Toward Disaster-Resilient Optical Networks with Open and Disaggregated Subsystems [Invited]

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***Abstract*—Novel open and disaggregated optical-networking technologies promise to enhance multi-vendor interoperability thanks to their open interfaces in both data-plane and control/management-plane (C/M-plane). From the viewpoint of disaster resilience in optical networks, such interoperability will significantly improve the flexibility in product selection with regard to replacing damaged subsystems with products of different vendors. In this paper, we discuss various approach for rapid post-disaster recovery in optical networks (including legacy optical networks) employing disaggregated subsystems, namely, the emergency first-aid unit (FAU) with open application programming interfaces and protocols. We address the following problems (and introduce the solutions that we are currently investigating): (1) how to take advantage of the new disaggregated resources and surviving legacy optical resources to achieve early recovery, (2) how to achieve integrated control of FAUs and non-FAU legacy ROADMs, and (3) how to quickly recreate the lost optical performance monitoring (OPM) capability with FAUs and perform a robust telemetry under the restricted bandwidth in the degraded C/M-plane networks.**

Keywords— Disaster recovery, open, disaggregation, emergency optical network, multi-vendor, OPM, telemetry

I. INTRODUCTION

In current optical transport networks, sophisticated protection and restoration schemes are used in both the network design phase and operation phase to enhance the resilience of networks and to protect services from failures [1]–[4]. In addition to proactive (protection) approaches [5]–[8], fast and efficient reactive (restoration) approaches are critical for network carriers in presence of large-scale disasters, such as megaquakes or tsunamis, [9]–[11]. Major disasters have demonstrated that the independent recovery of individual original optical transport networks is expensive and time consuming as this process takes several days to weeks for completion [12]. Requirements for disaster recovery of optical networks can be found in [13].

One recent trend in optical networking is to employ the disaggregated optical systems to respond to rapid changes in network service requirements [14]. With a disaggregated approach, it is easier for network carriers to add/replace desired subsystems/functions in optical networks, hence reducing capital expenditure and operating expense required to achieve target performance requirements. Open communities (e.g., OpenROADM [14], OpenConfig [15], Open Disaggregated Transport Network (ODTN) [16] in Open Networking Foundation (ONF) [17], Open Optical & Packet Transport (OOPT) [18] in Telecom Infra Project (TIP) [19], and Cyber Photonic Platform Consortium (CPPC) [20]) accelerate the deployment of automated network control/management in optical networks based on software-defined networking (SDN), and enhance the interoperability between multi-vendor disaggregated optical networks.

Following the growing importance of open and disaggregated subsystems, in this paper we discuss new approaches for rapid post-disaster recovery in disaster-resilient optical networks employing disaggregated subsystems with open application programming interfaces (APIs) and protocols. In particular, we introduce advanced disaster-recovery schemes in a prototype of a disaggregated portable subsystem, called the *emergency first-aid unit (FAU),* specifically designed for early and low-cost post-disaster recovery. In this paper, we address the following problems : (1) how to employ the different new disaggregated FAU resources and surviving legacy optical resources (e.g., reconfigurable optical add/drop multiplexers (ROADMs)) to create an emergency optical network, achieving early recovery of both the data-plane (D-plane) and control and management-plane (C/M-plane) [21], (2) in the C-plane, how to perform the integrated control of FAUs and non-FAU legacy ROADMs in an emergency optical network [22], (3) in the M-plane, how to quickly recreate the lost optical performance monitoring (OPM) capability with FAUs and perform a robust telemetry under the restricted bandwidth (BW) in the degraded or emergency C/M-plane networks [23].

The remainder of this paper is organized as follows: Section II states the three main classes of problems that arise in early post-disaster recovery, and that are threated in this paper; Section III describes the disaggregated emergency FAUs, and discusses how to use them for D-plane and C/M-plane recovery; Section IV presents the integrated control of FAUs and non-FAU-based multi-vendor legacy ROADMs; Section V introduces FAU-based early OPM recreation and robust telemetry; Section VI concludes the paper.

