Operational Evaluation of ASON/GMPLS Interdomain Capability over a JGN II Network Testbed

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ABSTRACT

Traffic engineering in backbone networks is an important issue in supporting an appropriate QoS level to accommodate various types of traffic flows efficiently. Automatically switched optical networks and generalized multiprotocol label switching control planes are promising functionalities to achieve the sophisticated mechanism of interdomain traffic engineering. In this article we address dynamic operational scenarios to control IP traffic flows using the ASON/GMPLS control plane. This includes cut-through IP/MPLS routers and the rerouting of failed links through the tunnel of optical label-switched paths. This article presents an operational evaluation of traffic engineering. More specifically, we present QoS recovery for protecting high priority traffic using policy controllers and fault recovery of inter-domain LSPs over the JGN II network testbed. This article evaluates and discusses the feasibility of these operational scenarios using state-of-the-art optical switching and control-plane technologies.

INTRODUCTION

Traffic engineering is a key technology to guarantee the quality-of-service (QoS) in large-scale backbone networks. In particular, the concept of traffic-engineered paths is quite important because this concept provides schemes to control explicitly the IP traffic flows. In actual commercial networks, traffic engineering already is used in many incumbent carriers. Many carriers manage paths based on a two-layer architecture, namely, the service path layer and the transport path layer in their networks. The rapid growth of data traffic has presented a great challenge in the architecture of networks and has made the adaptation of optically traffic-engineered paths a reasonable solution for the transport path layer; namely, the control of IP traffic flows is executed on an optical path basis.

In such networks, lambda-switching nodes such as optical cross connects (OXCs) handle a large amount of traffic efficiently because these approaches can reduce the complexity and node costs to handle especially high bit rate traffic, such as 10 Gb/s, 40 Gb/s, and more. In these lambda-switching networks, the operation, administration, and maintenance (OAM) functionality is achieved by optical transport network (OTN) architecture specified in the International Telecommunication Union-Telecommunication Standardization Sector (ITU-T) G.872 [1].

The automatically-switched optical network (ASON) and generalized multi-protocol label-switching (GMPLS) control-plane technologies are an effective solution to control these lambda-switching nodes such as OXCs and to provide next-generation high-performance transport networks. The ASON architecture is standardized by the ITU-T G.8080 [2], and the GMPLS architecture is standardized by the Internet Engineering Task Force (IETF) RFC3945 [3]. Here, ASON and GMPLS are used to refer to the control-plane architecture; in other words, heterogeneous control-plane architecture including various types of protocol sets and homogeneous control-plane architecture with only the set of GMPLS protocols, respectively.

JGN II is a national testbed employing such control-plane technologies and provides attractive opportunities to evaluate the inter-domain control-plane architecture. This architecture is essential for considering future deployment of these technologies. The JGN II network testbed includes three types of reference points, namely, IETF GMPLS internal network-network interface (I-NNI), external network-network interface (E-NNI), and Optical Internet Forum user-network interface (OIF-UNI) [4] to evaluate the

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operability of the inter-domain control-plane architecture.

This article discusses the capability of the ASON/GMPLS control plane and the optical path-based traffic engineering of IP traffic flows transmitted over these reference points. The rest of this article is organized as follows. We introduce the JGN II network testbed, which includes an explanation of key deployed technologies, such as the ASON/GMPLS gateway and ITU-T G.872 OTN technology [1]. We conducted a field evaluation of the traffic engineering focusing on the QoS recovery for protecting high priority traffic transmitted over OIF-UNI using policy controllers. We also conducted a failure recovery experiment of label-switched paths (LSPs) established over E-NNI. Finally, we summarize and conclude the article.

