Monitoring and Failure Localization in the Optical Internet Backbone

I Recent Progress in Research Activities Related to the Proposal

We identified a missing piece in the proposed research in how a source node can instantly and precisely identify the failed Shared Risk Link Group (SRLG) that affects its connections, such that proper alternative routes can be found for traffic recovery. Thus, we have engaged in extensive research activities in the area of failure localization in all-optical mesh Wavelength Division Multiplexing (WDM) networks in the past 3 years, and would like to continue the topic in the near future, as it is a highly desired while insufficiently exploited feature reported in the literature and state-of-the-art industry deployment. The published and accepted research results are listed as [1-10].

The proposed research in this NSERC Discovery Grant competition is on localization for SRLG failures via out-of-band monitoring in all-optical mesh WDM networks, and then to come up with a new framework of survivable routing for failure-dependent protection (FDP). Failure localization via out-of-band monitoring has long been studied in communication networks. In general, a set of supervisory lightpaths (S-LPs) is deployed in the network; and each S-LP is closely monitored by a *monitor* equipped at the receiver of the S-LP, which generates an alarm if it detects any irregularity (e.g., loss of light (LoL)). The alarm is then broadcast in the control plane with the highest priority. Here, an alarm is a binary bit representing the on-off status of the corresponding S-LP. The network controller thus can collect the flooded alarm bits and form an *alarm code.* Assume there are a number of b S-LPs, which lead to each alarm code of b bits in length. A necessary condition for the feasibility of the set of b S-LPs to achieve *unambiguous failure localization* (UFL) is that one-to-one mapping exists between all the considered failure events and alarm codes. With such one-to-one mapping, failure of any SRLG would result in a unique alarm code which is distinguished from any other. Thus, the network controller can read the alarm code and localize the failed SRLG. Clearly, the length of the alarm codes should be at least $\log_2(m+1)$, where m is the number of SRLGs considered in the failure localization plane.

With the above system description, it immediately comes up with a problem: *given a set of SRLGs and the network topology, how will we allocate/route a set of S-LPs such that every single SRLG failure corresponds to a unique non-zero alarm code*? As a research group pioneering on this topic, we investigated the S-LP allocation problem by formulating it as a *topology coding* and *constrained multi-path routing* task. We have studied various structures of S-LPs under different networking scenarios, such as that using non-simple cycles [1], non-simple trails [2-8], and trees [9,10], with the objectives of reducing the number of S-LPs and required wavelength-links (WLs). We have considered different SRLG scenarios, such as single-link SRLGs [1-5,7], sparse SRLGs [8,9], SRLGs with all/some adjacent links to each node [6], and dense SRLGs with up to d links [10]. A preliminary study on a signaling-free framework was proposed in [5].

In general, the above studies first ensure that each SRLG is assigned a unique non-zero alarm code, while the S-LPs are routed based on the codes. The key difficulty is that the alarm codes are assigned to links while the alarm code of an SRLG is the bitwise OR of its link codes. We discovered that a feasible S-LP solution should accomplish the following two tasks: (1) ensuring SRLG alarm code uniqueness; (2) ensuring formation/routing of the S-LPs according to the link codes. For (1), the link codes must be not only distinguished from each other but also with sufficient Hamming distance, such that their respective SRLGs can be uniquely coded. After each link being assigned a code, the task of S-LP allocation follows as pointed out in (2). Let the code assigned to link e be $A_e = [a_{e,1}, a_{e,2}, ...a_{e,b}]$ where $a_{e,j} = \{0,1\}, 1 \le j \le b$. Let L_j denote the j-th *link set* which contains a set of links with $a_{e,j} = 1$. The j-th S-LP should be routed such that it traverses through every link e with $a_{e,j} = 1$ while disjoint from any link f with $a_{f,j} = 0$. The tasks (1) and (2) ensure that any SRLG failure event will trigger alarms in a unique set of S-LPs, which forms a unique alarm code different from that by any other.