II. RESEARCH PROBLEMS IN EARLY POST-DISASTER RECOVERY WITH DISAGGREGATED FAUS

In the early phase of disaster recovery, it is desirable to reconnect, at least partially, the optical networks and to satisfy the highest priority traffic as early as possible. Progressive recovery strategies for optical networks have been introduced for post-disaster recovery [5]–[8]; the target of these strategies is to restore the damaged nodes and links gradually using an optimal scheduling of repair actions. To speed up recovery of D-plan communications, an emergency optical network can

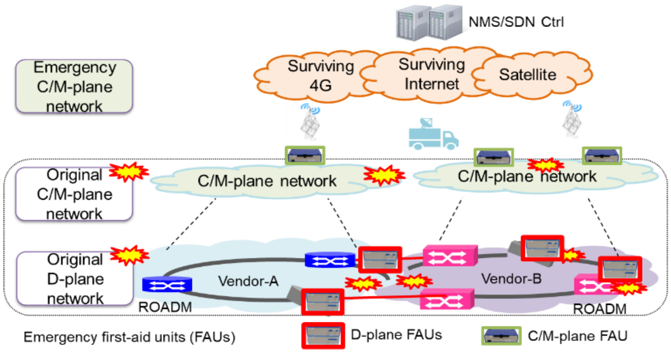

Fig. 1. Multi-vendor interconnection-based emergency optical network and the emergency C/M-plane network in a disaster area.

be created in a disaster area by interconnecting the surviving resources in multi-vendor networks those are owned by the same network carrier [9], [10], as shown in Fig. 1. With this approach and keeping in line with the new trend of open and disaggregated optical networking, we investigate the possibility of employing open and disaggregated subsystems to achieve early disaster recovery. We address three problems and introduce our corresponding studies in the following sections.

(1) How to create an emergency optical network with FAUs and multi-vendor legacy ROADM interconnection to quickly recover D-plane and C/M-plane (see Section III.)

(2) In C-plane, how to perform integrated control of the FAUs and non-FAU legacy ROADMs in an emergency optical network (see Section IV.)

(3) In M-plane, how to quickly recreate the lost optical performance monitoring (OPM) capability with FAUs and perform a robust telemetry (see Section V).

III. Early Recovery of the D-plane and C/M-plane with Disaggregated FAUs

A. Concept of Disaggregated FAU

Fig. 2 shows the concept of our portable disaggregated FAU designed for disaster recovery. Under the concept of disaggregation, the functions (e.g., Fun-A, Fun-B, etc.) that were originally integrated within one closed ROADM, are now identified and disaggregated. These different functions can be customized and implemented within individual units forming different small and portable FAUs, such as optical amplifier, transponder, Add/Drop, optical performance monitors, etc. New functions can also be added, such as emergency C/M-plane support and optical supervisory channels (OSC) handshake support in FAUs to offer advanced functions for efficient recovery. Fig. 2 shows a reference model of the FAUs, showing high flexibility in function selection. Unit functions (e.g., optical amplification, transponder, etc.) or compound functions (e.g., Add/Drop, OPM, etc.) and corresponding FAUs can be selected according to degree and condition of optical node damage. The recovery with FAUs are detailed in the following section.

B. D-Plane Recovery with FAUs

Fig. 3(a) shows a replacement scheme for ROADM restoration where the Add/Drop function is damaged. The failed subsystems in the damaged ROADMs which are hard to restore immediately (e.g., due to shortage of the original vendor's products) can be replaced with portable FAUs to recreate lost capabilities. In addition to the Add/Drop FAU as shown in Fig. 3(a), other modules such as optical amplifiers, transponder, and performance monitor FAUs, etc., can be employed. Note that, in emergency ROADM restoration, the performance of the corresponding FAUs would be lower than that of the original ROADMs, yet still sufficient to recover the highest-priority communications.

