Hardware-supported Softwarized and Elastic Optical Networks

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***Abstract*—We present elasticity and agility in softwarized optical network construction, service continuation, and service update. Programmability among multiple network protocols and multiple classes of transmission and processing speeds is a necessary solution for lower CAPEX and agile network setup. We present beyond 100 Gbps hardware-support programmability in optical edge. Existing services should be kept transient quality against sudden traffic changes and failures. We also show proper optical power management using burst-tolerable EDFAs in network protection for service continuation of in-service paths.**

Keywords—optical networks; softwarization; elasticity; agility

I.2 SOFTWARIZATION, ELASTICITY AND AGILITY

Optical switching and transmission technology is a key enabler for provision of huge, long-distance, and energy-aware communication in 5th generation mobile networks (Fig. 1), where low-latency (< 1 msec in wireless), peak data rate (20 Gbps), and energy efficiency (100x) are expected capabilities [1]. The capabilities come from diverse and extreme application requests such as vehicle communications and video entertainment with greening environment. A high-quality network is generally costly so desired quality with cost-efficiency is different among different services. Network softwarization or virtualization is a concept for sharing but isolating a common network and computing infrastructure with QoS satisfaction [2]. Figure 2 is an example of a softwarized and elastic network where each service is provided on a separated edge-cloud network for QoS. Optical resources are also shared and isolated among different services.

Traditionally, optical core networks, which consist of a number of optical paths, are likely static. The optical paths (or wavelength paths) are provisioned according to the increase in the amount of traffic at the related communication sites. Topological change is slow. On the other hand, in network softwarization era, the optical paths are dynamically and agilely set up or torn down according to the birth/emerging and death/environmental change of services (e.g., a lot of human movement) [3]. An example case is illustrated in Fig. 2, where computing resources are elastically expanded in respond to the scene change of an event proactively or reactively. The optical networks also elastically provide different-rate communication channels between edge and cloud computing resources. For this purpose, elastic optical network technology provides different spectrum, modulation, and symbol rate wavelengths in an optical fiber to meet a predefined service quality [4]. Future softwarized optical network should be tolerated to the dynamic and elastic behavior of optical signals [5]. Softwarized and elastic optical networking are intensively studied for application to optical transport networks (e.g., [6]), optical access (e.g., [7]), mobile fronthaul networks (e.g., [8]), and data center networks (e.g., [9]).

Kitayama *et al.* [10] identified the capability to synthesize desired switching and transmission functions by software control as a key solution while mentioning following situation of the network operators:

●2 The cost reduction is the crucial issue to be profitable under a strict price cap of their services with coming capacity crunch.

●2 Current network operation and management (OAM) is labor intensive. The operating expenditure (OPEX) can be saved and the time for service delivery can be minimized if the module or card of the OTPs can be automatically

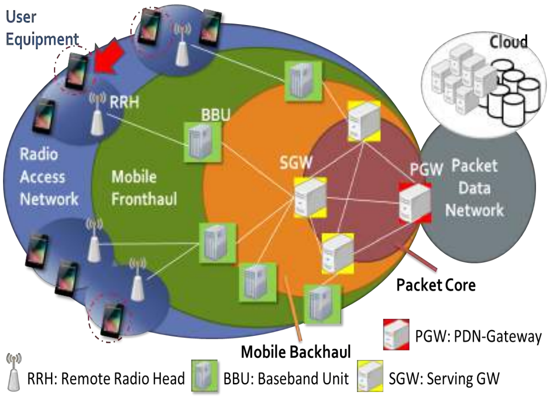

Fig. 1. A mobile network.

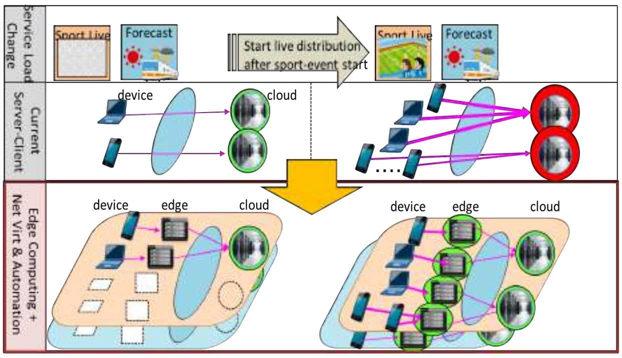

Fig. 2. A softwarized and elastic network. Each service is allocated a separated edge-cloud network with optical technology (green: stable, red: congested).