II Objectives

The project is committed to study failure localization problem in all-optical mesh networks via out-of-band monitoring, and our long-term objective is to achieve a comprehensive framework of survivable routing for high-availability service provisioning. We will develop a suite of distributed and autonomous schemes to provide viable solutions for all-optical network failure localization that can push the frontier of the state-of-the-art techniques. The short-term research goals of the project are listed as follows:

(1) Investigate the scenario of Local UFL (L-UFL) and the corresponding S-LP allocation problems.
(2) Investigate monitoring burst (M-Burst) for all-optical mesh network failure localization.
(3) Integrate failure localization techniques into the design of failure-dependent protection (FDP) schemes.

III Literature Review

Extensive research efforts have been made to explore the structures of S-LPs and solutions to the S-LP allocation problem under different design scenarios. Monitoring Cycle (m-cycle) was first proposed in [12] by using a set of simple cycles to cover the network topology for localization of any single link failure. Non-simple m-cycle which can pass through a node multiple times, were studied in [1] and positioned as a better way to explore the network connectivity due to the more flexible monitoring structure. Monitoring trail (or m-trail) was introduced and analyzed in [2-8], where the cycle constraint as in m-cycles was removed. It is shown in [2] that simple cycle is a special case of non-simple cycle, and both simple and non-simple cycles are special cases of trails. [5] and [6] investigated the UFL scenario of sparse SRLGs using m-trails, where an ILP was developed in [5], and an intelligent heuristic algorithm was proposed in [6] for adjacent links failure localization. Besides using undirected lightpaths, some studies assumed bi-directional S-LPs with loopback switching, where m-tree was firstly studied in [13] and further explored in [7,9,10] for SRLGs with up to d links. [14] has considered the failure localization scenario for SRLGs with up to d links using m-cycles, with a focus on minimizing the number of monitoring nodes (MNs) solely based on the network topology. Here, an MN is a node at each one or multiple S-LPs are terminated and monitored. [15] exploited monitoring systems built upon existing working lightpaths with a goal of minimizing the number of active monitors under a hierarchical structure.

The studies on FDP appeared extensively in the literature such as [18-20], where the restoration path selection and spare capacity allocation take place after the failure event is identified. Obviously, FDP can take full advantage of failure localization for achieving much improved capacity efficiency, at the expense of higher control and management complexity. To the best of our knowledge, most (if not all) of the FDP related research efforts have assumed the ability of fast and precise failure localization in the network. Nonetheless, the proposed project is to position and integrate the failure localization mechanism into the FDP design.

IV Proposed Research

IV.A *Network-Wide Local UFL (NWL-UFL)*

We propose a novel scenario of all-optical failure localization via out-of-band monitoring approach in the project, called *Network-Wide Local UFL* (NWL-UFL), which is characterized by completely operating in the optical domain without taking any control plan signalling. Here we define *Local UFL* (L-UFL) at a node if the node can individually perform UFL based on locally available on-off status of the traversing S-LPs; and thus *Network-Wide Local UFL* (NWL-UFL) can be achieved in the optical domain if all the nodes are L-UFL capable. By assuming any node on an S-LP can obtain the on-off status of the S-LP via optical signal tapping, the proposed NWL-UFL scenario targets at minimizing the total supervisory wavelength-links (WLs) in the

S-LP allocation solution. It is clear that the number of S-LPs is no longer of interest under NWL-UFL, because the number of S-LPs stands for the number of alarm bits that need to be collected, which is only a valid target when alarm dissemination is needed in the alarm collection process.

The proposed NWL-UFL problem using S-LPs is formally defined as follows. Given an undirected graph $G = (V, E)$ with node set V (with a size of $n = |V|$) and link set E, the NWL-UFL S-LP allocation problem is to establish a set of b S-LPs with the minimum cover length, denoted by $T = \{t_1, \ldots, t_b\}$ where $b = |T|$ is the number of S-LPs, such that each S-LP t_i satisfies a specific *connectivity requirement*, and each node $v_j \in V$ can achieve L-UFL according to the on-off status of the S-LPs in T^j - a subset of T containing the S-LPs passing through v_j. The total cover length is denoted by $\|T\|$ and is defined as the total number of WLs taken by T. Formally, $\|T\| = \sum_{j=1}^{n} |t_j|$, where $|t_j|$ is the number of links on t_j.