In a metropolitan area, network carriers may operate two or more optical transport networks (e.g., for different business purposes or because of business mergers and acquisitions). These networks may be built with products of different vendors. As shown in Fig. 1, after a disaster, the surviving and quickly restored ROADMs in these multi-vendor networks can be interconnected with FAUs and short-distance fibers in an all-optical fashion to form an emergency optical network. Such network can be employed to convey the most important traffic in both original networks ensuring quick and efficient D-plane recovery. For the interconnection between FAUs and the surviving existing legacy ROADMs (in particular, for the interconnection of the surviving existing legacy ROADMs of different vendors) special processing of OSC signals is performed with an OSC handshake FAU. Fig. 3(b) shows an OSC-handshake scheme and the corresponding OSC-handshake FAU (e.g., in the case of node of degree 2). For example, the west and east ports of the OSC-handshake FAU are connected to two adjacent legacy ROADMs from different vendors. Within the OSC-handshake FAU, data-pass filter modules and vendor-specific OSC-pass filter modules are employed. The OSC signals of the ROADMs of individual vendor are looped back to the original ROADMs to enable data transmission through the line ports in the original ROADMs. This loopback process is necessary because the OSC systems of different vendors (e.g., different wavelengths, optical transmission schemes, and negotiation methods) are incompatible with each other.

C. C/M-Plane Recovery with FAUs

As shown in Fig. 1, in the event of disasters, the C/M-plane network could be destroyed as well. To rapidly recover the damaged C/M-plane, an external emergency C/M-plane

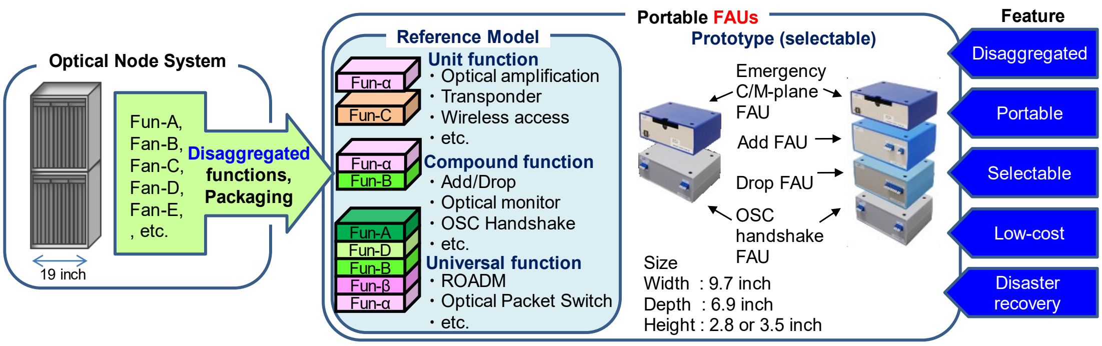

Fig. 2. Concept of portable disaggregated emergency optical subsystem: First-aid unit (FAU).

