A Novel Framework of Fast and Unambiguous Link Failure Localization via Monitoring Trails

Bin Wu, Pin-Han Ho, János Tapolcai and Xiaohong Jiang

Abstract—**The concept of monitoring trail (m-trail) has been proposed for achieving Fast and Unambiguous Link-failure Localization (FULL) in all-optical WDM (Wavelength Division Multiplexing) mesh networks. Previous studies on m-trails assumed the presence of alarm dissemination at each node such that a remote routing entity can collect the flooded alarm bits and form the alarm code to localize the failed link. This obviously leads to additional delay and extra control complexity in the electronic domain process. In this paper, we propose a novel framework based on m-trails for FULL, aiming at avoiding any possible alarm flooding and electronic domain mechanism such that each individual monitoring node (MN) can localize a single link failure according to locally available alarm bits. To save the supervisory wavelength-links, the proposed framework enables that the status of an m-trail can be monitored by multiple MNs along the m-trail by tapping the optical supervisory signal, rather than only by the destination node of the m-trail. An ILP (Integer Linear Program) is formulated and solved in a case study to verify the ILP and show the effectiveness of the proposed framework. We demonstrate that the status sharing among MNs of a common m-trail can effectively suppress the increase of supervisory wavelength-links as the number of MNs increases.**

Keywords-Failure localization; ILP (Integer Linear Program); monitoring trail (m-trail); Wavelength Division Multiplexing(WDM).

I. INTRODUCTION

WDM (Wavelength Division Multiplexing) allows hundreds of high-speed wavelengths, each with a bandwidth of 40Gbps or above, to be multiplexed onto a single fiber for parallel data transmission. Due to its high-speed nature, even a very short service downtime caused by a single fiber-cut can lead to huge data and revenue loss. Therefore, network survivability against possible link failures is an important issue in all-optical WDM networks [1]. To achieve fast optical recovery against a link failure, it is critical to precisely localize the failure in a timely manner, such that the routing entities can immediately reroute the disrupted traffic to bypass the failed link.

We define *Fast and Unambiguous Link-failure Localization* (FULL) as an optical-layer localization mechanism which can fast and unambiguously identify any possible link failure based on a set of alarm signals observed in the optical domain. Note that all-optical monitoring is the key to achieve fast link failure localization, where no O/E process and signal dissemination should be allowed. Several fast link failure localization schemes have been proposed [2], including simple and non-simple m-cycle [3-7], m-path [4-5] and m-trail [8-9]. Although they differ from each other by adopting different monitoring structures (i.e., simple/non-simple cycles, paths, or trails), a common feature is that each monitoring structure is all-optically pre-cross- connected as a supervisory lightpath to support the transmission of an optical supervisory signal. The on-off status of the optical supervisory signal, as detected by a monitor equipped on each structure, indicates whether or not a link failure event occurs on the structure. By reading the status of a single structure, which denotes a single binary bit of an alarm code (to be discussed in Section II), the failure can be localized to the set of links on the structure (but not yet to the specific failed link) if an "off" status is observed. Generally, a solution consists of a set of monitoring structures. By collecting the status of all the monitoring structures, an alarm code can be generated, and the failure location decision can be made by a table lookup process.

Among all the monitoring structures, m-trail [8-9] is shown to be the most general and flexible one with the best performance, while all other monitoring structures can be taken as special cases. However, previous studies on m-trails set the destination node of each m-trail as the only node that can detect the status of the m-trail using a single monitor, and each m-trail may terminate at a different node from others. Therefore, alarm dissemination/flooding has to be performed at all the destination nodes upon a failure event, such that a remote routing entity can collect the flooded alarms and form the alarm code to localize the failure. We claim that the use of electronic signaling in the alarm bits collecting process makes this approach not qualified as an all-optical monitoring framework. Note that such an issue was addressed in [4] where the number of monitoring nodes (MNs) was taken as a parameter to minimize. However, limited by using simple paths and cycles as monitoring structures, the solution in [4] most likely needs multiple monitoring nodes if the network is not densely meshed enough. It is clear that a practical solution for FULL without any signaling dissemination has never been reported.

