Emergency OPM Recreation and Telemetry for Disaster Recovery in Optical Networks

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***Abstract*— Optical performance monitoring (OPM) and the corresponding telemetry systems play an important role in modern optical transport networks based on software-defined networking (SDN). There have been extensive studies and standardization activities to build high-speed and high-accuracy OPM/telemetry systems that can ensure sufficient monitoring data for effective network control and management. However, current solutions for OPM/telemetry assume that control and management planes (C/M-plane) always provide sufficient bandwidth (BW) to deliver telemetry data. Unfortunately, in the event of several concurrent network failures (e.g., following a large-scale disaster), C/M-plane networks can become heavily degraded and/or unstable, and even experience isolation of some of their parts. Under such circumstances, the existing OPM systems would hardly function. To enhance resiliency and to ensure the quick recovery of OPM/telemetry in case of disaster, we propose an approach for quick recreation of OPM and for achieving robust telemetry based on OpenConfig YANG. Our proposal addresses three key problems: (1) how to quickly recreate the lost OPM capability, (2) how to address the mismatch between the high data rate of OPM and the low BW in the C/M-plane network, and (3) how to flexibly reconfigure the telemetry system to be adaptive to sudden BW changes in the C/M-plane network. We implement a testbed and experimentally demonstrate that our proposal can tolerate low post-disaster bandwidth and can adapt the telemetry system following the changing conditions of the C/M-plane network.**

***Index Terms*— Disaster recovery, emergency optical network, optical performance monitoring, OpenConfig, robust telemetry.**

I. INTRODUCTION

To enhance the resiliency of modern optical transport networks, sophisticated protection and restoration schemes have been proposed [1]–[5], based on both proactive and reactive approaches. In case of large disasters, such as megaquakes or tsunamis, a quick recovery of the destroyed optical transport network is critical for network carriers (hereinafter called carriers). Major disasters in the past have taught us how costly and time-consuming it is to recover an optical transport network, as this process takes several days to several weeks to complete [6]. Detailed requirements for post-disaster recovery of optical networks can be found in [7]. For the early recovery of optical transport networks, in addition to data-plane (D-plane) recovery [8]–[16], control and management-plane (C/M-plane) recovery methods have been proposed, for example, using an external *emergency C/M-plane network* created with the surviving wired/wireless network resources outside of the optical transport network, e.g., surviving 4G/5G, Internet, and satellite links, [15], [17], [18].

As the sensory nervous system of an optical network, optical performance monitoring (OPM) and the corresponding telemetry functionalities in the C/M-plane play an important role in modern optical transport networks based on software-defined networking (SDN). They provide precise and real-time physical-layer state information as the basis of SDN intelligence. Extensive studies and standardization activities have been conducted to design high-speed and high-accuracy OPM and telemetry systems that provide sufficient OPM data for network control and management [19]–[31]. However, existing solutions rely on a C/M-plane network that is assumed to be always capable of providing sufficient bandwidth (BW). Instead, in the case of several concurrent failures (e.g., following a large-scale disaster), the C/M-plane networks can become heavily-degraded and even experience isolation of some of their parts. With a heavily-degraded C/M-plane network or an external *emergency C/M-plane network* [15], [17], [18], the C/M-plane BW would be limited and unstable, and the existing OPM and telemetry systems would hardly function as expected. To the best of our knowledge, no previous study has dealt with resilient OPM and telemetry systems under large-scale failure.

To ensure the rapid recovery of OPM and telemetry in case of disasters, we propose an approach to achieve quick recreation of OPM and robust telemetry. In our approach, we propose open system-based solutions, e.g., with OpenConfig-YANG [27], that address three key problems: (1) how to quickly recreate the failed OPM capability, (2) how to solve the mismatch between the high data rate of OPM and the

This paper is submitted for review November 22, 2019, and revised by January 15, 2020. A preliminary version of this work was presented at ECOC 2019 [32]. This work was supported in part by US-Japan JUNO2 project: NSF Grant no. 1818972.

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low BW in a degraded or *emergency C/M-plane network*, and (3) how to flexibly reconfigure the telemetry system according to the BW changes in the C/M-plane network. To experimentally demonstrate the new best-effort OPM/telemetry capability for quick disaster recovery, we implement a testbed. Through the experiments, we show that our proposed OPM/telemetry system can tolerate low post-failure bandwidth and adjust telemetry requirements based on the changing conditions of the C/M-plane network.

The remainder of this paper is organized as follows: Section II introduces related work; Section III addresses the use-case and three key problems in early recovery of OPM/telemetry after disasters; Section IV presents our proposal corresponding to three problems in early recovery of OPM/telemetry; Section V presents the demonstration and experimental results; Section VI discusses a series of open issues in need of further investigation to improve the framework; Section VII concludes the paper.

II. Related Work

Post-disaster recovery of optical networks: Progressive network recovery strategies have been previously proposed for post-disaster recovery [8]–[12]; the aim of these strategies is to restore the damaged nodes and links gradually with optimal scheduling. To achieve further early recovery of communications in the D-plane of optical transport networks, instead of waiting for the recovery of the original optical transport networks, Ref. [13] and [14] propose an emergency optical network in single-carrier recovery to accommodate the important emergency traffic first. A carrier can quickly create this emergency optical network by integrating the surviving and easy-to-restore optical nodes (e.g., reconfigurable optical add/drop multiplexer (ROADM)) and fiber links from different optical networks, which might be built up with different vendors' products. For early recovery of the necessary optical nodes, studies involving a function-disaggregation-based emergency first aid unit (FAU) have been initiated [15], [16]. In the event of an emergency, the damaged parts in those optical nodes that are difficult to restore (e.g., because of a shortage of the original vendor's products) can be replaced with corresponding FAUs to quickly recreate the lost functionalities, e.g., add/drop, optical amplification, and enable a multivendor interconnection.

After a disaster hits an optical network, the control/management plane (C/M-plane) network is typically heavily affected, resulting in BW degradation. When the original C/M-plane network is isolated, instead of waiting for the restoration of the original C/M-plane network, in [15], [17], [18] an external *emergency C/M-plane network* is created by integrating surviving wired/wireless network resources outside of the optical transport network, e.g., surviving 4G/5G, Internet, satellite links, and even IoT devices, etc. This *emergency C/M-plane network* is beneficial not only for emergency control and management of the surviving optical network resources, but also for quick collection of information related to network damage/survivability so that the optimal recovery plan can be decided as early as possible.

OPM: Ref. [21] presents a comprehensive survey of continuous and real-time OPM technologies and mature commercial OPM devices used for adaptive impairments compensation, efficient resource allocation, impairment-aware routing, and reliable network operation. Another survey, dealing with machine learning (ML) techniques in modern optical networks (including ML-based OPM) can be found in [22]. For OPM analytics in the presence of a huge amount of data, Ref. [23] presents an ML-based alarm-filtering technique that automatically identifies the desired critical events from a large amount of OPM data.

Monitoring/Telemetry-related works: Simple Network Management Protocol (SNMP) [24] can be used to retrieve monitoring data, but SNMP and standardized management information base (MIB) modules often lack efficient support for device configuration and have a number of shortcomings, e.g., scaling problems for the retrieval of large amounts of data, lack of a standard automatic discovery process to find the MIB modules that the device is using, lack of efficient commit mechanism, etc. [25]. To overcome these shortcomings of SNMP, IETF is advocating standardization of the advanced network configuration protocol (NETCONF) and YANG-based models [26]–[28] to offer a unified approach for configuration and monitoring in modern SDN networks, and promote interoperability among different devices, networks, and services. Extensive studies and standardization activities for NETCONF/YANG-based telemetry in large-scale SDN networks have been conducted in IETF and other open communities (e.g., OpenConfig) [29]–[32]. OpenConfig collaborates with other active open communities, such as OpenROADM [33], the Open Disaggregated Transport Network (ODTN) [34] in the Open Networking Foundation (ONF) [35], and the Open Optical & Packet Transport (OOPT) [36] in the Telecom Infra Project (TIP) [37]. These open communities accelerate the deployment of automated network control/management in modern SDN networks and enhance the interoperability of different vendors' devices and different operators' services.