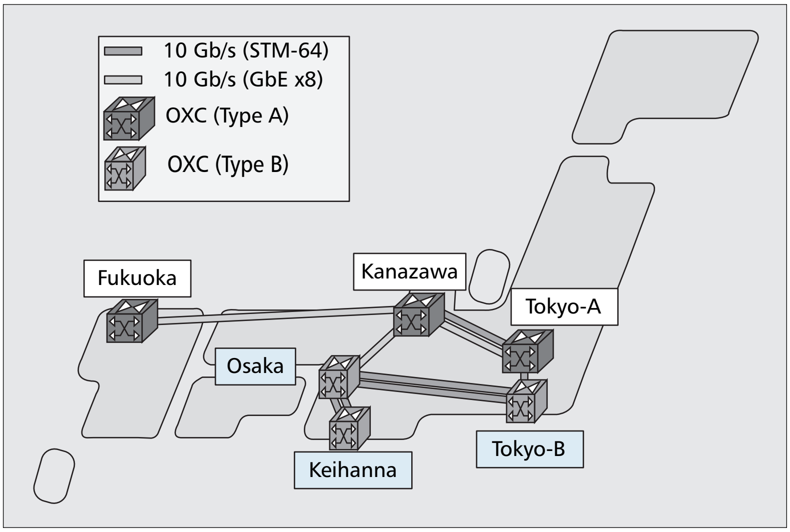
JGN II NETWORK TESTBED

The JGN II network testbed has been operated by the National Institute of Information and Communications Technology (NICT) since April 2004 to promote R&D activities related to advanced networking technologies [5, 6]. One main R&D target includes the operational evaluation of GMPLS inter-carrier networking technologies considering the prevalence of inter-carrier MPLS transport services such as MPLS-virtual private network (VPN) services. On the other hand, the JGN II network testbed also provides various types of network services such as the Ethernet connection service (L2 service) and IP connection service (L3 service), as well as optical wavelength service based on the ASON/GMPLS controlled OXCs.

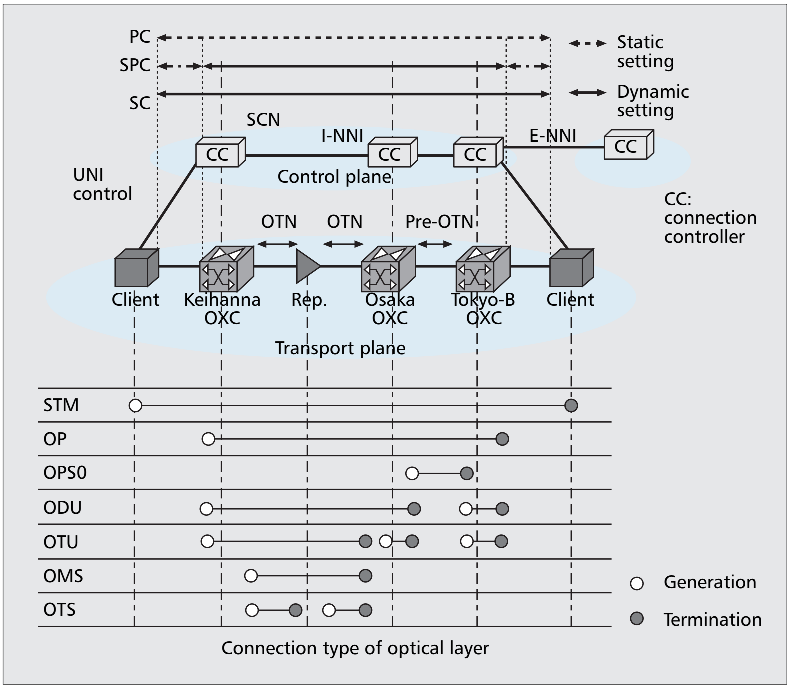
Figure 1 shows an overview of the GMPLS network in the JGN II network testbed. The network consists of two domains constructed using two different types of OXCs called the Type-A OXC and Type-B OXC. Type-A OXCs comprise three-dimensional micro electro-mechanical systems (3DMEMS) in optical switch fabric, and Type-B OXCs employ planar light wave circuits (PLCs) controlled by the thermal effect. The Type-A OXC equipped in the northern part of the network cross-connects gigabit or synchronous transport module-64 (STM-64) optical paths, whereas the Type-B OXC equipped in the southern part cross-connects STM-64 optical paths. In the southern network domain, Type-B OXCs support integrated management of the optical switch fabric and wavelength multiplexed fiber links. Type-B OXCs can isolate in a sophisticated way the failure of optical switches, fiber links, or optical amplifiers based on ITU-T G.872 OTN architecture. Also, Type-B OXCs support two kinds of section architecture, namely, the OTN section and the pre-OTN (synchronous digital hierarchy/ synchronous optical network [SDH/SONET] based wavelength division multiplexing) section.