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upgraded by updating software from a remote site, and if the switch can be automatically configured.

These points show the necessity of softwarization and elasticity in the optical network. Moreover, optical edge nodes as well as optical transmission and computing environment are also desired target components for softwarization and elasticity. In a service level, the optical edge nodes accommodate various network protocols such as Ethernet, IP and MPLS in client networks with low capital expenditure (CAPEX) and OPEX. Programmable hardware, which provides different protocols time-by-time in a single component (e.g., line card) based on reconfiguration of electronic circuit and/or software, is powerful for not only service continuity and quick service launch but also CAPEX reduction. However, the requested performance is diverse and higher speed components like 400 Gbps capacity are not yet programmable. Accordingly, optical edge nodes are much costly.

The network operators cannot predict the volume of service requests perfectly. Towards smooth service launch, they prepare some redundant resource pools. The size of the pools is likely proportional to the number of speed grades and number of network protocols. The solution is the *equipment communization* and *hardware elasticity*. In other words, we need reconfigurable technology about *network functions* such as switching, processing and management, *protocols* and *performance* in terms of capacity (e.g., 25 to 400 Gbps with 25 Gbps granularity), availability and manageability in common hardware, in response to the demands from the edge services. Thus, sharp cut of CAPEX and OPEX is achieved.

Network operators dynamically configure appropriate functions such as packet framing and packet processing with requested performance by using an appropriate number of hardware resources like FPGAs, network processors, and CPUs. Collaborative processing functions for meeting a capacity, availability and manageability are also facilitated.

When the optical networks are agile and softwarized, optical signals should be managed carefully. A bulk of optical paths are setup at the initial construction of a network service and many backup paths are activated in the case of a failure event. Here, the input optical power to EDFAs suddenly changes. The gain transient of conventional EDFA causes optical power fluctuation for multiple wavelengths [11]. Generally, the setting of EDFAs and variable optical attenuators (VOA) are readjusted to suppress the power fluctuation. However, this operation takes long time and insufficient for prompt path provision or quick restoration. We need agile and stable power management for such sudden power changes to avoid service interruption.

In this paper, we present elasticity and agility in softwarized optical network construction, service continuation, and service update. Optical hardware is the key to all the situations. Beyond 100 Gbps optical reconfigurable edge nodes and burst tolerable optical amplifiers are presented toward this purpose. These are also beneficial to quick service launch and cost reduction.

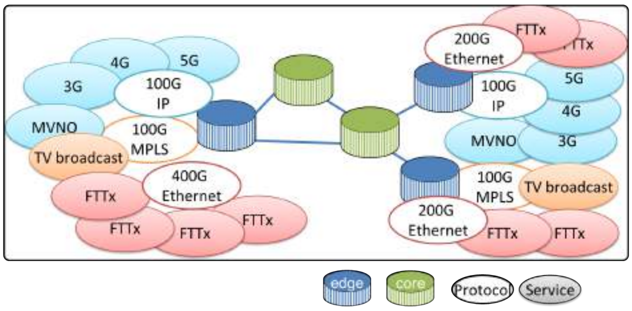


Fig. 3. Optical core and edge nodes for accommodation of diverse protocols and services.

II.2 Softwarized and Elastic Network Architecture

Our designed network consists of optical core nodes, reconfigurable optical edge nodes and access networks. The core nodes provide a circuit-switched based optical network and are tolerant to power fluctuation against sudden simultaneous addition and deletion of a set of lightpaths. The optical edge nodes support multiple access network protocols and data is encapsulated into (decapsulated from) optical network format such that optical network separately transmits data on each of access network by using WDM and other multiplexing technologies. Figure 3 shows an optical network that accommodates multiple access services on different network protocols.

The network is designed with aware of the following general requirement of optical networks.

●2 Save existing service interruption. New additional service accommodation and failure should not affect to continuation of the optical paths for in-progress services.
●2 Save unused equipment stock and/or increase utilization of equipment. CAPEX should be minimum.
●2 Hasten the service launch and update.