For the telemetry integrated with OPM and data analytics in optical networks, a distributed monitoring and data analytics platform called CASTOR is presented in [38]. CASTOR is also used in [39] to perform soft-failure detection and identification [39]. In [40], new promising telemetry stream services enabling soft-failure detection in future SDN-based disaggregated optical networks have been investigated. Ref. [41] presents a field demonstration of real-time optical network diagnosis using deep neural network and telemetry.

Several recent studies have pointed out the necessity of reliable OPM/telemetry to support continuous and real-time physical-domain monitoring and data analytics. However, the design and management of resilient OPM/telemetry in the event of large-scale failures or disasters is rarely tackled in practical form. In current networks, restoration of original OPM capability in the damaged optical network would still involve an extended period of time. Moreover, with a heavily-degraded C/M-plane network or an external emergency C/M-plane network, due to the limited and unstable BW, the existing OPM and telemetry systems would hardly function as expected. All of these factors motivate us to investigate the problems of resilient OPM/telemetry systems in optical networks in case of large-scale failures.

In line with IETF and open communities, we apply a NETCONF/YANG approach and corresponding APIs, and implement the OpenConfig telemetry YANG model (e.g., an openconfig-channel-monitor module [32]) as an open and unified reference model to simplify the integration of the OPM/Telemetry system from OPM FAU devices, agents, collectors, to network management system (NMS) and SDN controller (Ctrl) in the disaster recovery. In addition, OpenConfig telemetry YANG model is employed to enhance interoperability in a multi-vendor-based emergency OPM/Telemetry system.

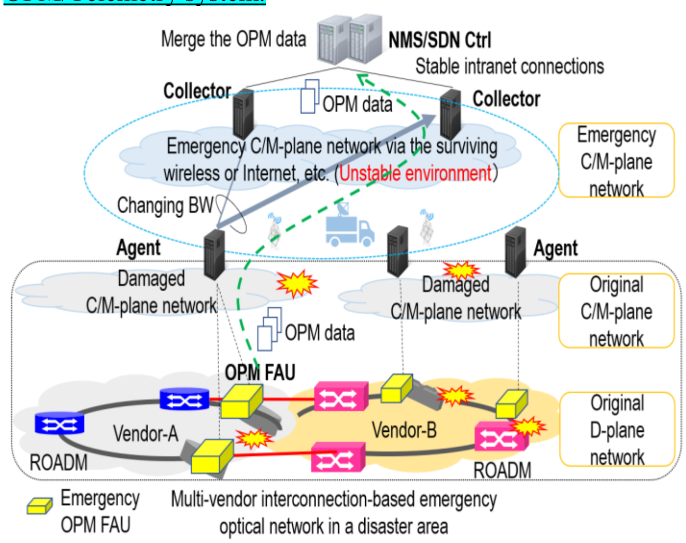

Fig. 1. Use-case scenario for OPM/telemetry early recovery in a multi-vendor interconnection-based emergency optical network.

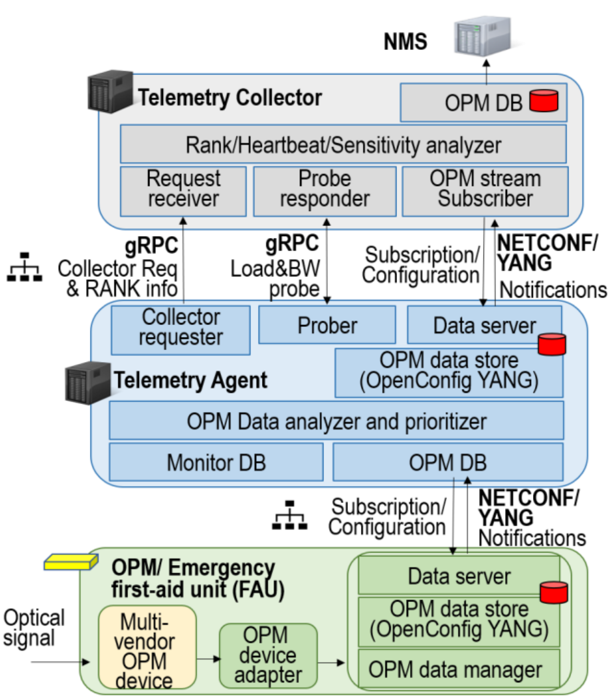

Fig. 2. Architecture of OPM first-aid unit (FAU), agents, and collectors.

III. Use Case and Problem Statement of the OPM/Telemetry Early Recovery

To achieve early recovery, rather than waiting for the recovery in the original optical transport network, which would take time, the carrier can establish/utilize an emergency optical network to accommodate the important emergency traffic first by interconnecting the surviving multi-vendor optical-network resources [13]. To recreate OPM/telemetry in the optical network, e.g., an emergency optical network, in line with the multi-level telemetry structure in [38], [40], we consider a four-level OPM/telemetry system. As a possible use case of our approach, we refer to the multi-vendor quick post-disaster recovery scenario in Fig. 1. In the affected optical network, the heavily-damaged OPM elements, e.g., OPM monitors in the ROADM, can be replaced with portable and disaggregated subsystems, called First Aid Units (FAUs) [15]. Within the C/M-plane network, telemetry agents (agent, for short) collect and analyze the data from the OPM devices (e.g., OPM FAUs). Above the agents, multiple telemetry collectors (collectors for short) collect the OPM data from the agents. After a large failure, using our proposed method, an external *emergency C/M-plane network* [15], [17], [18] can be created, where agents and collectors act as border nodes between the original C/M-plane and the external networks, e.g., for appropriate isolation. The NMS/SDN Ctrl (e.g., outside of the disaster area) receive the OPM data from collectors with stable intranet connections for OPM analysis of the entire networks.

For early recovery of the OPM/telemetry, the following three key problems must be solved:

(1) How to quickly recreate the lost OPM capability.

Following disaster damages, OPM capabilities may be lost. If a stock of the original vendor's OPM products is not available, we need to create the emergency OPM by integrating the OPM devices of different vendors. Furthermore, the emergency OPM must be easy to integrate into a widely-applicable telemetry system (e.g., an open system) so as to avoid complexities when using it, especially in a multi-vendor optical network.

(2) How to solve the mismatch between the high data rate of OPM (e.g., for providing detailed real-time performance monitoring on individual optical channels) and the low BW in the degraded or *emergency* C/M-plane network.

When the C/M-plane network has a low surviving BW, it is desirable that the agents remain capable of performing local OPM data analytics so that the most-critical OPM data can still be delivered in time even under limited and unstable BW. Moreover, rather than filtering out non-critical data, the agents will postpone their delivery to collectors until the BW is improved or recovered. In this way, soft failures and/or silent failures, which are hard to recognize locally, can be analyzed later at NMS/SDN Ctrl, which has a global view of the networks.

(3) How to flexibly reconfigure the telemetry system according to the BW changes in the C/M-plane network.