MANAGEMENT OF OTN

Figure 2 shows termination points in optical-layer network management of Type-B OXCs. The OC192/STM64 of client data is managed as an optical path (OP) inside the OTN management network. Forward error correction (FEC), which is added to the optical transport unit (OTU) frame, provides supervisory functions to transport client data between optical channel termination points. The OTU overhead is inserted at the termination point of every optical multiplex section (OMS), which comprises a single or multiple optical transmission section(s) (OTS) [7]. In the pre-OTN section, the OXCs manage the section trail without assigning a specific wavelength and define the OPS0 (optical path section [OPS]) layer [8]. The OXC that terminates both the OTN and pre-OTN sections converts particular alarm indication signals between the OPS0 and OMS/OTS layers to achieve seamless OAM between these sections.



■ **Figure 1.** *GMPLS network configuration of JGN II.*



■ **Figure 2.** *Optical layer management and ASON architecture for type B OXCs.*

The main target of this study is the feasibility evaluation of the traffic engineering capability of the ASON/GMPLS control-plane technology to control the QoS of IP traffic flows that traverse over multiple domains and various types of reference points.

ASON/GMPLS CONTROL PLANE

Figure 2 also outlines the ASON architecture constructed over the OXC system. The architecture and requirements of ASON are described in ITU-T G.8080 [2]. The control plane consists of connection controllers (CCs) and a signaling control network (SCN) to enable CCs to communicate with each other. The ASON architecture specifies three kinds of reference points, namely, I-NNI, E-NNI, and UNI in the SCN.

On the other hand, the ITU-T G.8080 architecture defines three types of paths. The first one is a permanent connection (PC). The PC path is established by statically setting each OXC. The second one is a soft permanent connection (SPC). The SPC path is established by incorporating static and dynamic settings of the OXC and consists of the PC path between the OXC and client network elements (NEs) and a switched connection (SC) path between the edge OXCs. The third path is the SC. The SC path is established by a dynamic setting using the control-plane signaling, which is triggered by client NEs. The static PC path is used in cases where there is no need for autonomous control, or the network operators want to preserve network resources for static service requests from their customers. On the other hand, dynamic SPC paths and SC paths are used in cases where a client or operator wants to set the end-to-end path easily. This easy path setting can significantly reduce not only the operational burdens such as the accommodation design of the path, but also perform various types of recovery schemes. In this article, for simplicity, we call these SPC and SC paths GMPLS paths. The OXCs deployed in the JGN II testbed support all types of paths. Furthermore, the Type-B OXC supports an OIF-UNI in conformance with the ITU-T ASON control-plane architecture and employs the transport network assigned addressing (TNA) architecture [4].

TARGET OF THE EXPERIMENTAL STUDIES

The main target of this study is the feasibility evaluation of the traffic engineering capability of the ASON/GMPLS control-plane technology to control the QoS of IP traffic flows that traverse over multiple domains and various types of reference points. Specifically, this study focuses on the feasibility evaluation of QoS recovery using dynamic cut-through optical label switched path (OLSP) creation and link failure recovery by restoration, making use of the inherent ASON/GMPLS control-plane functionality and the state-of-the art OXC and OTN technologies. QoS recovery link and failure recovery represent the fundamental motivation behind deploying the ASON/GMPLS control-plane technologies in the Research and Educational (R&E) testbed community. In addition, implementing even part of these promising functionalities will pave the way to new types of services in commercial networks.