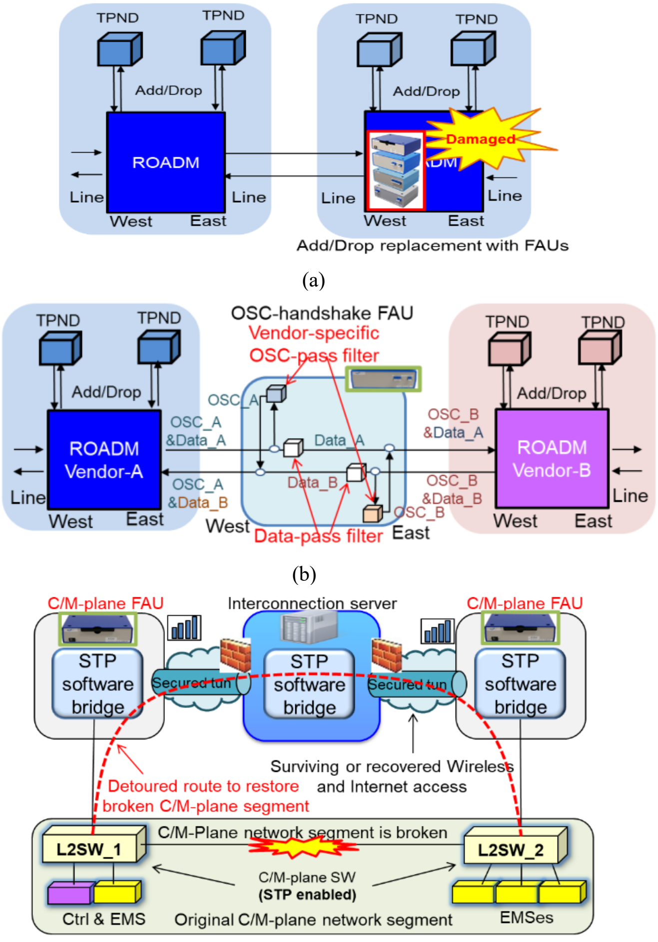

Fig. 3. Schemes of D-plane recovery with FAUs: (a) Replacement of damaged legacy ROADMs with desired FAUs, (b) interconnection of multi-vendor legacy ROADMs with OSC-handshake FAU, and (c) emergency C/M-plane network creation with emergency C/M-plane FAU based on the external wireless/internet resources.

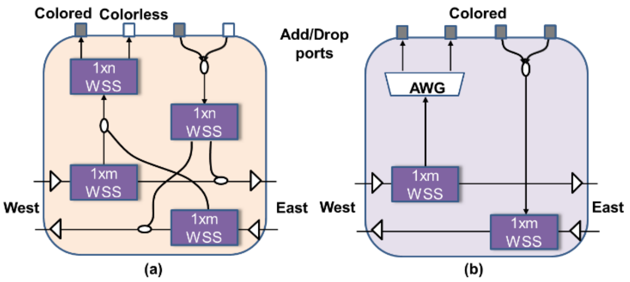

Fig. 4. Diverse internal structures of Add/Drop FAUs meeting different performance requirements. (a) with colored/colorless and directionless features, (b) with colored and directional features.

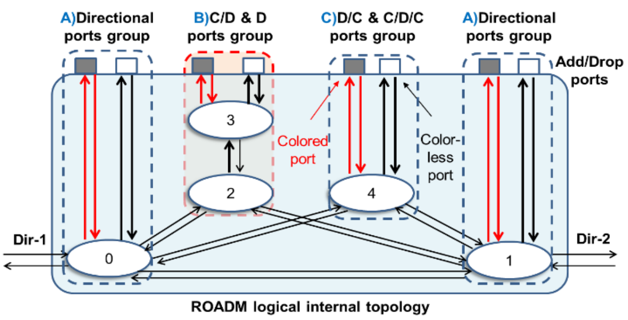

Fig. 5. Unified modeling of the internal logical topologies of Add/Drop FAUs and Legacy ROADMs.

network can be created by employing the surviving wired/wireless network resources outside of the optical transport network [21], e.g., surviving 4G, satellite links, and even IoT devices, etc. To employ this emergency C/M-plane network, emergency C/M-plane FAUs with corresponding wireless interfaces can be set at the desired locations to connect the surviving C/M-plane segments and the external emergency C/M-plane network. Fig. 3(c) illustrates an example of an Ethernet-based C/M-plane network recovery with C/M-plane FAUs and a remotely located emergency server (ES) which is connected to the surviving Internet. A spanning tree protocol (STP)-enabled software bridge system is implemented in each of the C/M-plane FAU and ES. By accessing the surviving wireless network that is connected to the Internet, each C/M-plane FAU can automatically create a secured layer-2 tunnel (e.g., over the secured shell (SSH) service) between the ES and itself. On the FAU side, this secured tunnel is bridged with the C/M-plane segment. On the ES side, all the secured tunnels from FAUs at different places are bridged together. Using FAUs and the ES, a collection of detoured routes can be created to reconnect the isolated C/M-plane. The readers are referred to [21] for detailed schemes and demonstrations of D-plane and C/M-plane recovery.

IV. Integrated Control of FAUs and non-FAU Legacy ROADMs

After establishing the aforementioned emergency optical network that consists of FAUs and multi-vendor legacy ROADMs, efficient and integrated control of this heterogeneous system is required. In this section, we introduce a unified node modeling method to abstract the diverse nodal color/direction/contention (C/D/C) features and internal constraints of Add/Drop FAUs and multi-vendor legacy ROADMs. We also present an architecture of C/M-plane facilitating the integrated control [23].