In this paper, we propose a novel framework of FULL based on m-trails, where each MN can individually achieve FULL for a single link failure without any alarm dissemination/flooding mechanism. This is achieved by having a sufficient number of m-trails to pass through each MN such that each MN can locally and all-optically form a valid alarm code to achieve FULL. We claim that this is the first work that ensures

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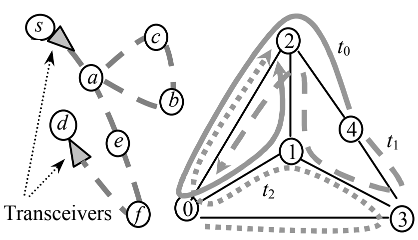
all-optical fault localization at each individual MN. To save supervisory wavelength-links, the proposed framework allows multiple MNs on a common m-trail to share the alarm bit of the m-trail by tapping the optical supervisory signal. By solving a formulated ILP for the proposed framework, we will show that such status sharing can effectively suppress the increase of monitoring resources as the number of MNs increases.

The rest of the paper is organized as follows. Section II briefly reviews existing failure localization schemes. Section III presents the proposed framework based on m-trails. An ILP (Integer Linear Program) is formulated in Section IV to allocate m-trails under the proposed framework. Numerical results are given in Section V. Section VI concludes the paper with some discussions on future work.

II. Literature Review on FULL Schemes

Several existing works [3-6] focus on FULL using simple m-cycles (which can pass through a node at most once). In particular, the studies in [4, 5] used simple paths (m-paths) and cycles (m-cycles) to localize single and SRLG failures. An interesting algorithm was developed to allocate the m-paths and m-cycles one by one. With a goal of minimizing the number of MNs, the performance of this algorithm is significantly limited due to the adoption of very simple monitoring structures. The study in [7] improved the monitoring structure flexibility and used non-simple m-cycles for single link failure localization, aiming at significantly improving the performance by better exploring the connectivity and topology diversity of mesh networks [10]. For example, if a network has $\|\boldsymbol{E}\|$ links and $\|\boldsymbol{V}\|$ nodes and the degree of each node is greater than 2, the algorithms in [3, 6] need $\boldsymbol{O}(\|\boldsymbol{E}\|-\|\boldsymbol{V}\|)$ simple m-cycles in contrast to $\boldsymbol{O}(\log_2\|\boldsymbol{E}\|)$ non-simple m-cycles in [7]. Another study [11] adopts a tree-based monitoring walk to launch probes for fault diagnosis as an upper layer protocol.



Link	t_2	t_1	t_0	Decimal
(0,1)	1	0	1	5
(0,2)	1	1	1	7
(0,3)	1	0	0	4
(1,2)	0	1	1	3
(1,3)	1	1	0	6
(2,4)	0	0	1	1
(3,4)	0	1	0	2

(a) m-trail (b) An m-trail solution (c) Alarm code table

Fig. 1. m-trail based fast link failure localization.

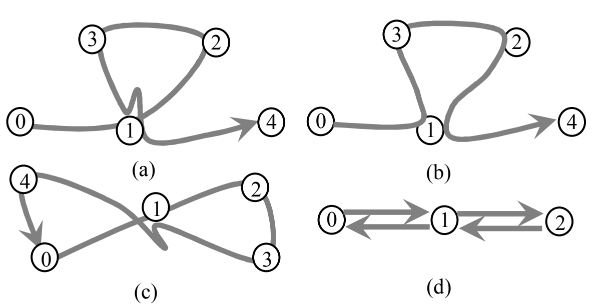


Fig. 2. Monitoring trail structures (open or closed).

Monitoring trails (m-trails) [8] provide the most general and flexible monitoring structures by removing the cycle and tree constraint. In essence, an m-trail is an all-optical supervisory lightpath which can pass through a node multiple times and a directed link once (or once per direction in a bidirectional network). All the previously reported monitoring structures can be taken as a special case of m-trails. For example, simple and non-simple m-cycles are closed m-trails, and m-paths are simple open m-trails. Fig. 1a shows the structure of an m-trail where the optical transmitter and receiver can be equipped at different nodes, and an optical supervisory signal is transmitted in the m-trail. Upon a link failure (as any one in Fig. 1b), any m-trail passing through the failed link will be broken, and a monitor equipped at the destination node of the m-trail will detect Loss of Light (LoL) and issue an alarm, which is denoted by a "1" bit in Fig. 1c. After collecting all the alarms via an electronic signaling mechanism, a remote routing entity can achieve FULL based on the alarm code table in Fig. 1c.