QOS RECOVERY EXPERIMENT

RELATED STUDIES

There are several studies that focus on achieving QoS recovery of IP traffic flows while optimizing network resource usage in ASON/GMPLS-based networks [9, 10]. In these studies, traffic engineering control is achieved by a network management system (NMS) or a centralized path computation element (PCE), which gathers network topology information from all NEs and exchanges a portion of information with peer domains. Also, the NMS and the centralized PCE can be used as network planning and provisioning tools to initiate transport services. In this architecture, LSPs are controlled dynamically by monitoring the amount of the traffic at each monitoring point. Furthermore, a traffic monitoring server collects the traffic information, projects a traffic matrix among monitoring points, and feeds back the suggested operation to the NMS or the centralized PCE.

Murayama et al. [9] proposed an optical VPN architecture based on centralized LSP traffic monitoring and an LSP routing scheme. Also, Nakahira et al. [10] reported the effectiveness of the routing of LSPs using centralized routing and NMS. The centralized scheme has global visibility of the network state and may potentially produce more optimal solutions. On the other hand, centralized schemes concentrate the processing load at the centralized traffic monitoring server and incur the round trip time of the control message between the NEs and centralized traffic monitoring. Therefore, we incorporate distributed control architecture into a part of the traffic engineering control. In other words, we evaluate the architecture that consists of a centralized policy setting point and distributed policy enforcement points to create and delete dynamically cut-through OLSPs.

EXPERIMENT OVER JGN II NETWORK TESTBED

Figure 3a shows details of the experimental configuration over the JGN II network testbed. As shown in the figure, the testbed in the trial comprises OXCs and routers at three locations, Keihanna, Osaka, and Tokyo-B, which are 500 km apart. In this experiment, 4K digital cinema is used as an example of a broadband application that requires optical networks to satisfy QoS requirements such as the GMPLS network. The NTT Network Innovation Laboratories are promoting and developing the 4K digital cinema system [11]. The 4K super high definition images used in the system have roughly 4,000 horizontal and 2,000 vertical pixels, offering approximately four times the resolution of the high definition (HD) television format and 24 times that of a standard broadcast TV signal. The system mainly consists of a 4K streaming server, decoder, and projector. We utilized two types of paths in the JGN II network testbed to confirm the traffic engineering mechanism. One is an MPLS-LSP whose bandwidth is 1 Gb/s Ethernet. The other type of path is a cut-through OLSP between Keihanna and Tokyo, which cuts through an intermediate router in Osaka.