A. Unified Modeling of FAUs and non-FAU Legacy ROADMs with Diverse Internal Structures

The Add/Drop FAUs and legacy ROADMs may have diverse internal structures and different corresponding C/D/C features. In particular, the internal structure of Add/Drop FAU may not be fixed prior to disaster so as to meet different communication and performance requirements during disaster recovery while keeping the cost as low as possible. For example, Fig. 4(a) shows an Add/Drop FAU with colored/colorless and directionless features, whereas Fig. 4(b) shows one with colored and directional features. To ease the integrated control of this heterogeneous system, the diverse C/D/C features and constraints of new Add/Drop FAUs and multi-vendor legacy ROADMs must be modeled and presented in a unified manner. To achieve this goal, instead of a presentation of the physical internal structures in modeling of a node and leaving the analysis of C/D/C features/constraints to network controller, we directly present the C/D/C feature and constraint of a FAU or legacy ROADM using a logical internal topology. For provisioning of a lightpath, the network controller can directly embed the nodal logical internal topology of the two ends of that lightpath into the network topology forming an extended network topology and perform the routing and wavelength assignment (RWA) computation and transponder selection. Fig. 5 presents such a unified modeling of Add/Drop FAUs and non-FAU legacy ROADMs of degree 2, as an example. The ports outside the

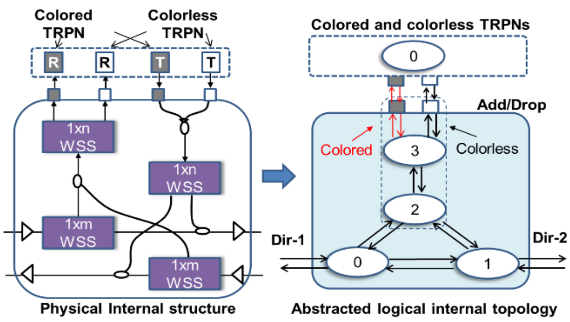

Fig. 6. An example of the unified modeling for a degree 2 Add/Drop FAU of C/D features (with contention).

frame, namely the Add/Drop ports (each for one transponder) and the line ports (Dir-1 and Dir-2) are the original physical ports of the Add/Drop FAU and legacy ROADM. Inside the shaded box, we show our proposed nodal logical internal topology including the virtual internal nodes. Among the internal nodes, there are colored or colorless unidirectional links. The Add/Drop ports are interconnected with the line ports via this logical internal topology.

The outside Add/Drop ports are grouped into three types of groups: (A) directional port group (restricted to the corresponding direction), (B) directionless and contention port group, (C) directionless and contentionless port group. Furthermore, for each group, there are colored and colorless two types of Add/Drop ports. All the ports in group B are subject to contention as they traverse a common link between the internal node 2 and 3. Whereas, all the ports in group C do not have any common internal link, hence they are not subject to contention, i.e., they yield the D/C or C/D/C features. Fig. 6 shows an example of the unified modeling for a degree 2 Add/Drop FAU of C/D features (with contention).

B. *Integrated Control of FAUs and non-FAU Legacy ROADMs*

Fig. 7 shows our proposed C-plane architecture design of the for an emergency optical network, such that FAU systems can be smoothly operated together with non-FAU legacy ROADMs during network recovery in a multi-vendor environment. An emergency C/M-plane FAU is employed for the control of FAUs, such as, Add/Drop FAU. A network controller controls the FAU-based nodes and other disaggregated transponder nodes (TRPN). TRPN, FAUs and the network controller communicate using NETCONF/YANG. The YANG model corresponding to the aforementioned logical internal topology modeling is developed for both the device model and the network model. Above the network controller, an emergency network management system (NMS) performs integrated control of the newly introduced disaggregated FAU systems and of the surviving multi-vendor legacy ROADMs, which are instead managed through vendors' proprietary controllers and northbound interfaces. Below the emergency NMS, a command translator (CMD translator) middle-ware is employed for the translation of the configuration information to the vendor-specific command via the vendors' proprietary northbound interface of the vendor's network controller. A path computation element (PCE) is employed for the RWA computation and transponder selection.