Instead of a fixed telemetry system with a fixed configuration between agents and collectors that is incapable of adapting to changes in the C/M-plane networks, a flexible and

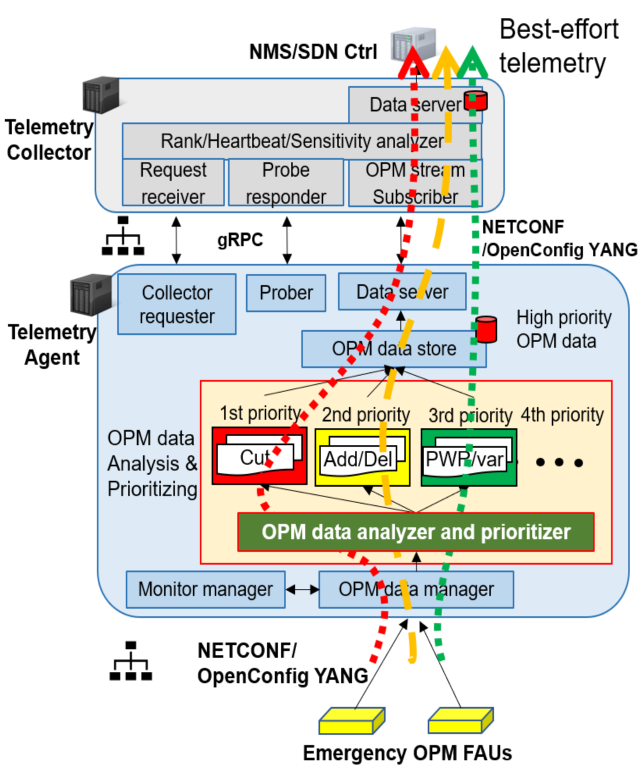

Fig. 3. Architecture of agent with OPM data analyzer and prioritizer for prioritizing the OPM data received from OPM FAUs.

reconfigurable telemetry system is desirable. Hence, the telemetry streaming rate and the connections between agents and collectors are reconfigurable, resulting in a flexible and robust telemetry system, adaptive to changes in the C/M-plane networks.

The above three challenges can be addressed using the system represented in Fig. 2, which depicts the structure of the system in our proposal. The following sections provide a detailed description of the system.

IV. Quick Recreation of OPM and Robust Telemetry for Early Disaster Recovery

A. Deployment of Multi-Vendor OPM FAUs via OpenConfig

Damaged OPM subsystems (e.g., the optical spectrum analyzer (OSA), etc., in ROADMs) might be difficult to restore due to a shortage of original-vendor products. Hence, instead of waiting for the re-supply of an original-vendor product, which may be time consuming, it would be highly desirable to quickly replace these products with, for example, OPM FAUs, so that the lost OPM functionality can be recreated as early as possible. However, due to the diversified vendor-specific application programming interfaces (APIs) of the OPM devices of different vendors, integrating these devices into an OPM system immediately after a disaster is difficult. We introduce an OPM FAU platform (see the green block in Fig. 2) that includes an *OPM device adapter* and a *data manager* (OPM-Man) to integrate multi-vendor OPM devices into the OPM FAU. In this way, the complexity in multi-vendor-based OPM FAU integration can be significantly reduced. This paper focuses on OPM in ROADM; the case of OPM capabilities in transponders is left for future work.

B. OPM Data Analytics/Prioritization and Triage in Agents

(1) Structure of an agent

Agents are located close to the OPM FAUs. They receive/analyze OPM data arriving from one or multiple OPM FAUs at a high data rate. When the C/M-plane network has only low surviving BW in the degraded or *emergency C/M-plane networks*, we introduce an *OPM data analyzer and prioritizer* module (see the green block in Fig. 3). Multiple queues are implemented in the *analyzer/prioritizer*, and each is assigned a *priority*.

(2) Analytics and prioritization of OPM data

The agent first analyzes and prioritizes the OPM data for each OPM FAU individually and labels them with a *priority*. Next, the agent stores the OPM data in corresponding queues according to the labeled *priority*. In this study, we focus on the optical spectrum analysis (e.g., the signal power of each channel), and, as an example, implement a four-*priority analyzer/prioritizer* that identifies four possible situations:

(P1) Fiber cut/recovery—all of the optical signals in a fiber monitored by an OPM FAU are lost, or a number of optical signals appear simultaneously when there were no monitored signals previously;

(P2) Path addition/deletion—signals in one or more channels (not all channels) monitored by an OPM FAU appear or disappear. When there was only one channel in the fiber previously, the loss of the signal is recognized as a (P2) event;

(P3) Strong optical power fluctuation—the signal power of one or more channels varies above a certain threshold;

(P4) Other OPM data not identified as P1–P3.

To identify a P3 situation, we introduce a new threshold parameter that we call *Sensitivity*. In the implementation for this paper, for each channel, when the difference between the value of the current measured power and the mean power value of the latest *W* times of measurement is greater than a given threshold—namely, *Sensitivity*—a P3 event is identified indicating power fluctuation; the current OPM data will thus be labeled with a P3 *priority*. The *Sensitivity* value is positive, with the same unit as the signal power. By adjusting the value of *Sensitivity*, the measurement of power variation can be tuned. When the BW of the C/M-plane network is limited, we can specify a larger *Sensitivity* value, such that a lower number of power variation events will be identified, resulting in a lower volume of high-*priority* OPM data being delivered, and hence avoiding congestion in the C/M-plane network. When the surviving BW is higher, we can specify a smaller *Sensitivity* value to identify and deliver more P3 data in time, resulting in a more precise OPM/telemetry system. The *Sensitivity* value is specified by the collectors. This is further discussed in Section IV. C.

Note that, in this paper, the prioritization analysis of the OPM data in the agent is still performed for each OPM FAU independently. Some OPM data received from different OPM FAUs (located at different places, e.g., different ports of a

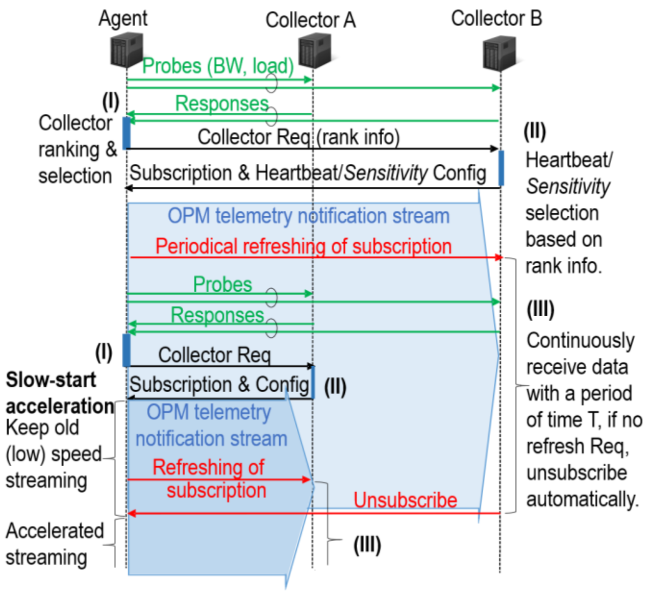

Fig. 4. Robust-telemetry protocol.

ROADM) would be correlated, e.g., caused by the same event or cascaded events. The correlation analysis of the OPM data that are received from different OPM FAUs can be performed at an agent locally, as well. In addition, the integration of other existing (or new) OPM-based detection schemes (e.g., based on machine learning) can be considered. These will help identify new situations in the D-plane and re-define the prioritization mechanism, resulting in more efficient OPM/telemetry, especially in the case of C/M-plane network failures/degradation. These new capabilities are envisioned as future work.