III.2 Reconfigurable Optical Edge Nodes

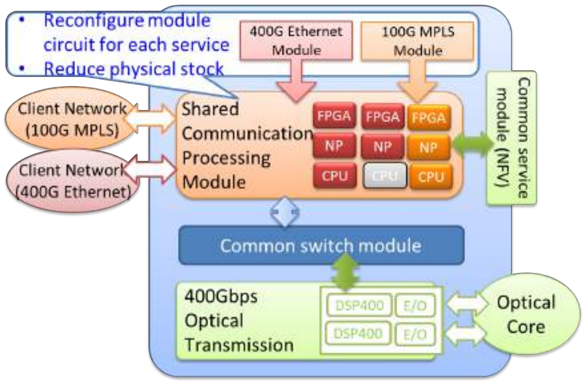
In the beyond 100 Gbps era, cost of equipment modules is higher and keeping redundancy with low CAPEX is difficult. Programmability of optical edge nodes presented in this section saves CAPEX and OPEX of optical networks and time for service launch and update.

Figure 4 shows a reconfigurable optical edge node, which consists of a shared communication processing module, a common switching module and an optical transmission system. The communication processing module co-exists multiple network protocols and sets the protocols accordingly by properly reconfiguring the FPGAs, network processors, and CPUs. By sharing the communication processing modules in different speed and protocols, CAPEX and OPEX can be saved.

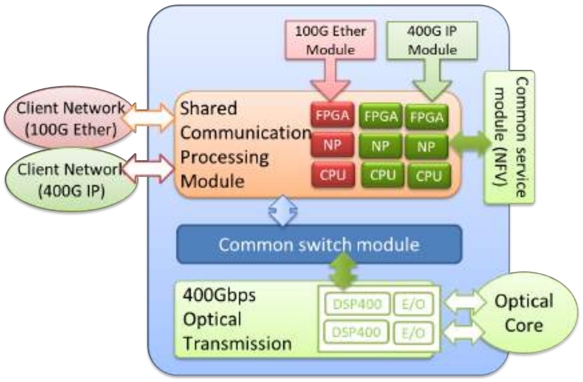
Reconfigurable Communication Processor (RCP) over Lambda Project [12][13] designs beyond 100Gbps programmable edge nodes. The node is intended to have resource pools consisting of reconfigurable service modules (RSM) such as filtering, DPI, OAM and IPsec, and reconfigurable processing modules (RPM) for network protocols such as IP, MPLS, and Ethernet. Figure 5 shows the RCP development module. An edge node has a Tbps class switching module and a number of pools of NPs, and FPGAs. Appropriate network protocols can be reconfigured into a portion of RSMs and RPMs.

Toward efficient accommodation of wide variety of different bandwidth client demands, it is expected that optical core network provides different bandwidth links to client networks based on the client requests. The optical core network elastically changes link bandwidth by organizing multiple beyond 100Gbps physical links. Flexible Ethernet (FlexE) is considered as the promising technology for realizing the bandwidth-variable multi-links [14]. FlexE accommodates wide variety of client MAC flows efficiently in the client side while it creates scalable multi-link in the optical network side [15].

FlexE lacks monitoring function for identifying flows that contain bit errors. Tanaka *et al.* [16] developed a function on electronic circuit hardware in which flows containing bit errors are detected by using 25 Gbps FlexE flows. We hope this function will be mapped into flexible channelized links in Fig. 5 toward elastic bandwidth provisioning at the client side. I becomes a promising monitoring technology for 100 Gbps and beyond reconfigurable hardware.



(a) 400Gbps Ethernet and 100Gbps MPLS.



(b) 100Gbps Ethernet and 400Gbps IP.

Fig. 4. Reconfigurable optical edge node. Multiple different network protocols and different speeds supported. Appropriate number of FPGAs, Network Processors and CPUs is used for a network service and it is reconfigured from a remote site.