The emergency NMS can previously store the internal topology YANG data models of the legacy ROADMs locally. By further retrieving the logical internal topology from FAUs

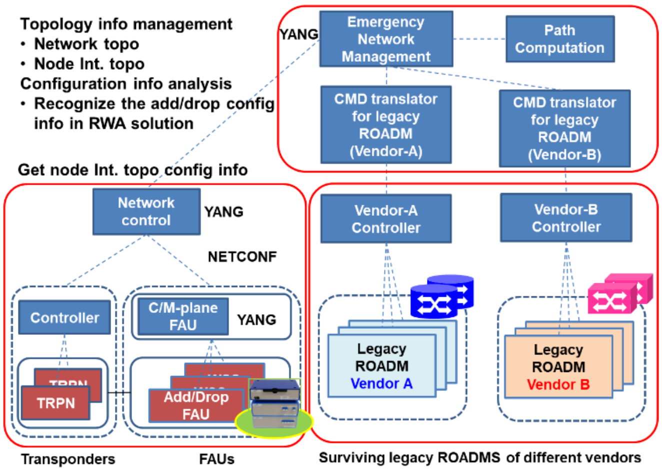

Fig. 7. Structure of the C/plane for the integrated control of FAUs and non-FAU legacy ROAMDs.

through the network controller of FAUs, the emergency NMS can correctly and easily recognize the C/D/C features and the corresponding internal constraints of individual FAU and non-FAU systems. Consequently, the emergency NMS can merge the logical internal topologies of individual physical nodes forming a network topology. Hence, based on this network topology that correctly presents the nodal constraints, calculations of RWA and transponders allocation for path provisioning can be performed correctly. The readers are referred to [22] for detailed schemes and demonstrations.

V. FAU-Based Early OPM Recreation and Robust Telemetry in the Emergency Optical Network

OPM and the corresponding telemetry functionalities in the C/M-plane are essential components of modern SDN-based optical transport networks. However, existing solutions rely on a C/M-plane network that is assumed to be always capable of providing sufficient BW. Instead, in the case of several concurrent failures (e.g., following a disaster), the C/M-plane networks can be heavily-degraded and even experience isolation of some of their parts. In case of a heavily-degraded C/M-plane network (heavy degradation can arise even in the case of the aforementioned external emergency C/M-plane network), the C/M-plane BW becomes limited and unstable, and the existing OPM and telemetry systems do not function as expected. To ensure rapid recovery of OPM and telemetry in case of disasters, we introduce, in this section, an approach to achieve the quick recreation of OPM and robust telemetry [23]. In our approach, we propose open system-based solutions, e.g., with OpenConfig-YANG. We address three key problems in this section: (1) how to quickly recreate the failed OPM capability, (2) how to solve the mismatch between the high data rate of OPM and the 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.

A. *System Structure*

Fig. 8 illustrates a scenario for multi-vendor post-disaster recovery, where the surviving multi-vendor optical-network resources are interconnected to create an emergency optical network in a disaster area. In the D-plane, the heavily damaged parts, including the OPM monitors of ROADM, can be replaced with portable OPM FAUs. Within the C/M-plane network, we employ telemetry agents (agent for short) to collect/analyze the OPM data from OPM devices (OPM

FAUs). Above the agents, multiple telemetry collectors (collector for short) are distributed to collect the OPM data from agents. When an external emergency C/M-plane network is created, agents and collectors act as border nodes between the original C/M-plane and the external networks, e.g., for appropriate isolation. The NMS and SDN controller (e.g., outside the disaster area) receive the OPM data from collectors with comparatively stable connections for the OPM analysis of the entire networks. Fig. 9 further depicts the structure of the system and will be described in details in the next subsections.