(3) Priority-based telemetry (Triage in agent)

To support the streaming of OPM telemetry data from agent to collector(s), when BW in the C/M-plane network is limited, instead of continuous high-speed streaming, periodic delivery (streaming) of a subset of OPM data is performed. Specifically, with a larger BW, a smaller interval between deliveries (called the heartbeat interval) can be specified for high-frequent delivery; with a limited BW, a larger interval is specified to avoid congestion in the C/M-plane network. For each delivery, the agent will check the aforementioned *priority* queues and deliver the highest *priority* OPM data first to NMS/SDN Ctrl. This is similar to the concept of medical Triage commonly practiced in the case of a medical emergency. Moreover, the agent can store lower-*priority* OPM data locally and deliver them when the BW is improved (e.g., with a smaller heartbeat interval), in a best-effort manner. Nonurgent but potentially important failure information that was not identified as high *priority* at the agent, can instead be collected and analyzed at NMS/SDN Ctrl later. In our testbed, the *priority* and *Sensitivity* parameters are introduced in OpenConfig [32] to enhance the resilience of an open telemetry system, as discussed in detail in the following sections.

C. Robust Telemetry Protocol

Based on NETCONF and OpenConfig YANG, we propose a robust telemetry protocol between agents and collectors to reconfigure flexibly the telemetry connections between agents and collectors, and adjust the data rate of the telemetry, to adapt to the BW/load conditions. Combined with the aforementioned *prioritization*, a best-effort OPM data collection can be achieved.

(1) Robust telemetry protocol behavior

As shown in Fig. 4, on the agent side, a *prober* negotiates with the collectors' *probe responders* (see the gray block in Fig. 3) to probe the BWs and the loads of individual collectors. The agent's *collector-requester* dynamically selects the high-rank collector (e.g., Collector-B) with the largest BW from that agent and having a lightweight load. The agent then sends a collector request (including the rank information) to the selected collector (see (I) in Fig. 4).

On the collector side, a *request receiver* receives the collector-request and rank information. The *Rank*/*Heartbeat*/*Sensitivity analyzer* (see the gray block in Fig. 3) decides the OPM data collection interval between agent and collector (heartbeat interval) and the *Sensitivity* value. The *Sensitivity* parameter is introduced into OpenConfig (openconfig-telemetry YANG module [32]) as a new feature to adjust the prioritization performed at the agents, as previously discussed in Section IV.B. For simplicity, in this paper, a *Rank/Heartbeat/Sensitivity* mapping table is assumed as given, i.e., pre-configured at the collectors. According to the received rank information, the corresponding values of the heartbeat interval and *Sensitivity* in the mapping table are utilized. Study of other, more sophisticated mechanisms for adjusting the heartbeat interval and *Sensitivity* value is envisioned as future work.

The collector's *OPM stream subscriber* subscribes to the agent and configures the heartbeat interval and *Sensitivity*, e.g., from Collector-B to agent (see (II) in Fig. 4). The telemetry notification streaming of the OPM data will then begin.

The aforementioned probing and collector selection/request processes are refreshed periodically between agents and collectors to adaptively keep the telemetry system updated to the C/M-plane changes (see (III) in Fig. 4).

(2) Adaptive reconfiguration and slow-start telemetry streaming acceleration

From the agent's viewpoint, when a better collector (i.e., Collector-A) with a higher BW than the old collector (i.e., Collector-B) is probed, the agent will send the new collector request to the new collector instead of the old one to reconfigure the telemetry system. The new collector will then subscribe to the agent and begin receiving the telemetry streaming.

Meanwhile, having not received the collector request, the old collector, i.e., Collector-B, will not immediately unsubscribe from the agent. Rather, it will continue to receive the OPM/telemetry streaming for period of time *T* to avoid data loss during the collector swap. Note that during this dual-collector streaming period, the heartbeat interval/*Sensitivity* of OPM delivery are not changed immediately to the configuration of new Collector-A. The agent maintains the old, long heartbeat interval (with low-speed telemetry streaming) to avoid overwhelming the C/M-plane network. After time period T, the old collector (i.e., Collector-B) unsubscribes from the agent, and the agent accelerates the telemetry streaming with a shorter heartbeat interval to the new collector (i.e., Collector-A). This is called "slow-start" telemetry streaming acceleration. The duplication of the received OPM data at the old and new collectors can be removed later by NMS/SDN Ctrl. The behavior of this robust-telemetry protocol is demonstrated in Section V.

V. Implementation and Demonstration

A. Demonstration Setup

To validate the proposed approach, we developed a prototype testbed (see Fig. 5). In the D-plane, three commercially-available ROADMs were connected with single-mode fibers. One lightpath with center wavelength 195.4 THz is shown. Three other parallel lightpaths were established as dummies, which, for simplicity, are not shown. It was assumed that monitors at the line ports of the three ROADMs had been damaged by a disaster and replaced by OPM FAUs. Two OSAs (in FAU-1/FAU-2) from vendor-A, and one (in FAU-3) from vendor-B were integrated into the three OPM FAUs. Agent-1 (A1) and Agent-2 (A2) were connected to FAU-1/FAU-2 and FAU-3, respectively. The agents, Collector-1 (C1) and Collector-2 (C2) were connected to an external *emergency C/M-plane network*. The NMS merged the OPM data collected at the collectors. Open-source Sysrepo [43] and Netopeer2 [44] were used to develop the NETCONF servers/clients. OpenConfig YANG [32] was extended to accommodate the *priority* of OPM data and *Sensitivity* employed in OPM data prioritization as discussed in Section IV. To focus on the OPM telemetry, a basic optical network NMS/SDN Ctrl (a customized backend application) was implemented to merely collect and visualize the OPM data from the collectors. The detailed OPM data analytics and optical network control capabilities are left for future work.

We demonstrated the BW variation between agents and collectors with the traffic-control command executed at each agent. Period (I) was characterized by low BW between agents and collectors (e.g., less than 50 Kbps), whereas, in Period (II), higher BW to C2 was recovered (e.g., 5 Mbps) (see Fig. 5 (upper)). In each period, we manually added events: fiber cut, fiber recovery, path deletion, path addition, and power fluctuation (e.g., caused by fiber twist) (see Fig. 5). In the agents, spectrum analysis, namely, recognizing and prioritizing events in descending order, was implemented as an example (see Section IV). The robust-telemetry protocol was implemented with gRPC and TLS (option) for probing and collector requests. Experimental results are described next.

B. Multi-vendor OPM-FAU integration via OpenConfig

Fig. 6 shows the selected messages regarding the multi-vendor OPM-FAU integration (e.g., related to OPM FAU-1 and A1 only, for simplicity) monitored with Wireshark. To ease the integration of OPM devices from different vendors with diverse APIs, an OPM device adapter for vendor-A and vendor-B OPM devices was developed. The OPM device adapter translated the OPM information of the individual vendors to a unified format. The OPM-Man in OPM FAU managed and delivered the OPM data to the agent based on the standard NETCONF and OpenConfig YANG. The complexity in multi-vendor-based OPM FAU integration was reduced significantly. For example, Fig. 6 shows the OPM data, generated in OPM FAU-1 from Dev-1, translated by Adapter-1, received by OPM-Man-1 and collected by A1 via NETCONF/YANG (OpenConfig).