III. Proposed Framework

Since m-trail is the most general and flexible monitoring structure, we propose our framework based on m-trails. Assume that a given set of MNs in the network need to achieve FULL against a single link failure. Our target is to let each MN be able to locally collect sufficient alarm information in optical domain to form a valid alarm code such that FULL can be achieved at this node. This essentially removes the alarm dissemination and collection process in the previous m-trail failure localization framework. In the example of Fig. 1b under the original m-trail framework, the two monitors equipped at node 2 for m-trails t_0 and t_2 can observe two bits of the alarm code, and the other bit is observed by the monitor equipped at node 0 for t_1. A node needs to collect all the three bits for FULL due to the dispersal of the alarm code bits. Such an alarm dissemination/flooding mechanism not only increases the failure localization latency, but also takes electronic signaling which breaks the premise of all-optical failure localization.

Motivated by the above observation, we extend the original m-trail framework [8] by ensuring every MN to individually achieve FULL without taking any electronic signaling and dissemination mechanism. Note that a MN can only detect the alarm bits issued by those m-trails passing through it. To save supervisory wavelengths, the proposed framework allows multiple MNs on an m-trail to share the status of the m-trail by tapping the optical supervisory signal. To ensure the operability in terms of optical power, we can further limit the number of MNs on each m-trail. With a set of properly allocated m-trails, every MN will be able to locally receive sufficient alarm code bits to achieve FULL in an all-optical manner.

It is possible that a MN uses the on-off status of some existing working lightpaths to achieve FULL. However, it is not considered in the proposed framework due to the dynamic nature of the working lightpaths which may lead to frequent reconfiguration of m-trail allocation. In addition, the information leakage on the status of working lightpaths between control and data planes will significantly complicate the monitoring resource deployment.

Basically, we should consider a general scenario in directed WDM networks using both open and closed m-trails. However, the m-trail allocation problem in this general scenario is very complex. In Figs. 2a-2c, assume that both nodes 2 and 4 are MNs and link (1, 3) fails. For the m-trail pre-cross-connected in Fig. 2a, only node 4 can detect the off status of the optical supervisory signal, because node 2 is an upstream node of the failed link (1, 3). If the m-trail is pre-cross-connected as in Fig. 2b, both node 2 and node 4 can detect the off status. This example shows that we have to formulate the pre-cross-connection pattern of the m-trails in order to properly describe the status sharing relationship among the MNs, which will dramatically complicate the design. On the other hand, this issue will be removed if the m-trail is in a shape of a cycle (i.e., a closed m-trail). For example, if link (1, 3) in Fig. 2c fails, both node 2 and node 4 can detect the off status of the closed m-trail. Although node 2 is an upstream node of the failed link, node 0 (which is both the source and the destination of the closed m-trail) will disable the transmission of optical supervisory signal when it detects a Loss of Light on the m-trail, and thus the off status can also be detected by node 2. Therefore, if an m-trail is closed, every MN on the m-trail can share the status of the m-trail no matter how the m-trail is pre-cross-connected. To simplify the design, we consider the simplified scenario in bidirectional WDM networks using only closed m-trails. Accordingly, a linear monitoring structure, such as 0—1—2 in Fig. 2d, will be treated as a closed m-trail 0→1→2→1→0.

IV. ILP Formulation

In this section, we formulate an ILP for m-trail allocation under the proposed framework. In our ILP, each supervisory wavelength-link on an m-trail is denoted by a directed *on-trail vector* (vector for short), where the direction of the vector gives the direction of the optical supervisory signal. *Decimal alarm code* [7-9] is adopted, which is a decimal translation of the corresponding binary alarm code as shown in Fig. 1c. The ILP is formulated based on the Voltage Analysis and the technique for ensuring unambiguous localization in [8]. Since those concepts and techniques have been well-established in [7, 8], in this paper we only give brief description on them. Readers may refer to [2, 7, 8] for more details.