B. *OPM Recreation with Multi-vendor OPM FAUs Integration via OpenConfig*

Failed OPM components in ROADMs can be quickly replaced with components such as OPM FAUs (e.g., optical spectrum analyzer, etc.), such that the lost OPM functionality can be recreated as early as possible. Meanwhile, owing to the diverse vendor-specific application programming interfaces (API) of multi-vendor OPM devices, it is hard to immediately integrate them. We introduce an OPM FAU platform (see the lower block in Fig. 9) including an OPM device adapter and data manager (OPM-Man) to integrate multi-vendor OPM devices into the OPM FAU. To further ease the utilization of OPM FAU, we adopt NETCONF and OpenConfig YANG models (e.g., openconfig-channel-monitor module [15]) to offer an open and unified northbound interface of the OPM FAU. Hence, the complexity of multi-vendor-based OPM FAU integration can be significantly reduced. Although our current focus is on the OPM in ROADM, the OPM capabilities in transponders is envisioned as future work.

C. *OPM Data Priority Analysis and Triage in Agents*

Agents are distributed and located close to the OPM devices. They receive/analyze OPM data arriving from one or multiple OPM devices at high data-rate. When the degraded C/M-plane network or emergency C/M-plane network has only low surviving BW, there is a mismatch between the large number of OPM data generated by OPMs (e.g., for providing precise and real-time performance monitoring on individual optical channels) and the low BW (between agents and collectors) in the degraded or emergency C/M-plane networks. In our approach, by employing the OPM data analyzer and prioritizer module (see the blue block in Fig. 9), the agent can analyze/prioritize OPM data and deliver high priority OPM data to collectors first. This is similar to the functioning of the medical Triage commonly practiced in case of emergency. Moreover, the agent can store lower priority OPM data in the local OPM DB and deliver them when the BW improves in a best-effort manner. The potential important failure information unidentified at the agent can instead be collected and analyzed at NMS/SDN controller.

In this study, we first focus on the optical spectrum analysis and we implement a four-priority analyzer that identifies four possible failure situations: (P0) fiber cut (all optical signals are lost), (P1) path addition/deletion (signals in one or more channels appear or disappear), (P2) strong optical power fluctuation (signal power of one or more channels varies above a certain threshold), and (P3) other OPM data not identified as P0–P2. The integration of other existing (or new) OPM-based detection schemes (e.g., based on machine learning) is envisioned as future work.

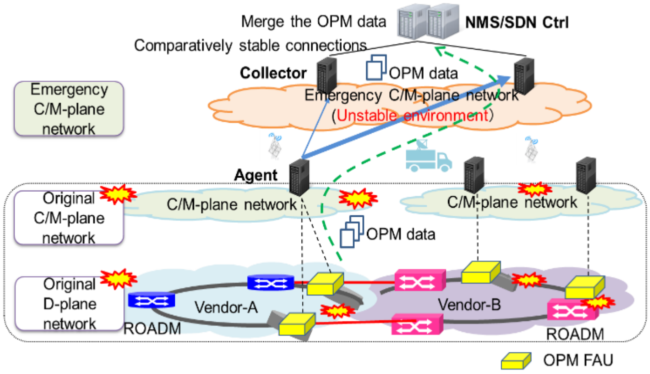

Fig. 8. OPM recreation in an emergency optical network.

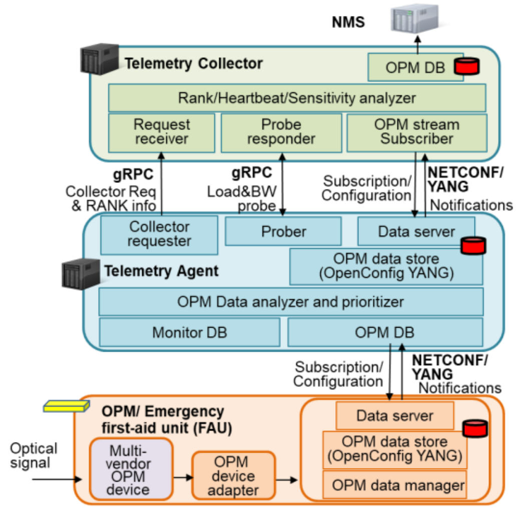

Fig. 9. Architecture of the OPM FAU, agents, and collectors.