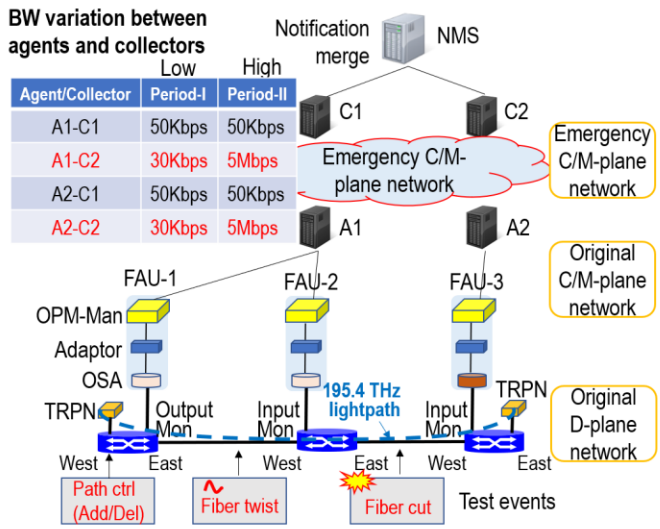

Fig. 5. Demonstration setup.

	Time	Source	Destination	Protoc	Length	Info
43	4.1397…	Dev-1	Dev-Adapter-1	TCP	756	scp-config(10001) → 60144 [PS
44	4.1403…	Dev-Adapter1	Mon-Man-1	TCP	119	60294 → documentum_s(10003) [
51	4.1983…	Mon-Man-1	Agent-1	TCP	134	netconf-ssh(830) → 36548 [PSH

Fig. 6. Selected messages about OPM data delivery from an OPM-FAU to an agent.

```
module: nict-channel-monitor
  augment /oc-chan-monitor:channel-monitors/oc-chan-monitor:channel-monitor/oc-c
an-monitor:channels/oc-chan-monitor:channel/oc-chan-monitor:state:
    +--ro timestamp?    oc-types:timeticks64
    +--ro peak-power?    decimal64
    +--ro priority?      decimal64
    +--ro osnr?          decimal64

  notifications:
    +---n channel-monitor-notification
       +--ro channel-monitors
          +--ro channel-monitor* [name]
             +--ro name            -> ../config/name
             +--ro config
             |  +--ro name?            -> /oc-platform:components/component/name
             |  +--ro monitor-port?    -> /oc-platform:components/component/name
             +--ro state
             |  +--ro name?            -> /oc-platform:components/component/name
             |  +--ro monitor-port?    -> /oc-platform:components/component/name
             +--ro channels
                +--ro channel* [lower-frequency upper-frequency]
                   +--ro lower-frequency    -> ../state/lower-frequency
                   +--ro upper-frequency    -> ../state/upper-frequency
                   +--ro state
                      +--ro lower-frequency?    oc-opt-types:frequency-type
                      +--ro upper-frequency?    oc-opt-types:frequency-type
                      +--ro psd?                oc-types:ieeefloat32
                      +--ro timestamp?          oc-types:timeticks64
                      +--ro peak-power?         decimal64
                      +--ro priority?           decimal64
                      +--ro osnr?               decimal64
```

Introduce "priority", etc. into OpenConfig Telemetry YANG, indicating priority info, aiding analysis in NMS/SDN controller

Fig. 7. Extension of OpenConfig YANG to accommodate *priority* information in OPM data.

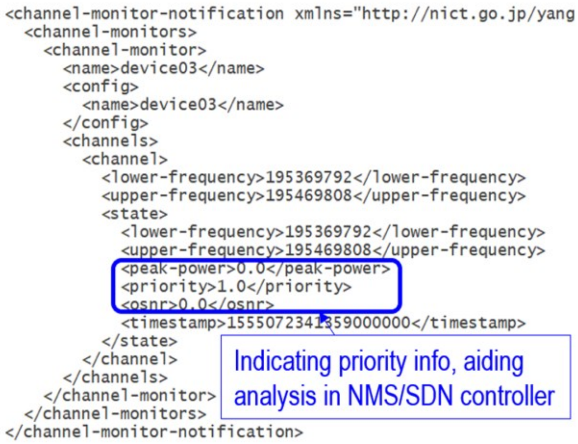

Fig. 8. Captured OPM data example delivered from agent to collector, indicating the analyzed *priority* P1 of the OPM data (e.g., fiber cut).

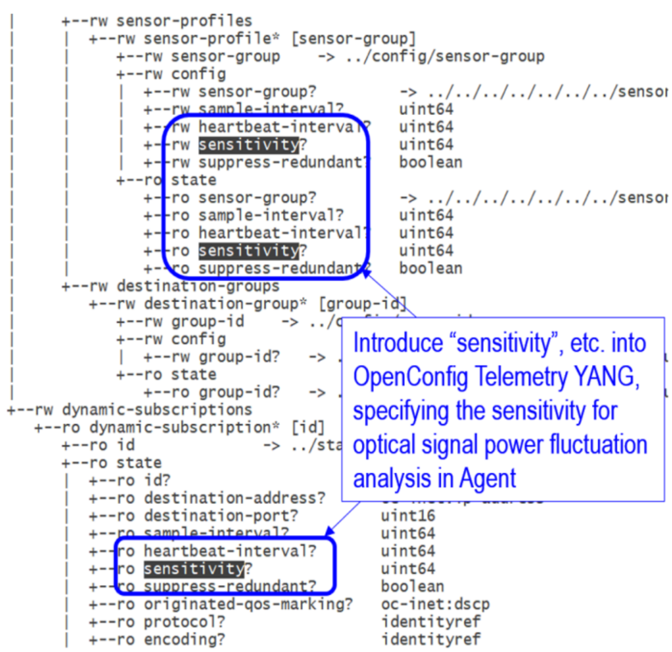

Fig. 9. Extension of OpenConfig YANG to accommodate *Sensitivity* specification information in P3 power-fluctuation analytics and prioritization process.

C. OPM Data Analytics, Triage in Agent, and Corresponding OpenConfig Extension

For agents, the new analytics and prioritization functionalities of OPM data mentioned in Section IV were developed. To accommodate the new information regarding the *priority* of OPM data and the *Sensitivity* value employed in OPM data prioritization, we extended OpenConfig YANG. Fig. 7 shows the extension of OpenConfig YANG (openconfig-channel-monitor.yang) to accommodate the *priority* information. Based on this extension, the agents labelled OPM data with the corresponding analyzed *priority* and delivered them to collectors, aiding further analysis in NMS/SDN Ctrl.

Fig. 8 shows an example of the prioritized OPM data delivered from A2 to C1. In the highlighted *priority* field, value 1.0 indicates a P1 *priority*, showing a fiber-cut event, with a peak-power value 0 of a representative channel (195.4 THz),

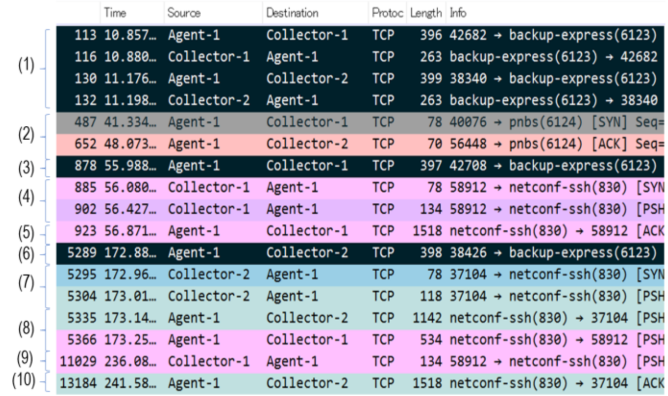

Fig. 10. Selected messages of robust-telemetry protocol.