Input Parameters:

- J: The maximum number of m-trails allowed in the solution.
- j: m-trail index where $j\in\{0, 1, \ldots, J-1\}$.
- $\boldsymbol{E}$: The set of all the links in the network.
- $\boldsymbol{V}$: The set of all the nodes in the network.
- $\boldsymbol{M}$: A given set of MNs.
- c_{uv}: Predefined cost of a supervisory wavelength on link (u, v). Either hop-count or distance-related cost can be used (hop-count is used in this paper).
- L: Predefined length limit of each m-trail.
- T: Maximum number of MNs on each m-trail.
- γ: Predefined cost ratio of a monitor to a supervisory wavelength-link.
- λ: A predefined small positive value ($\|\boldsymbol{E}\|^{-1}/2\geq\lambda>0$). It is the minimum step of voltage increase in the voltage constraint.
- β: A predefined small constant and $2^{-J}\geq\beta>0$.

Decision Variables:

- e^j_{uv}: Binary variable. It takes 1 if $u\rightarrow v$ is an on-trail vector of m-trail t_j, and 0 otherwise.
- l^j_{uv}: Binary variable. It takes 1 if m-trail t_j has at least one on-trail vector (either $u\rightarrow v$ or $v\rightarrow u$, or both) on link (u, v), and 0 otherwise.
- r^j_u : Binary variable. It takes 1 if node u is the root node of m-trail t_j, and 0 otherwise.
- z^j_u: Binary variable. It takes 1 if node u is traversed by m-trail t_j, and 0 otherwise.
- q^j_{uv} : Nonnegative fractional variable. It is the voltage of vector $u\rightarrow v$ on m-trail t_j. It takes 0 if $u\rightarrow v$ is not an on-trail vector of t_j.
- s^{jk}_{uv} : Binary variable. It takes 1 if MN k detects an off status on m-trail j due to a failure at link (u, v), and 0 otherwise.
- α^k_{uv}: General integer variable. It is the decimal alarm code of link (u, v) observed at MN k.
- $f^k_{uv/xy}$: Binary variable. For two distinct links (u, v) and (x, y), it takes 1 if $\alpha^k_{uv}>\alpha^k_{xy}$, and 0 if $\alpha^k_{uv}<\alpha^k_{xy}$.

Objective Function:

$$\text{minimize}\left\{\gamma\sum_j\sum_{k\in\boldsymbol{M}}z^j_k+\sum_j\sum_{(u,v)\in\boldsymbol{E}}c_{uv}\left(e^j_{uv}+e^j_{vu}\right)\right\};\qquad(1)$$

Similar to [7-8], the objective of our design is to minimize the total cost of all monitors and supervisory wavelength-links. The difference is that the total number of all monitors in the new framework is obtained by summing up the number of MNs on each m-trail.

Closed m-Trail Formulation Constraints:

$$\sum_{(u,v)\in\boldsymbol{E}}\left(e^j_{uv}-e^j_{vu}\right)=0,\qquad\forall u\in\boldsymbol{V},\ \forall j;\qquad(2)$$

$$\sum_{u\in\boldsymbol{V}}r^j_u\leq 1,\qquad\forall j;\qquad(3)$$

$$\sum_{u\in\boldsymbol{V}}r^j_u\leq\sum_{u\in\boldsymbol{V}}z^j_u,\qquad\forall j;\qquad(4)$$

$$z^j_u\geq e^j_{uv},\qquad\forall u\in\boldsymbol{V}:(u,v)\in\boldsymbol{E},\ \forall j;\qquad(5)$$

$$z^j_u\leq\sum_{(u,v)\in\boldsymbol{E}}e^j_{uv},\qquad\forall u\in\boldsymbol{V},\ \forall j;\qquad(6)$$

$$q^j_{uv}\leq e^j_{uv},\ q^j_{vu}\leq e^j_{vu},\qquad\forall(u,v)\in\boldsymbol{E},\ \forall j;\qquad(7)$$

$$r^j_u+\sum_{(u,v)\in\boldsymbol{E}}\left(q^j_{uv}-q^j_{vu}\right)\geq\lambda\times z^j_u,\qquad\forall u\in\boldsymbol{V},\ \forall j;\qquad(8)$$

Constraint (2) defines closed m-trails by requiring each node to have an equal number of inbound and outbound vectors. Since this constraint may lead to multiple disjoint closed m-trails, the Voltage Analysis technique in [8] is used to ensure a single m-trail t_j by excluding others. In particular, constraints (3)-(4) define a single *root node* in each *non-empty m-trail* t_j (a non-empty m-trail must have some on-trail nodes). Constraints (5)-(6) check whether a node u is on m-trail t_j. Constraint (7) assigns a *voltage* value to each vector. Then, the *voltage constraint* (8) ensures that all disjoint closed trails without passing through the root node will be excluded, and thus a single m-trail t_j can be obtained [8].