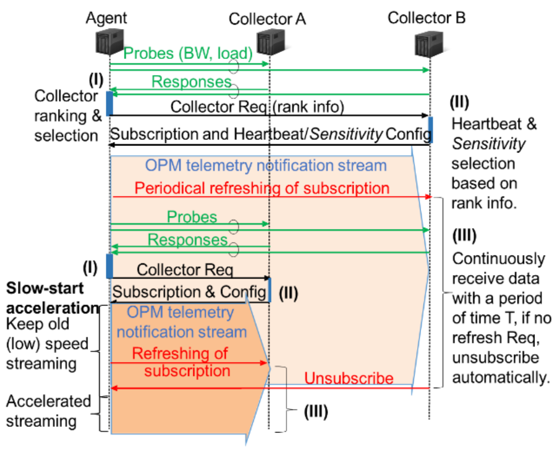

Fig.10 Robust-telemetry protocol behavior.

D. *Robust Telemetry Protocol*

On the basis of NETCONF and OpenConfig YANG, we introduce a robust telemetry protocol between the agents and collectors to flexibly reconfigure the data rate of the connections between the OPM (OPM collection) and agents as well as between agents and collectors, in order to adapt to the BW/load conditions. Combined with the aforementioned prioritization, a best-effort OPM data collection can be achieved. As shown in Fig. 10, at the agent side, a prober negotiates with collectors' probe responders (see the higher block in Fig. 9) to probe the BWs and the loads of individual collectors. The agent's collector-requester (see the middle block in Fig. 9) dynamically selects a high-rank collector with the largest BW from that agent and a light CPU/Memory load, and it sends a collector request (including the rank information) to the desired collector, see (I) in Fig. 10. At the collector side, a request receiver receives the collector-request and rank information. The rank/heartbeat/sensitivity analyzer decides the OPM data collection interval between the agent and collector (heartbeat-interval). In addition, a "sensitivity" parameter is introduced into OpenConfig (openconfig-telemetry YANG module [15]) as a new feature to adjust the prioritization in agents. The collector can specify a high sensitivity, e.g., a smaller value threshold in aforementioned (P2) analysis, to collect more OPM data in the case of large BW, and can specify a low sensitivity to collect the data of the most serious situations under a limited BW. The collector's OPM stream subscriber subscribes to the agent and configures the heartbeat-interval and sensitivity (see (II) in Fig. 10). The aforementioned process is periodically repeated (refreshed) to adaptively update the telemetry system to the changes in C/M-plane. When a better collector is selected, the old one will continuously receive the notifications for a period of time to avoid data loss during collector swapping, and will unsubscribe later (see (III) in Fig. 10). Note that, the main focus of our present work is the overall framework design and control mechanism under disaster conditions. The sensitivity introduced herein is an illustrative example, and there are many more applications. The readers are referred to [23] for detailed schemes and demonstrations.

Based on our preliminary studies, we have identified a series of possible open issues to enhance disaster resilience in optical networks. Several new requirements and capabilities are envisioned as future work, such as, 1) the prioritization of disorderly data, 2) how to improve scalability of our framework, 3) how to ensure recovery in extreme conditions, 4) how to deploy and integrate OPM FAUs with non-FAU legacy ROADMs, and 5) how to further improve the openness of our framework.

VI. CONCLUSION

In line with the new trends of open and disaggregation in optical networking, we are motivated to investigate the approaches of quick post-disaster recovery of optical networks with open and disaggregated subsystems, namely, the emergency FAU as new resources to achieve disaster-resilient optical networks. In this paper, we summarize our current works to achieve three goals: (1) employing new disaggregated FAU resources and surviving legacy optical or wireless resources to create an emergency optical network and emergency C/M-plane network for the D-plane and C/M-plane recovery, respectively; (2) in the C-plane, performing the integrated control of FAUs and non-FAU legacy ROADMs in an emergency optical network; and (3) for the M-plane, adopting an open and disaggregated approach to quickly recreate the lost OPM capability and to perform robust telemetry to tolerate the restricted BW in the degraded or emergency C/M-plane networks.

ACKNOWLEDGMENTS

Part of the works presented in this paper are supported by US-Japan JUNO2 project: NSF Grant no. 1818972, which is gratefully acknowledged. The authors thank Mr. Weiping Ren for his technical support in the experiments.

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