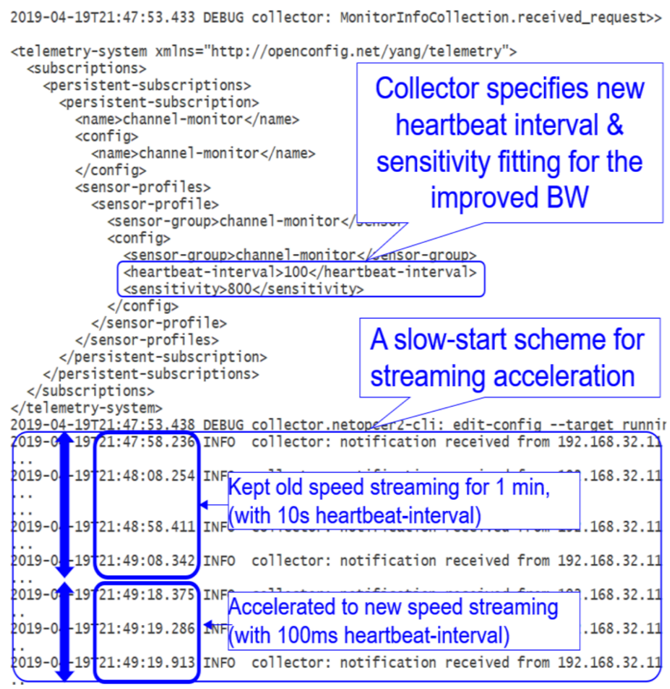

Fig. 11. Selected log information captured at new collector showing high-speed telemetry with smaller values of heartbeat interval and *Sensitivity* configuration (to agent), and corresponding received OPM streaming notifications (from agent) indicating slow-start streaming acceleration.

which had been non-zero previously. Examples of the other priorities are omitted here.

Fig. 9 shows the extension of OpenConfig YANG (openconfig-telemetry.yang) to accommodate the *Sensitivity* specification (i.e., specified by collectors) in the P3 power-fluctuation analytics and prioritization process. At the agents, the mean power value of the latest W (W was set to 100) times of measurement of each channel per OPM FAU was maintained. Upon receiving the new OPM data from an OPM FAU, if the agent identified neither a P1 nor a P2 event, the agent performed the P3 analysis. That is, for each channel, the agent checked the difference between the value of the current measured power and the mean power value. If the power difference for a channel was greater than the specified *Sensitivity*, the agent labelled the current OPM data as a P3 *priority*. Based on this extension, collectors are able to specify the appropriate *Sensitivity* to meet the BW condition in the

C/M-plane network, as demonstrated below.

D. Robust Telemetry Protocol Behavior

Fig. 10 shows selected messages (e.g., related to A1 only, for simplicity) captured by Wireshark, demonstrating the behavior of the proposed robust-telemetry protocol between agents and collectors which reconfigures the telemetry system, flexibly adapting to the BW changes in the C/M-plane network.

In Period (I), Groups (1) and (2) show the collector load probe and BW probe (5 s Iperf probe per 60 s), respectively. In our implementation, the agents calculated the corresponding rank information of each collector as shown in (1). For instance with a probed BW of 50 Kbps and 30 Kbps, and almost 0% CPU load for C1 and C2, A1 calculated the rank values of the collectors, namely, 15 and 13 for C1 and C2, respectively. Since C1 had the higher rank value of 15, A1 selected C1 for OPM notification streaming. Message (3) shows the corresponding collector-request (including the rank information) from A1 to C1 (via gRPC). Upon receiving the collector-request, based on the rank value of 15, C1 selected a corresponding heartbeat interval of 10 s and a *Sensitivity* value of 1000 from a preconfigured *Rank/Heartbeat/Sensitivity* mapping table, which was a default configuration at all of the collectors, as shown in Table I. Note that *Sensitivity* is of the same unit as signal power, which, for simplicity, was measured in our experiments with a power count (integer) according to the monitor vendor's specification. The unification from the vendor-specific power-count value to power (e.g., dBm) is treated as the next-step implementation. Group (4) illustrates the notification subscription and edit-config messages issued by C1 (heartbeat interval 10 s); similar edit-config messages for the *Sensitivity* configuration were omitted in Fig. 10. Message (5) shows the notification streaming from A1 to C1.

$$\text{rank} = \left(\frac{\text{BW}}{10\ \text{Kbps}}\right) + \left(\frac{100\% - \text{CPU\_load}}{10\%}\right) \qquad (1)$$

TABLE I
PRE-CONFIGURATION OF RANK/HEARTBEAT INTERVAL/*SENSITIVITY* MAPPING

Range of rank	Heartbeat interval	*Sensitivity*
1-9	20 s	1000
10-99	10 s	1000
100-399	1 s	800
400-	100 ms	800

In Period (II), similarly to what was shown in Group (1), A1 periodically probed that C2 had a larger BW (5 Mbps), i.e., rank 510. A1 sent a new collector-request to C2 in Message (6). Upon receiving the collector-request, C2 selected the heartbeat interval (100 ms) and *Sensitivity* value (800). Group (7) shows the corresponding C2 notification subscription and heartbeat interval configuration (a shorter heartbeat interval of 100 ms). Group (8) shows the parallel notification streaming from A1 to both old C1 and new C2 (to avoid data loss). After a timeout of T ($T = 60$ s), having not received the refreshed collector-request, C1 unsubscribed the notification as shown in Message (9). Message (10) shows the remaining notifications from A1 to C2.

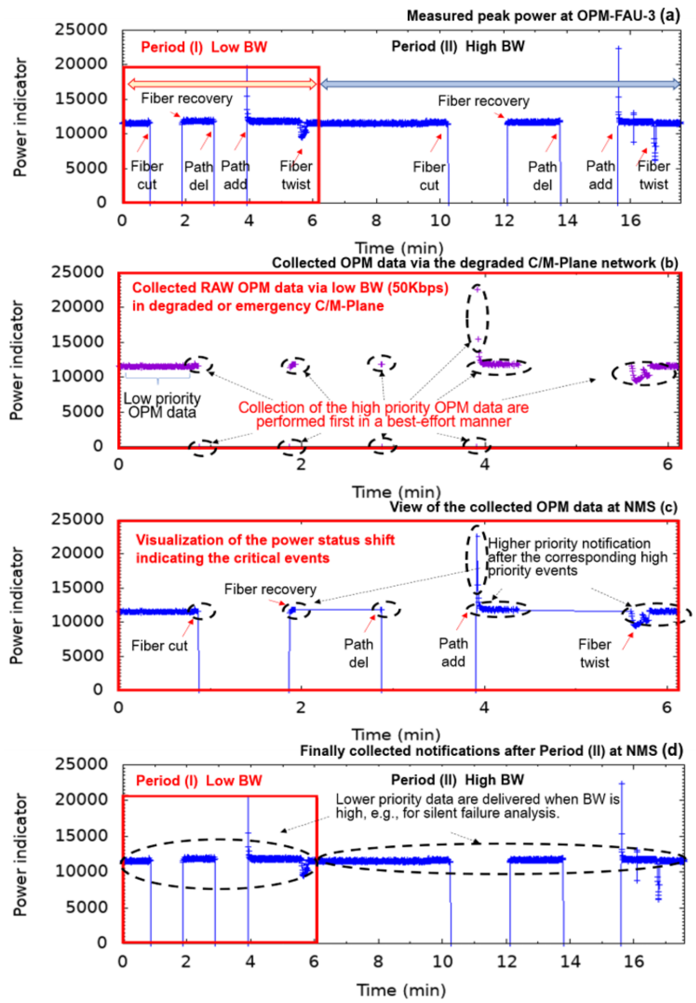

Fig. 12. Comparison of original and collected OPM data: (a) measured peak power at OPM-FAU-3; (b) collected raw OPM data at collector via degraded C/M-plane network in Period (I); (c) view of peak-power shift trend based on collected OPM data at NMS in Period (I); (d) finally collected full OPM data after Period (II) with improved C/M-plane BW at NMS.