The connectivity requirement in the above problem definition is determined by desired structure of the S-LPs. For example, each S-LP can simply be a connected subgraph of G if bi-directed lightpaths with loopback switching are launched [7,10,13]. Accordingly, an S-LP of undirected m-trail [2-6,8,9] should be a connected subgraph of G with no more than two odd-degree nodes; an S-LP of simple m-cycle [12] should have all the on-cycle nodes with a nodal degree 2; while an S-LP of non-simple m-cycle [1] should have all on-cycle nodes with an even nodal degree. The specific research topics under the NWL-UFL framework are listed as follows.

(1) Develop necessary and sufficient conditions for the existence of NWL-UFL solutions in general k-connected topologies with a given set of SRLGs. Based on the conditions, develop fast heuristic algorithms for solving the S-LP allocation problem under various SRLG scenarios (i.e., single-link, dense SRLG and sparse SRLG), various S-LP structures (i.e., simple and non-simple cycles, trails, and trees), and/or other constraints/requirements (e.g., reuse of existing working lightpaths, localization of fibers with physical impairments, and link delay monitoring and estimation).

(2) Develop optimal solutions via polynomial-time deterministic constructions on the cover length of S-LP solutions for some special topologies, such as rings, line graphs, stars, and complete graphs.

IV.B *Monitoring Burst* (*M-Burst*)

Out-of-band monitoring via static NWL-UFL S-LPs can surely provide instant and precise failure localization functions. However, it may consume a large number of WLs when the number of considered SRLGs is large. Our study [10] showed that it takes over 10 WLs along each link when bi-directional S-LPs with a tree structure are deployed for localizing any SRLG with up to 3 links. To consider the scenarios with very dense SRLGs, we propose a novel failure localization structure called *monitoring bursts* (m-burst), aiming to compromise the monitoring responsiveness and signaling efforts with the required monitoring resources. With m-burst, an MN is allocated with a set of close-loop S-LPs that pass through the MN (or referred to as *L-UFL m-cycles*). The MN launches optical bursts with a duration δ along the L-UFL m-cycles to detect the on-off status of each m-cycle. The burst length δ is determined by switching speed at each node and the required system robustness. A launched burst returns to the MN via the m-cycle if all the fiber links along the m-cycle are good, while getting lost if any of them failed. Thus, an m-burst MN determines each bit of the alarm code based on whether or not the corresponding burst returns to the MN at the expected time instant.

With static S-LPs, k WLs are consumed at a link if k S-LPs pass through the link. With m-bursts, nonetheless, the monitoring resources can be much reduced by time-domain multiplexing of burst traversals of different m-cycles along a WL. For example, a link can be allocated with a single WL in the above case if traversal time of the k bursts can be properly multiplexed at the WL. This can obviously save a great number of WLs in an m-cycle solution, while at the expense of longer delay in collecting the bursts at the MN as well as the signalling effort required to manipulating the burst switching at the intermediate nodes of each m-cycle.

The proposed m-burst has a prerequisite that any burst loss should be due to link failure instead of any other reason such as burst collision; otherwise the MN would be falsely alarmed. Thus, an immediate problem comes up in the proposed m-burst framework: *how will we avoid any burst collision, or at least, how will we distinguish a burst loss event due to burst collision from that due to link failure?* To solve the problem, the project plans to investigate the following research topics that are essential to the proposed m-burst framework:

(1) **Develop light-weighted resource reservation scheme and signalling mechanism for collision-free and bufferless burst multiplexing**. We plan to borrow the idea of Just-in-Time (JIT) algorithm [17] that takes advantage of *tell-and-go* signalling and *delayed reservation* mechanism in the context of optical burst switched (OBS) networks. We will conduct a thorough analysis on the feasibility of the proposed signalling protocol along with its performance in terms of signalling overhead.

(2) **Develop, analyze, and evaluate scheduling algorithms under the scenario of single L-UFL MN**, such that the MN can determine the timing of launching a burst for each L-ULF m-cycle without any burst collision. A joint design of L-UFL m-cycle allocation and collision-free burst scheduling will be considered, aiming to minimize the monitoring delay (i.e., the shortest duration since the MN launches the first burst until the MN can come up with a valid alarm code).