MN Constraints:

$$l_{uv}^{j} \le e_{uv}^{j} + e_{vu}^{j}, \qquad \forall (u,v) \in \boldsymbol{E}, \ \forall j; \tag{9}$$

$$l_{uv}^{j} \ge \frac{1}{2}\left(e_{uv}^{j} + e_{vu}^{j}\right), \qquad \forall (u,v) \in \boldsymbol{E}, \ \forall j; \tag{10}$$

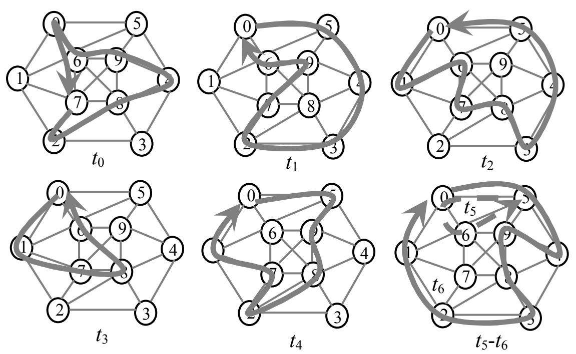
$$s_{uv}^{jk} \le l_{uv}^{j}, \qquad \forall (u,v) \in \boldsymbol{E}, \ \forall j, \ \forall k \in \boldsymbol{M}; \tag{11}$$

$$s_{uv}^{jk} \le z_{k}^{j}, \qquad \forall (u,v) \in \boldsymbol{E}, \ \forall j, \ \forall k \in \boldsymbol{M}; \tag{12}$$

$$s_{uv}^{jk} \ge l_{uv}^{j} + z_{k}^{j} - 1, \qquad \forall (u,v) \in \boldsymbol{E}, \ \forall j, \ \forall k \in \boldsymbol{M}; \tag{13}$$

$$\sum_{u \in V} r_{u}^{j} \le \sum_{k \in M} z_{k}^{j}, \qquad \forall j; \tag{14}$$

Constraints (9)-(10) check whether an m-trail t_j passes through a particular link (u, v). From constraints (11)-(13), the necessary and sufficient condition for a MN k to detect the off status of m-trail t_j upon a link failure at (u, v) is that both link (u, v) and node k are on m-trail t_j. Constraint (14) means that a non-empty m-trail must pass through at least one MN.



$\boldsymbol{M}$={0}, cost=54=7m+47w, $\boldsymbol{A}$=[$\boldsymbol{A_0}$]=[$\alpha_{01}^{0}, \alpha_{05}^{0}, \alpha_{06}^{0}, \alpha_{12}^{0}, \alpha_{16}^{0}, \alpha_{17}^{0}, \alpha_{23}^{0}, \alpha_{27}^{0}, \alpha_{28}^{0}, \alpha_{34}^{0}, \alpha_{38}^{0}, \alpha_{45}^{0}, \alpha_{48}^{0}, \alpha_{49}^{0}, \alpha_{56}^{0}, \alpha_{59}^{0}, \alpha_{67}^{0}, \alpha_{68}^{0}, \alpha_{69}^{0}, \alpha_{78}^{0}, \alpha_{79}^{0}, \alpha_{89}^{0}$]=[92, 118, 43, 64, 4, 24, 66, 19, 17, 6, 68, 70, 1, 65, 32, 16, 5, 8, 3, 12, 2, 80]

Fig. 3. SmallNet topology with a single monitoring node 0.

Unambiguous Localization Constraints:

$$\alpha_{uv}^{k} = \sum_{j} 2^{j} s_{uv}^{jk}, \qquad \forall (u,v) \in \boldsymbol{E}, \ \forall k \in \boldsymbol{M}; \tag{15}$$

$$\alpha_{uv}^{k} \ge 1, \qquad \forall (u,v) \in \boldsymbol{E}, \ \forall k \in \boldsymbol{M}; \tag{16}$$

$$\beta + \beta\left(\alpha_{uv}^{k} - \alpha_{xy}^{k}\right) \le f_{uv/xy}^{k}, \quad \forall (u,v),(x,y) \in \boldsymbol{E} : (u,v) \ne (x,y), \ \forall k \in \boldsymbol{M}; \tag{17}$$

$$\beta + \beta\left(\alpha_{xy}^{k} - \alpha_{uv}^{k}\right) \le 1 - f_{uv/xy}^{k}, \quad \forall (u,v),(x,y) \in \boldsymbol{E} : (u,v) \ne (x,y), \ \forall k \in \boldsymbol{M}; \tag{18}$$

Constraint (15) translates binary alarm codes to decimal ones. Constraint (16) requires each decimal alarm code to be larger than 0. Constraints (17)-(18) ensure unambiguous link failure localization at each MN [8].