Fig. 11 shows the selected log information captured at the new collector C2, which configured A1 to achieve high-speed telemetry with smaller values for the heartbeat interval (100 ms) and *Sensitivity* (800) configuration after subscription. A slow-start streaming acceleration scheme was implemented at the agents and is demonstrated, with A1 sending data to both the old low BW C1 and new high BW C2. To avoid congestion to C1, instead of immediately using the new 100 ms heartbeat interval, we maintained the old 10 s heartbeat interval for 1 min. After the old C1 unsubscribed, A1 automatically enabled the 100 ms heartbeat interval to C2, which could collect notifications faster. If the BW decreases, a new longer heartbeat interval will be enabled without slow-start.

E. Demonstration of Triage and Reconfigurable Best-Effort Telemetry Transitioning from Failure to Recovery

To demonstrate the triage and reconfigurable best-effort telemetry, the experiment with the aforementioned BW variation scenario was repeated. In each period, we manually added events: fiber cut, fiber recovery, path deletion, path addition, and power fluctuation (e.g., caused by fiber twist) (see Fig. 5). Fig. 12 plots the measured results of Period (I) and (II). The data sequence was processed based on the timestamp of each measured OPM data to show the data sequence with a start time "0", for simplicity.

Fig. 12(a) plots the peak-power intensity (numbered with the power counter value according to the vendor's specification) for an example lightpath between two end transponders with center wavelength 195.4 THz, 100 GHz width (as shown in Fig. 5). The signals were measured continuously at OPM FAU-3 with a sampling interval of 400 ms. All the test events are marked accordingly. The corresponding OPM data were collected through A2. In Period (I), A2 selected C1 with a larger BW (50 Kbps). A2 was configured by C1 with a heartbeat interval of 10 s and a *Sensitivity* value of 1000.

Fig. 12(b) plots the corresponding raw OPM data delivered from A2 and collected at C1 after Period (I) under 50 Kbps BW. Because of the limited BW, only a restricted amount of notification data (10 aggregated records each 10 s) could be collected on time. With our proposal, the agent identified the critical test events successfully and labelled them as high *priority*. These events were the first to be delivered to and captured by the collectors and NMS. In the agents, to observe the impact of each critical event, we intentionally prioritized a certain amount of subsequent data (which might indicate some new important events, such as a large peak power observed after path addition) as high *priority* (e.g., P1); these cases are highlighted by the dashed circles in Fig. 12(b). In addition to the high-*priority* OPM data notifications, a limited amount of low-*priority* OPM data (e.g., data with *priority* P4) was collected within the available BW. Fig. 12(c) plots the corresponding view of the peak-power shift trend of the optical signals based on the collected and limited OPM data at the NMS/SDN Ctrl, which is employed to assess, approximately, the network state change.

In Period (II), A2 selected C2 with recovered BW (5 Mbps) and was configured by C2 with a heartbeat interval of 100 ms and a *Sensitivity* of 800. Fig. 12(d) plots the collected OPM data after Period (II), a collection of the data in C1 [Period (I)] and in C2 [Period (II)]. Compared to that in Figs. 12(b) and 12(c), the OPM data in Period (I) that were logged in A2 and not collected in Period (I) were delivered successfully to C2 during Period (II) in a best-effort manner. These could then be employed in further analysis, e.g., silent failures that are hard to recognize locally can be analyzed later at NMS/SDN Ctrl, which has a global view of the networks.

The main novelty of this paper is the overall framework design and control mechanism under disaster conditions that it presents. The sensitivity introduced herein is an illustrative example, but there are many more applications.

VI. Discussion of Open Issues and Future Work

In this paper, we proposed an approach and a corresponding framework to achieve resilient OPM/telemetry and showed preliminary experimental results. There remain a number of open issues in need of further investigation to improve the framework.

A. *Prioritization of Disorderly OPM Data*

Due to the limited post-disaster BW, only a small amount of important OPM data (i.e., data analyzed and labeled as higher priority) can be immediately delivered to and analyzed by NMS/SDN Ctrl, where it can be used to trigger alarms. Subsequently, when BW improves, the stored lower-priority old OPM data can be delivered to NMS/SDN Ctrl, which would result in disorderly OPM data arrivals at NMS/SDN Ctrl. Hence, at NMS/SDN Ctrl, if analysis of the newly-arrived lower-priority OPM data is performed independently of the analysis of the previous high-priority OPM data, false alarms would be triggered. For example, without considering the original time of occurrence of the lower-priority OPM data, when the low-priority OPM data have the same root causes as the previous high-priority OPM data, redundant alarms would be triggered, resulting in a false reaction.

To avoid false alarms, a new requirement must be imposed on the root-cause analytics implemented at NMS/SDN Ctrl. The analytics framework must be capable of dealing with disorderly OPM data. Specifically, since the OPM data (especially the low-priority OPM data) may be out-of-date upon arrival at NMS/SDN Ctrl, the original occurrence time needs to be taken into account in the root-cause analytics, leading to "prioritization of disorderly OPM data" in the analytics performed at NMS/SDN Ctrl. For example, assume that the earliest-collected latest high-priority OPM data triggered root-cause analytics to issue an urgent repair action. Later, other older lower-priority OPM data will arrive. Both these older lower-priority OPM data and the results of the previous root-cause analytics (e.g., based on the earliest-collected latest high-priority OPM data) are treated as the inputs of the root-cause analytics. Consequently, the root-cause analytics processing is performed, so as to validate the previous analytic results, or find new unidentified root causes and trigger alarms accordingly.

At the agents, when no higher-priority OPM data have been collected, a choice for first delivery between older and more recent OPM data those have been collected and have the same lower priority needs to be make. Here, since the older data may present a "cause" event, whereas the later data may present the cascaded "effect" events, the older data should be delivered first. On the other hand, when the latest high-priority OPM data are collected at the agents and first delivered to NMS/SDN Ctrl, due to the existent data limitations, NMS/SDN Ctrl can perform its root-cause analytics approximately and triggers an alarm as appropriate. To perform a more detailed analysis with more relevant data, e.g., for validating the approximated analytics, more recent, lower-priority OPM data should be treated as more important and be delivered earlier than older OPM data with the same priority. Hence, to identify the important OPM data, in addition to the priority definition based on the value of the monitored objects (e.g., the optical signal power employed as an example in this paper), the time information (i.e., timestamp) should be treated as an additional factor in the prioritization of data performed at the agents. Moreover, we need a new capability to differentiate the order of the same-priority (with lower priority) OPM data deliveries in different situations: old low-priority OPM data delivery first for finding root causes when no higher-priority OPM data have been produced recently, and recent low-priority OPM data delivery first for detailed analytics over the previous approximated analytics based on the latest high-priority OPM data. This prioritization for delivering the important OPM data first and followed by the backlogs can be achieved as described below:

(1) When no high-priority data produced, agents can apply a first-in-first-out (FIFO) strategy for each priority queue, so that the older OPM data (e.g., a "cause" event) will be delivered earlier than the later same-priority OPM data (e.g., cascaded "effect events).

(2) When the latest high-priority OPM data are first collected, NMS/SDN Ctrl can perform root-cause analytics approximately and triggers an alarm as mentioned above. To validate the approximated root-cause analytics, NMS/SDN Ctrl can request the relevant agents to deliver the most recent (within a time span) lower-priority OPM data first. Upon receiving the request, agents can interrupt the aforementioned FIFO lower-priority OPM data delivery and first deliver the recent data.