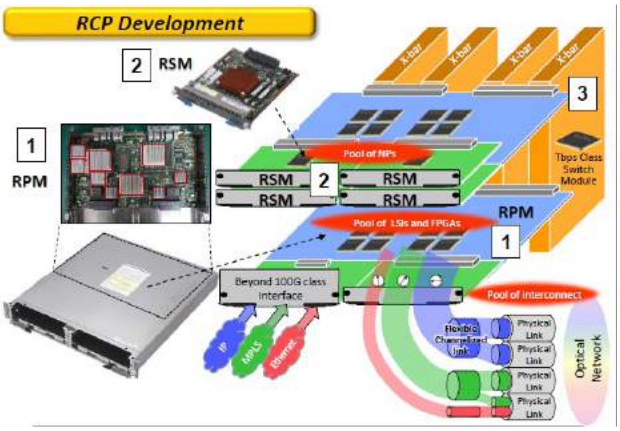


Fig. 5: A reconfigurable optical edge node [12]. Multiple network protocols and diverse network functions are configured into RPM and RSM, respectively. Beyond 100 Gbps interfaces are provided to client networks. Arbitrary rate (e.g., multiple of 25 Gbps) are reserved at optical core network using Flex Ethernet.

IV.2Power Management in Agile Optical Networks

A. Optical Power Fluctuation

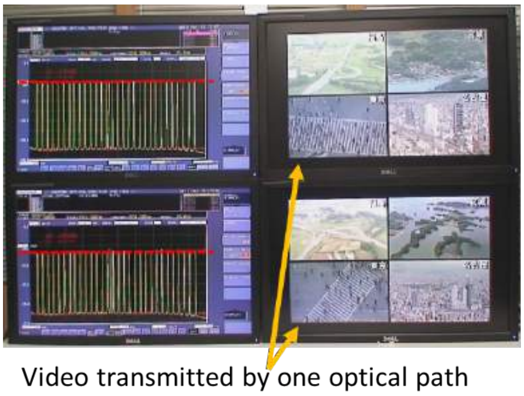
A problem in the agile optical networks is the optical power management of the amplifier-assisted optical networks in dynamic path setup and release. Usually optical paths are setup one-by-one with careful power management with gain-controlled optical amplifier and variable optical attenuators (VOAs) so as not to cause disruption of other paths due to power fluctuation. Several minutes may be acceptable for multi-path setup. On the other hand, in the case of a fiber cut failure on 1:1 protection, we have to recover optical signal reach immediately. At an upstream node of a failed link, we switch the direction of the optical signals to a different optical fiber to deliver the optical signals to the proper destinations.

Assume that 80 wavelengths are multiplexed in a fiber. Up to 80 wavelengths are switched to the different fibers and go into the optical amplifier systems simultaneously. Dynamic gain controlled function does not respond properly and quickly. Existing services multiplexed on a fiber may experience transient signal degradation. Figure 6 shows an image of a service disruption by simultaneous loss of 30 wavelengths. Figures 6(a) and 6(b) have wavelength spectrum and received video on a single wavelength. In each subfigure, top is a result of using burst-tolerable EDFA and bottom is that of conventional EDFA. Through transition from Fig. 6(a) to Fig. 6(b), we observe that the received video quality of the bottom degrades due to slow gain control of the conventional EDFA.

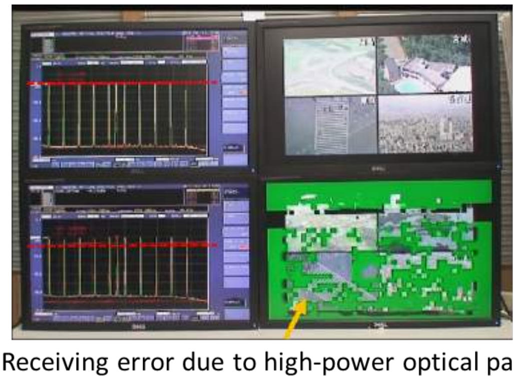
A straightforward way is path-by-path recovering. However, recovery time is too long. For example, recovering time is proportional to the number of damaged optical paths.

B. Burst-Tolerated Optical Amplifiers for Protection

We proposed a simultaneous protection framework in wavelength switched optical network (WSON), where burst-tolerated (burst-mode) erbium-doped fiber amplifiers (EDFA) are installed for transient optical power management [11]. This is beneficial to the dynamic environmental change, where a set of lightpaths are setup and released as well as recovery from a failure.