(3) **Investigate the scenario with multiple L-UFL MNs**. A single L-UFL MN can achieve collision-free scheduling since the MN can be aware the precise timing of burst traversal along each link by manipulating the launching times of the bursts. With multiple MNs, nonetheless, collision of bursts from different MNs may occur no matter how each MN schedules its bursts. This is due to the assumption that the MNs have no (or limited) information exchanged real-time between each other. In the project, we will employ a random back-off mechanism if a burst time-out is detected, and will develop an algorithm to obtain the network failure status according to the observed irregularities (e.g., burst loss events with and without collision notification), with a goal to guarantee a zero false-positive and/or false-negative probability. Analysis will be conducted on the proposed burst scheduling and random back-off mechanism for expected monitoring delay.

IV.C *Integrated Design for Failure-Dependent Protection and S-LP Allocation problems*

With the knowledge of S-LP allocation problem defined in IV.A, the project will investigate a novel framework of FDP, called *Failure Presumed Protection* (FPP), which aims to perform traffic restoration in a distributed manner without taking any additional signaling effort while consuming minimum monitoring resources. Different from the L-UFL S-LP allocation problem, each FPP source node monitors the on-off status of the working lightpaths that traverse through or terminate at the node (i.e., the lightpaths are *local* to the node). Since the local working lightpaths may not provide complete information for L-UFL at the node, the node can only “presume” the failed links based on the available information. To fight against the possible inaccuracy of failure localization, the subsequent traffic restoration is performed such that all the suspicious links defined in the failure state are avoided. With the FPP framework, the project will investigate the following topics:

(1) Propose fast yet efficient approaches for identifying suspicious links based on the status of local lightpaths.

(2) Develop various dynamic survivable routing algorithms under the FPP framework. Formulate the informatics that can be gained at a node by newly adding a lightpath local to the node.

(3) Integrate the design of shared protection schemes with the S-LP allocation problem where shared protection lightpaths can be taken as S-LPs during normal operations. We will consider the scenario of adding some

Local S-LPs to a source node in order to increase the accuracy of failure localization along with the local working lightpaths.

V Anticipated Significance of the Work

Conventional approaches for network status monitoring and failure localization generally involve a vast amount of cross-layer signalling efforts and dedicated monitoring resources, even only for a small number of SRLGs. This is envisioned as a critical barrier in provisioning high-availability services in the future Internet with an all-optical WDM mesh backbone. Motivated by the importance of the problem that is nonetheless subject to less attention, the project is positioned to tackle the related research topics by developing a suite of novel approaches, namely Network-Wide Local UFL (NWL-UFL) S-LPs, monitoring bursts (m-bursts), and failure presumed protection (FPP), aiming to come up with a complete solution plane for fault management and high-availability service provisioning in the next-generation backbone networks.

The project firstly investigates the NWL-UFL scenario and defines the related S-LP allocation problem, in which every node in the network can perform instant and precise SRLG failure localization without taking any control plane signalling for alarm dissemination. This is considered a viable solution to the state-of-the-art Internet backbones with a moderate number of SRLGs. The m-burst framework is positioned to serve in networks with very dense SRLGs where using static S-LPs could lead to intolerable resource consumption. At last, the proposed FPP framework aims to integrate the task of failure localization with survivable routing algorithm design, which is expected to create a completely new design paradigm of network survivability strategies and fault management systems. We are confident to present the above three topics in the project proposal, since they fairly form a convergence of our developed technologies in the context of survivable network design in the past decade.

In addition to the direct contributions to the state-of-the-art of optical network fault management and control, we have also anticipated that the developed technologies can be migrated to other related areas and applications. For example, based on the developed failure localization constructions [6,7], we have developed a touch screen system with laser beams which can identify any single and dual touch by consuming the least amount of laser transmitter/receiver pairs [11]. Further, we expect that the m-burst framework can be extended to link quality/node availability monitoring in ad hoc and sensor networks.