B. *Possible Scalability Improvements*

As optical networks grow in scale, both the number of optical nodes/links and the number of channels increase significantly, and a huge amount of OPM data is generated. In addition to the increased load on the data analytics, BW consumption for telemetry will also increase dramatically. Hence, scalability of the OPM/telemetry system is critical. Mechanisms for offloading data analytics to distributed data-processing resources (e.g., edge computing resources), and deployment of a C/M-plane network with higher BW can be considered. In the event of large-scale failures (e.g., those caused by disasters) and after the recreation of OPM, e.g., with OPM FAUs, the reduced amount of computing resources and BW degradation of the C/M-plane network become the major hindrance to an effective utilization of OPM/telemetry data during early post-disaster recovery. Moreover, concurrent failures (e.g., fiber cuts, etc.) may be captured by multiple OPM FAUs and collected at the associated agent. This large number of concurrent events are all labeled with the same high priority. With only a simple prioritization scheme, these same-priority urgent OPM data need to be delivered sequentially based on the order of their arrival time at the agent; this will result in late delivery and therefore late response due to the limited BW. To deal with these problems and improve the scalability of the OPM/Telemetry system, we need to introduce new capabilities into the existing framework:

(1) To cope with the increased post-disaster OPM-data load, NMS/SDN Ctrl can be augmented by other locally-available edge computing resources or disaster-recovery ICT units/trucks [15, 45]–[47] to partially offload the OPM data analytics from NMS/SDN Ctrl. Moreover, to collect the analytics results from the edge computing resources and deliver them to NMS/SDN Ctrl (where the final analytics on the entire network will be conducted), different prioritization schemes can be applied in the edge computing resources, forming a hierarchical telemetry system with improved scalability.

(2) To address the problem of the reduced BW of the C/M-plane, the following capabilities can be integrated to improve BW utilization and collect larger amounts of urgent OPM data:

i) Message compression for data storage and delivery at the agents to deliver more information under the limited BW.

ii) More efficient binary encoding with reduced message size, e.g., employing the gRPC Network Management Interface (gNMI) [48] between agents and collectors instead of the conventional NETCONF encoding.

iii) At each agent, aggregation of the concurrent same-priority OPM data (i.e., concurrently generated by different monitors in a time window) into a single message, which reduces redundant contents in the original multiple messages.

iv) If an agent has certain OPM data analytics capability to identify some concurrent and corelated urgent events, the agent then can summarize the correlated urgent events into a single high-priority message and deliver it first, notifying NMS/SDN Ctrl of the problem, resulting in a more efficient collection of multiple correlated high-priority OPM data.

v) When the BW is extremely restricted, NMS/SDN Ctrl can further schedule the collection of OPM data among different agents into different time slots. In each time slot, NMS/SDN Ctrl can specify the area and time span to the desired agents to avoid congestion of the C/M-plane.

C. *OPM/Telemetry Recovery Schemes under Extreme Conditions*

In case of disconnection of the original C/M-plane network, an emergency C/M-plane network (with the surviving wireless/wired resources outside of the optical network) can be created for reconnecting the broken C/M-plane [15]. In case of extreme degradation of the C/M-plane network (between agents and collectors), the extremely low BW, high-latency and loss make the recovery of the C/M-plane (including OPM/telemetry recovery) more challenging. For example, the conventional NETCONF/YANG APIs which rely on the comparatively smooth TCP/IP communications in the original C/M-plane network may not work as expected due to the extremely low TCP/IP throughput. Moreover, when an emergency C/M-plane network is created with the outside surviving non-IP wireless environment, the recovery of the C/M-plane (with TCP/IP-based NETCONF/YANG) needs additional capability for supporting non-IP message exchange. To investigate the C/M-plane recovery under such conditions, we conducted a study demonstrating how to implement a high-latency and loss-tolerant emergency SDN C/M-plane recovery technique based on an IoT-based low-power wide-area (LPWA) wireless mesh network (non-IP) [17]. Two types of entities, namely, a delegator and delegatee, are introduced into the emergency SDN C/M-plane. These function as the gateways intermediating and translating the messages between the surviving original C/M-plane network segments (carrying the conventional NETCONF/YANG messages) and the outside emergency C/M-plane (carrying the non-IP messages, with extremely low BW, high latency and loss in message exchange). In [17], to tolerate the high latency and message losses introduced by the LPWA mesh network, we implemented a timeout/redelegation mechanism in NMS/SDN Ctrl. Through a field-trial experiment, the survivability-status collection and emergency control of the surviving optical resources were demonstrated, testing the possibility of CM-plane recovery under extreme conditions. Readers are referred to [17] for the details of the schemes and experimental results. Note that other possible robustness enhancements for tolerating the high latency and message losses can be implemented in the delegators/delegatees; for example, implementing an acknowledgement/timeout/retry mechanism between delegator and delegatees.

For OPM/Telemetry recovery, it is possible to integrate the schemes introduced in [17] into the framework presented in this paper, e.g., by merging the delegator into the collector, and merging the delegatee into the OPM agent. When agents are damaged (e.g., caused by a disaster), it is possible to place emergency recovery ICT units [15, 45]–[47] to host the agent again when placing the OPM FAUs and recreating the OPM capability. The integration of the schemes in [17] into this framework is envisioned as a future work.

D. Integration and Deployment of OPM FAUs with Non-FAU Legacy ROADMs

During post-disaster recovery, it is possible to integrate the existing OPM systems of the surviving ROADMs (e.g., based on the vendors' proprietary APIs or SNMP) into our OPM/Telemetry framework to collect the desired OPM data and efficiently utilize the limited BW. For integrating legacy systems that have proprietary APIs, APIs and data format conversion from the legacy OPM subsystems to OPM FAU can be implemented within the device adaptor of the OPM FAU platform (see the green block in Fig. 2). For integrating SNMP systems into the NETCONF/YANG-based system, existing IETF standardizations, e.g., RFC6643 [49], RFC7407 [50], can be considered.

In this paper, OPM FAUs are assumed to be deployed physically at the individual damaged ROADMs as needed. The associated costs for recreating the emergency OPM capability at each damaged ROADM include the cost of the OPM devices and the comparatively low cost of the OPM FAU platform software. Assuming that the legacy ROADMs are integrated into the framework, each ROADM has an additional cost for implementing the OPM FAU platform software (e.g., in the element management system), which can be installed before the occurrence of a disaster.

E. Improvement of the Openness of the Framework

Note that in our experiments for proof-of-concept, we developed customized application to support messaging capabilities, such as prioritization, in agents. Other popular open-source message systems, such as RabbitMQ [51] based on advanced message queuing protocol (AMQP) [52], for cloud systems can be extended to support the desired new prioritization/protocol capabilities, to further improve the openness of this framework.

VII. Conclusion

We investigated a new approach to achieving resilient OPM/telemetry in optical networks in the presence of large-scale failures (such as disasters). We proposed an OpenConfig-based approach for quick recreation of OPM during disaster recovery and for achieving robust telemetry that adapts the emergency C/M-plane network flexibly to post-disaster bandwidth changes. We implemented a testbed and demonstrated for the first time a new best-effort OPM capability for efficient disaster recovery. Through experiments, we demonstrated that our proposed approach can tolerate low post-disaster bandwidth and adjust the telemetry system according to the changing conditions of the C/M-plane network.

Acknowledgments

Financial support from US-Japan JUNO2 project: NSF Grant no. 1818972 is gratefully acknowledged. The authors thank Mr. Weiping Ren for his technical support in the experiments.

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