(a) 40 wavelengths. Fine video services provided.



(b) 10 wavelengths (top) service continues (bottom) service is disrupted.

Fig. 6. Sudden change of the number of multiplexed wavelengths in a fiber and received video quality on a single wavelength.

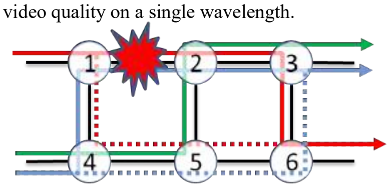


Fig. 7. A link failure and rerouted paths (solid lines are working paths and dashed are backup.

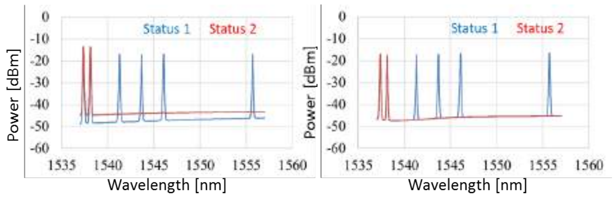


Fig. 8. Spectral waveform. (left) conventional EDFA (right) burst-mode EDFA.

Figure 7 shows a long-distance WSON, where EDFAs are embedded into optical nodes. Denote $l_{i,j}$ for link between nodes i and j. Working wavelength paths are drawn in solid lines and backup ones are dashed lines. 1:1 protection (not 1+1 protection) is assumed for red and blue working paths. In the case of link $l_{1,2}$ cut, backup paths on links $l_{1,4}$, $l_{4,5}$, $l_{5,6}$, and $l_{3,6}$ become active and link $l_{2,3}$ loses two wavelength paths simultaneously. If a number of wavelengths paths in a link are active or disappear in a very short period of a time, optical power at the link may steeply reduce and/or increase by the gain fluctuation due to time dependent saturation effect of the optical amplifier [17] and this phenomenon may give ill influences to the optical systems and the working paths for different services. For example, the green-colored working path from node 4 to node 3 remains at link $l_{1,2}$ cut so automatic gain controller (AGC) in an EDFA in node 2 may increase power of the green path suddenly by the effect of sudden loss of working paths (red and blue lines). On the other hand, the green path may decrease its power at link $l_{4,5}$ due to sudden appearance of backup paths (dashed lines). Then, a network system to prevent such power fluctuations is necessary.

Problem in the traditional system is that optical nodes sequentially process the path setup for multiple wavelengths due to the signal power stability of optical network even though the prompt activation of backup paths is required. As a result of the sequential processing, the processing time increases in proportion to the number of the channels to handle by one wavelength each. Therefore, the parallel processing method is necessary to reduce the processing time.

We proposed to use the parallel path processing with burst-tolerant EDFA [11] so that optical nodes can setup of multiple wavelength paths by only one command. For dynamic optical paths, transient-suppressed burst-mode EDFAs are key components for the power management and the system stability. Conventional EDFAs with burst input signals due to setup and release of multiple wavelength paths may cause optical power surges which damage optical components or impose gain transients which impair the signal quality. Here, we introduced the parallel path processing method with burst-tolerant EDFA into the protection framework to cope with sudden loss and appearance of optical signals on multiple wavelength paths. We showed the framework works well experimentally and achieved 9-sec path setup for 4 wavelengths with no transient signal degradation. Notably, a remaining wavelength path can keep high-quality data and video transmission. Figure 8 shows the wavelength spectrum after a link failure in the experiment, where 6 paths (blue) are reduced to 2 paths (red) [18]. We observed that conventional EDFA raised optical power in the status change while burst-tolerant one did not. This framework is extendible to M:N protection, where N backup paths are prepared for M working paths.

C. Signal Fluctuation Propagation

A link failure causes degradation of quality of transmission (QoT) to the paths which do not transit the failed link as well as the disconnected paths at downstream nodes, as we discussed in the previous subsection. That is, optical signals are simultaneously disappeared at the later-hop nodes. More impressively, the QoT (Quality of Transmission) degradation propagates over a wide range of the network. We identified that a link failure causes temporal QoT degradation propagation of roughly 40 % existing paths in a whole network by conventional EDFA [19], which will be described below. Note that paths in the failure link are called disconnected paths in this paper. Paths of which quality is degraded by a link failure is called QoT damaged paths.