Optional Constraints:

The following optional constraints can be used to limit the length and the number of MNs of each m-trail.

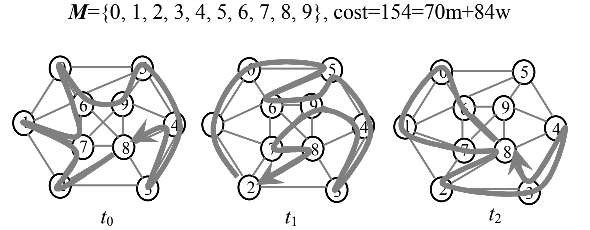
$$\sum_{(u,v) \in \boldsymbol{E}} \left(e_{uv}^{j} + e_{vu}^{j}\right) \le L, \qquad \forall j; \tag{19}$$

$$\sum_{k \in \boldsymbol{M}} z_{k}^{j} \le T, \qquad \forall j. \tag{20}$$

V. Numerical Results

We consider SmallNet [3] with 10 nodes and 22 links in Figs. 3 & 4. The ILP is solved in sufficiently long time to get good feasible solutions using CPLEX 11.0 on a high-end Dell dual-core workstation. Figs. 3 & 4 show the solutions for two extreme cases, with a single MN $\boldsymbol{M}$={0} as in Fig. 3 and all nodes as MNs as in Fig. 4. The cost is optimized based on (1) where we set γ=1 and c_{uv}=1 for each link (u, v). Let a and b be the total number of monitors and supervisory wavelength-links required in the solution, respectively. In Figs. 3 & 4, am+bw means that a monitors and b supervisory wavelength-links are required in total, and $\boldsymbol{A_k}$ is the decimal alarm code vector as observed at MN k. Note that in our previous works [7-8] we put great emphasis on minimizing the total number of monitors required. Under the new framework in this paper, each MN achieves FULL in a distributed manner according to the locally observed optical signals. As a result, a large number of monitors (due to the increase of the number of MNs as in Fig. 4) is no longer an issue, because it will not complicate alarm

$\boldsymbol{M}$={0, 1, 2, 3, 4, 5, 6, 7, 8, 9}, cost=154=70m+84w



$\boldsymbol{A} = [\boldsymbol{A_0}; \dots; \boldsymbol{A_9}] =$

$\boldsymbol{A_k}$	α_{01}^{k}	α_{05}^{k}	α_{06}^{k}	α_{12}^{k}	α_{16}^{k}	α_{17}^{k}	α_{23}^{k}	α_{27}^{k}	α_{28}^{k}	α_{34}^{k}	α_{38}^{k}	α_{45}^{k}	α_{48}^{k}	α_{49}^{k}	α_{56}^{k}	α_{59}^{k}	α_{67}^{k}	α_{68}^{k}	α_{69}^{k}	α_{78}^{k}	α_{79}^{k}	α_{89}^{k}
$\boldsymbol{A_0}$	582	130	709	706	128	133	516	1	71	647	132	131	513	2	514	3	193	196	579	6	66	512
$\boldsymbol{A_1}$	582	130	709	722	144	133	516	17	71	647	132	131	513	2	530	19	193	196	579	6	82	512
$\boldsymbol{A_2}$	582	130	709	722	144	133	516	17	71	647	132	131	513	2	530	19	193	196	579	6	82	512
$\boldsymbol{A_3}$	518	130	645	642	128	133	516	1	7	935	164	131	513	34	514	3	129	132	515	6	2	544
$\boldsymbol{A_4}$	518	130	645	642	128	133	516	1	7	935	164	131	513	34	514	3	129	132	515	6	2	544
$\boldsymbol{A_5}$	514	130	641	658	144	129	512	17	3	643	128	131	513	2	538	27	137	136	515	10	18	520
$\boldsymbol{A_6}$	582	130	709	722	144	133	516	17	71	647	132	131	513	2	538	27	201	204	579	14	82	520
$\boldsymbol{A_7}$	70	130	197	210	144	133	4	17	71	135	132	131	1	2	26	27	201	204	67	14	82	8
$\boldsymbol{A_8}$	582	130	709	706	128	133	516	1	71	679	164	131	513	34	522	11	201	204	579	14	66	552
$\boldsymbol{A_9}$	578	2	577	594	16	1	512	17	67	547	32	3	513	34	538	27	73	72	579	10	82	552

