks over optical networks." He is serving or served as a TPC member for many international conferences, such as IEEE ICC, IEEE ONDM, IEEE ICNC, and OSA Photonic Networks and Devices.

Changcheng Huang received his B. Eng. in 1985 and M. Eng. in 1988 both in Electronic Engineering from Tsinghua University, Beijing, China. He received a PhD degree in Electrical Engineering from Carleton University, Ottawa, Canada, in 1997. From 1996 to 1998, he worked for Nortel Networks, Ottawa, Canada, where he was a systems engineering specialist. He was a systems engineer and network architect in the Optical Networking Group of Tellabs, Illinois, USA, during the period of 1998 to 2000. Since July 2000, he has been with the Department of Systems and Computer Engineering at Carleton University, Ottawa, Canada, where he is currently a professor. Dr. Huang won the CFI new opportunity award for building an optical network laboratory in 2001.

Jing Wu (M'97-SM'08) obtained a BSc degree in information science and engineering in 1992, and a PhD degree in systems engineering in 1997, both from Xi'an Jiao Tong University, China. He is now an engineer in Environment Canada, Science and Technology Branch, working on data analysis and modeling, statistics, and data mining. In the past, he worked at the Communications Research Centre Canada (Ottawa, Canada), an Agency of Industry Canada as a research scientist; Nortel Networks Corporate (Ottawa, Canada) as a system design engineer; Queen's University (Kingston, Canada) as a postdoctoral fellow; and Beijing University of Posts and Telecommunications (Beijing, China) as a faculty member. Currently, he is also appointed as an Adjunct Professor at the University of Ottawa, School of Electrical Engineering and Computer Science. He has contributed over 70 conference and journal papers. He holds three patents on Internet congestion control, and two patents on control plane failure recovery. Dr. Wu is a member of the technical program committees for many international conferences such as IEEE ICC, IEEE GLOBECOM.