Figure 9 shows QoT degradation propagation in a network. There are three provisioned wavelength-multiplexed optical paths. After link 7 failed, optical signals disappeared at links 18 and 22 due to disconnection of path A. Then, paths B and C are excessively amplified due to the gain transient of EDFAs. It means that the QoT of provisioned paths B and C are degraded even if the paths do not transit the failure link. In this paper, we call these paths as QoT damaged paths. In addition, the QoT of paths which share links with the damaged paths is also degraded. Thus, QoT degradation is widely propagated. For example, in Fig. 9, after link 7 failed, path D is also insufficiently amplified due to the increased power of paths B and C. The QoT of path D is also degraded in spite of no sharing with path A via QoT damaged paths B and C.

The QoT degradation would be recovered by readjusting EDFAs and VOAs at each link, however, dynamic gain controlled function does not respond properly and quickly. Moreover, this gain control function is operated sequentially along the paths. During these sequential operations, many existing services, regardless of whether they transit through a failed link or not, suffer from signal quality degradation.

We confirmed network-scale impact of the QoT degradation propagation by computer simulation when conventional EDFAs are used [19]. We firstly adopted JPN12 network (12 nodes, 34 unidirectional links, Fig. 9) as evaluated topology. Optical paths are provisioned between all source-destination pairs. Each simulation trial, a link failure occurs and the optical paths through the failed link are disconnected. Figure 10 shows the number of affected links by link failure event. The horizontal axis means disconnected link ID. The vertical axis shows the number of affected links. From this figure, a link failure event forces other neighbor links to suffer optical signal power reduction. In the worst case, a link failure event (i.e., link 4) affects 10 links. This is roughly 30% of links, where the QoT of optical paths are damaged. Figure 11 plots the maximum, average, and minimum ratio of damaged paths per link in arbitrary one link failure cases. Note that this result does not include disconnected paths. Edge side links such as link 1 has no damaged paths. From this figure, when a link failure occurs, roughly 25% paths are encountered QoT degradation on average even if the paths do not transit a failure link. We suppose 7.5 dB or more variation of power gives severe influence on the paths through the conventional EDFAs from our previous empirical knowledge. Paths on 4 links among working 32 unidirectional links are damaged by a failure of a single link due to QoT degradation propagation.

From these results, optical paths on a wide range of networks are impacted even if a single link failure occurs. On the other hand, because burst tolerable EDFA can suppress transient optical power quickly, it is more effective for mitigating QoT degradation propagation compared with conventional EDFAs.

We experimentally demonstrated the signal power behavior of remaining optical paths at downstream in a link failure event [19]. 44 wavelengths with 100 GHz spacing are multiplexed at a single fiber, where 8 wavelengths come from a single source, *x* and (36-*x*) wavelengths come from other different sources. 36 wavelengths are multiplexed at first and remaining 8 wavelengths are then multiplexed at a different link.

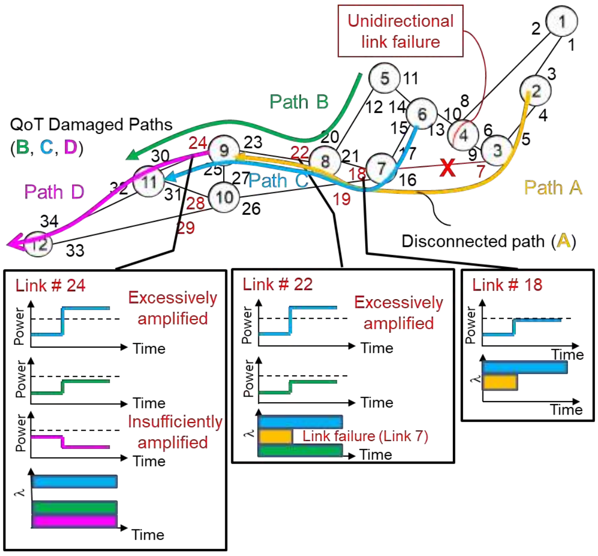


Fig. 9. QoT degradation propagation.