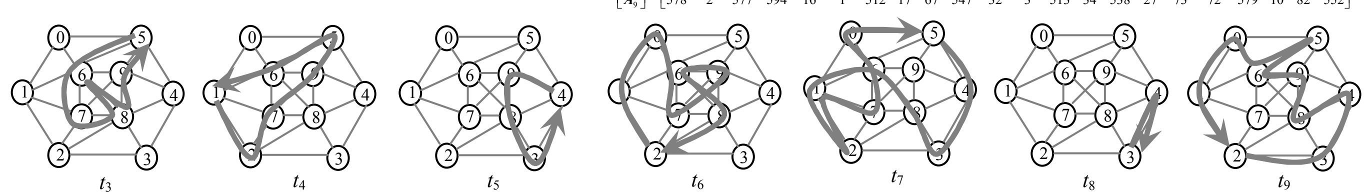
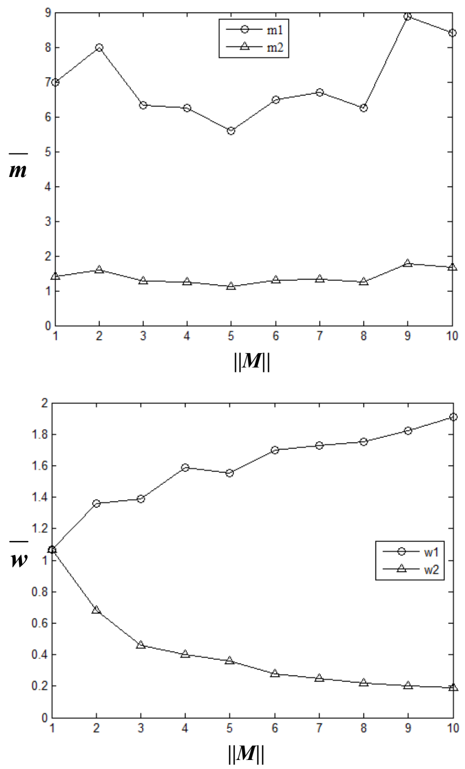


Fig. 4. SmallNet topology with all nodes as monitoring nodes.



Experiments in SmallNet based on $\boldsymbol{M}$={0}, {0,3}, {0, 4, 7}, {0, 1, 3, 9}, {0, 2, 4, 6, 8}, {0, 2, 4, 7-9}, {0, 2, 4, 6-9}, {0-7}, {0-8} and {0-9}.

Fig. 5. The trend of $\overline{\boldsymbol{m}}$ and $\overline{\boldsymbol{w}}$ as $\|\boldsymbol{M}\|$ increases.

management at each individual node.

Define $\overline{\boldsymbol{m}}=\{m_1, m_2\}$ and $\overline{\boldsymbol{w}}=\{w_1, w_2\}$ where $m_1=a/\|\boldsymbol{M}\|$, $m_2=m_1/(\lfloor\log_2\|\boldsymbol{E}\|\rfloor+1)$ [7, 8], $w_1=b/\|2\boldsymbol{E}\|$ (each bidirectional link is counted as two directed links) and $w_2=w_1/\|\boldsymbol{M}\|$. Fig. 5 shows how $\overline{\boldsymbol{m}}$ and $\overline{\boldsymbol{w}}$ change with the number of MNs $\|\boldsymbol{M}\|$. We can see that when $\|\boldsymbol{M}\|$ increases, m_1 remains quite stable and is close to $\lfloor\log_2\|\boldsymbol{E}\|\rfloor+1$ [7-9] as shown by m_2. Although w_1 increases moderately (which is indeed the cost for removing the dissemination of alarm bits), w_2 actually decreases which shows the capacity efficiency on supervisory wavelength-links by allowing status sharing among multiple MNs on the same m-trail.