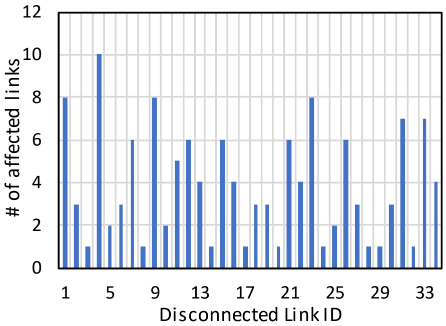


Fig.10: The number of affected links by one link failure in JPN12 topology.

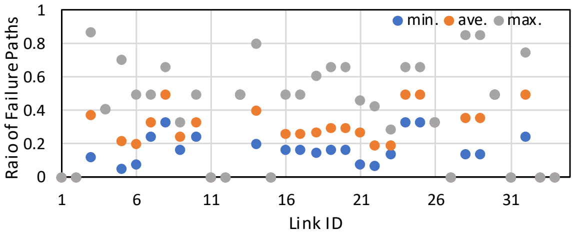
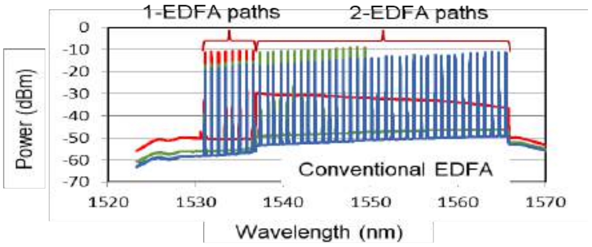
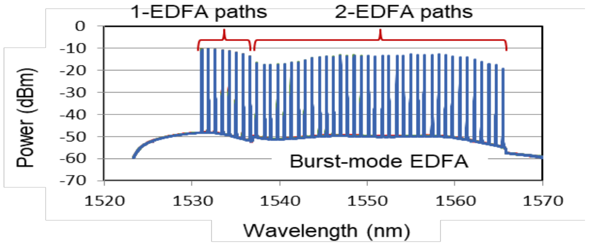


Fig. 11: Affected link ID v.s. Ratio of damaged paths against transit paths per link under arbitrary link failure case.



(a) with conventional EDFAs.



(b) with burst tolerated EDFAs.

Fig. 12: Spectra of optical paths measured.

At outputs of 36 and 44 wavelengths multiplexed, conventional EDFAs or burst tolerant EDFAs are inserted for compensating loss given by VOA. Therefore, optical paths on 36 wavelengths from two sources are transmitted through two-stage EDFAs and other optical paths on 8 wavelengths from the remaining source are transmitted through an EDFA. In each condition, *x* wavelengths are lost by the failure of the link.

Here, we investigated the variation of optical signal power of working optical paths. Figure 12 shows the spectra of optical paths measured in the case of conventional EDFAs and burst tolerable EDFAs. Three spectra acquired in 3 conditions ($x = 0$, 20, and 36) were superimposed. In conventional EDFA (Fig. 12(a)), we confirmed that disconnected optical paths due to a link failure gave the power change into remaining optical paths at multiple downstream nodes of the failure link. In addition, the power change became bigger as the number of disconnected paths increased. On the other hand, burst tolerant EDFAs did not affect the spectra and the signal power of remaining optical paths in all conditions (see Fig. 12(b)). When this experimental data is fed into simulation using JPN12 in Fig. 9, we observed that link 7 failure gives damage to paths on 4 links due to QoT degradation propagation [19].

V.2CONCLUDING REMARKS

Elastic and agile features for softwarized optical networks are promising to accommodation of diversified services. We have presented elastic and agile technologies for network construction, service continuation, and service update. Optical edge nodes that provide programmability among multiple network protocols and multiple classes of transmission and processing speeds for lower CAPEX and agile network setup, has been presented. Optical burst mode EDFAs for proper optical power management in network protection for service continuation of in-service paths have also been presented.

ACKNOWLEDGMENT

The authors wish to thank to Drs. Yoshinari Awaji, Masaki Shiraiwa, and Naoya Wada for continuous discussion of this work. This work includes direction and current outcome of Reconfigurable Lambda Project conducted by ALAXALA Corporation, NTT Corporation and Keio University.

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