VI. Conclusion and Future Works

The paper introduced a novel framework for Fast and Unambiguous Link-failure Localization (FULL) based on m-trails. The proposed framework is characterized by completely removing any electronic signaling mechanism that was required in the previously reported counterparts. As a result, the failure localization latency can be significantly reduced at each monitoring node (MN). Under the proposed framework, each MN can individually achieve FULL by observing the locally available m-trail status. To save supervisory wavelengths, the proposed framework allows multiple MNs on an m-trail to share the status of the m-trail by tapping the same optical supervisory signal. An ILP was formulated for the proposed framework by employing closed m-trails, and was solved in a case study. The results verified the formulated ILP model and demonstrated the feasibility of the framework. Interestingly, we found that the status sharing among MNs on the same m-trail effectively suppressed the increase of monitoring resources when the number of MNs increases.

There are a number of distinguished future topics under the proposed framework: 1) the ILP solution can hardly reach optimality. To provide an accurate benchmark for our future research, we will try to improve our ILP model to make it more computationally efficient; 2) efficient heuristic algorithms will be developed that can complement the ILP model; 3) with a fast heuristic algorithm, we will investigate whether the average number of required monitors per monitoring node (i.e., $\overline{m}$) still remains stable and the number of supervisory wavelength-links still increases moderately with the number of MNs in large-size networks with various topologies; 4) a more general framework will be considered by defining a *monitoring set*. The nodes in a common monitoring set are allowed to exchange alarm bits they detected respectively via signaling dissemination. This is practical since a monitoring set can be a set of adjacent nodes such that the extra delay due to alarm dissemination among them is tolerable; and 5) most importantly, those frameworks should be considered in the more general scenario of directed WDM networks using both closed and open m-trails, and both ILP models and heuristics are of significant importance for performance investigations and real applications.

References

[1] J. Li and K. L. Yeung, "A novel two-step approach to restorable dynamic QoS routing," *IEEE Journal of Lightwave Technology*, vol. 23, no. 11, pp. 3663-3670, Nov. 2005.

[2] B. Wu, P.-H. Ho, K. L. Yeung, J. Tapolcai, "Optical layer monitoring schemes for fast link failure localization in all-optical networks," *IEEE Communications Surveys and Tutorials*, to appear.

[3] H. Zeng, C. Huang and A. Vukovic, "A novel fault detection and localization scheme for mesh all-optical networks based on mmonitoring-cycles," *Photonic Network Communications*, vol. 11, no. 3, pp. 277-286, May 2006.

[4] S. 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, no. 4, pp. 1080-1093, Aug. 2009.

[5] S. S. Ahuja, S. Ramasubramanian and M. Krunz, "SRLG failure localization in all-optical networks using monitoring cycles and paths," *in Proc. IEEE INFOCOM '08*, pp. 700-708, Apr. 2008.

[6] B. Wu and K. L. Yeung, "M^2-CYCLE: an optical layer algorithm for fast link failure detection in all-optical mesh networks," *in Proc. IEEE GLOBECOM '06*, Dec. 2006.

[7] B. Wu, K. L. Yeung and P.-H. Ho, "Monitoring cycle design for fast link failure localization in all-optical networks," *IEEE/OSA Journal of Lightwave Technology*, vol. 27, no. 10, pp. 1392-1401, May 2009.

[8] B. Wu, P.-H. Ho and K. L. Yeung, "Monitoring trail: on fast link failure localization in WDM mesh networks," *IEEE/OSA Journal of Lightwave Technology*, vol. 27, no. 18, pp. 4175-4185, Sept. 2009.

[9] J. Tapolcai, B. Wu and P.-H. Ho, "On monitoring and failure localization in mesh all-optical networks," *in Proc. IEEE INFOCOM '09*, Apr. 2009.

[10] B. Wu, K. L. Yeung and P.-H. Ho, "ILP formulations for non-simple *p*-cycle and *p*-trail design in WDM mesh networks," *Elsevier Computer Networks*, to appear.

[11] N. J. A. Harvey, M. Patrascu, Y. G. Wen, S. Yekhanin and V. W. S. Chan, "Non-adaptive fault diagnosis for all-optical networks via combinatorial group testing on graphs," *in Proc. IEEE INFOCOM '07*, pp. 697-705, May 2007.