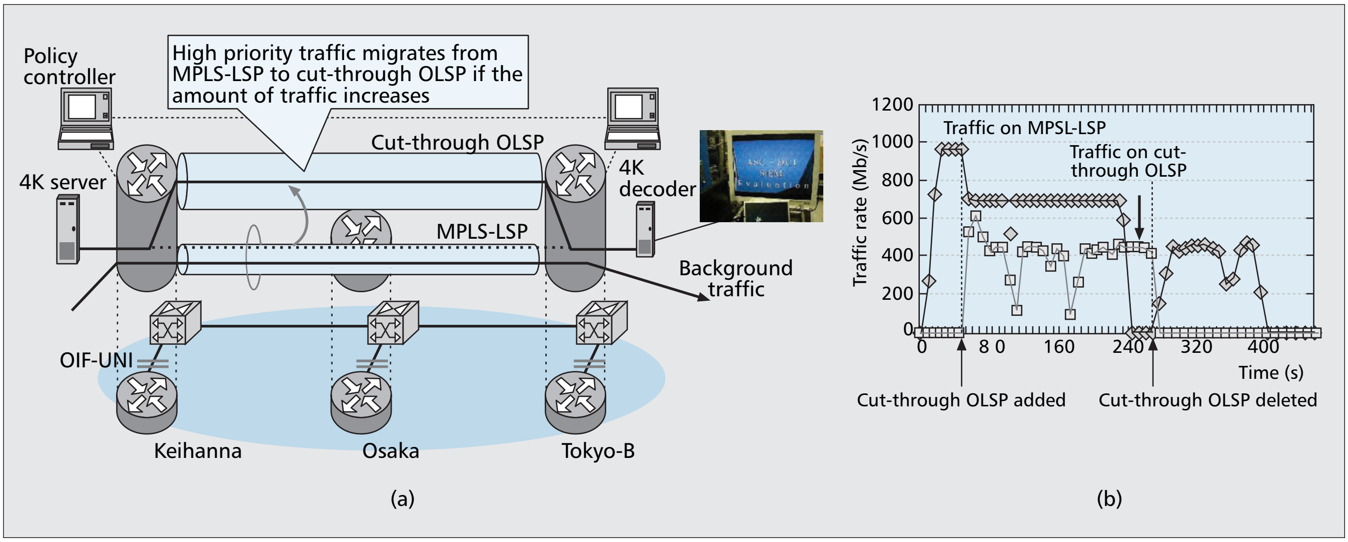


Figure 3. *a) Experimental configuration in JGN II network; b) traffic monitors during the migration of 4K traffic between MPLS-LSP and cut-through OLSP.*

In the actual experiment, initially both the 4K digital cinema traffic, which is given higher priority, and the background best effort traffic are transmitted from the router in Keihanna to the router in Tokyo through the router in Osaka. The policy controllers are configured with threshold bandwidth $R_{thh}(\alpha)$ (= $\alpha \times$ Bw) for the purpose of moving the appropriate traffic flows from the MPLS-LSP to the cut-through OLSP and for the opposite case, $R_{thl}(\alpha)$. Here, α is the threshold parameter set according to the operational policy, and Bw is the MPLS-LSP bandwidth [12]. According to the configuration, the policy controllers for the QoS recovery determine when the cut-though OLSP is set up/torn down by monitoring the traffic flows on the MPLS-LSP. These controllers also manage the routing functionality in the routers so that the 4K traffic flow, as expedited forwarding (EF) traffic, can use the cut-through OLSP, and other traffic can use the MPLS-LSP. When the traffic flow in the MPLS-LSP exceeds $R_{thh}(\alpha)$, the 4K digital cinema traffic migrates automatically from the MPLS-LSP to the cut-through OLSP controlled by the policy controllers. Each policy controller monitors the volume of traffic flow every eight seconds. For the threshold bandwidth of $R_{thh}(\alpha)$ and $R_{thl}(\alpha)$, the upper threshold parameter a was set to 80 percent of the bandwidth of the MPLS-LSP, and the lower threshold parameter was set to 30 percent of the bandwidth.

Traffic monitoring data during the migration of the 4K digital cinema traffic flow between the MPLS-LSP and the cut-through OLSP is shown in Fig. 3b. The amount of 4K digital cinema traffic is approximately 450 Mb/s, and the total amount of background traffic is 700 Mb/s. The policy controllers require approximately 16 seconds to make the determination to set up or tear down the cut-through OLSP. As shown in Fig. 3b, the 4K digital cinema traffic flow successfully moved from the MPLS-LSP to the cut-through OLSP when the background traffic was injected at eight seconds, and moved back from the cut-through OLSP to the MPLS-LSP when the background traffic was terminated at 248 seconds. Each migration takes approximately 32 seconds, including the determination time of the policy controller and the time to physically set up/tear down the cut-through OLSP.

In both cases, we confirmed that there was no confusion in the video images when migrating the 4K digital cinema traffic flow and that the QoS recovery of the 4K digital cinema traffic was successfully achieved.

LINK FAILURE RECOVERY EXPERIMENT

Next we conducted a link failure recovery experiment. We focused in particular on the link failure recovery of intercarrier LSPs. We describe the requirements for inter-carrier LSP recovery and evaluate the stitching LSP architecture to meet these requirements.

REQUIREMENTS FOR INTER-CARRIER LSP RECOVERY

Considering the basic inter-carrier operational environment, independent LSP control in each domain is desired. Furthermore, it is desired to support not only end-to-end LSP recovery operation, but also recovery operation on a domain-to-domain basis to prevent the failure affecting one domain to another. The "logically" hierarchical LSP architecture is an effective solution to enhance the independency of LSP control in each carrier domain while ensuring end-to-end LSP control over multiple carrier domains.

The stitching architecture prevents undesired outflow of the link failure information to other domains in a sophisticated way. Figure 4a shows the logical architecture of a single layer (contiguous) LSP and hierarchical (stitching) LSP compared from the viewpoint of the intercarrier operation [13]. In the case of contiguous LSPs, the operation is very simple, and this

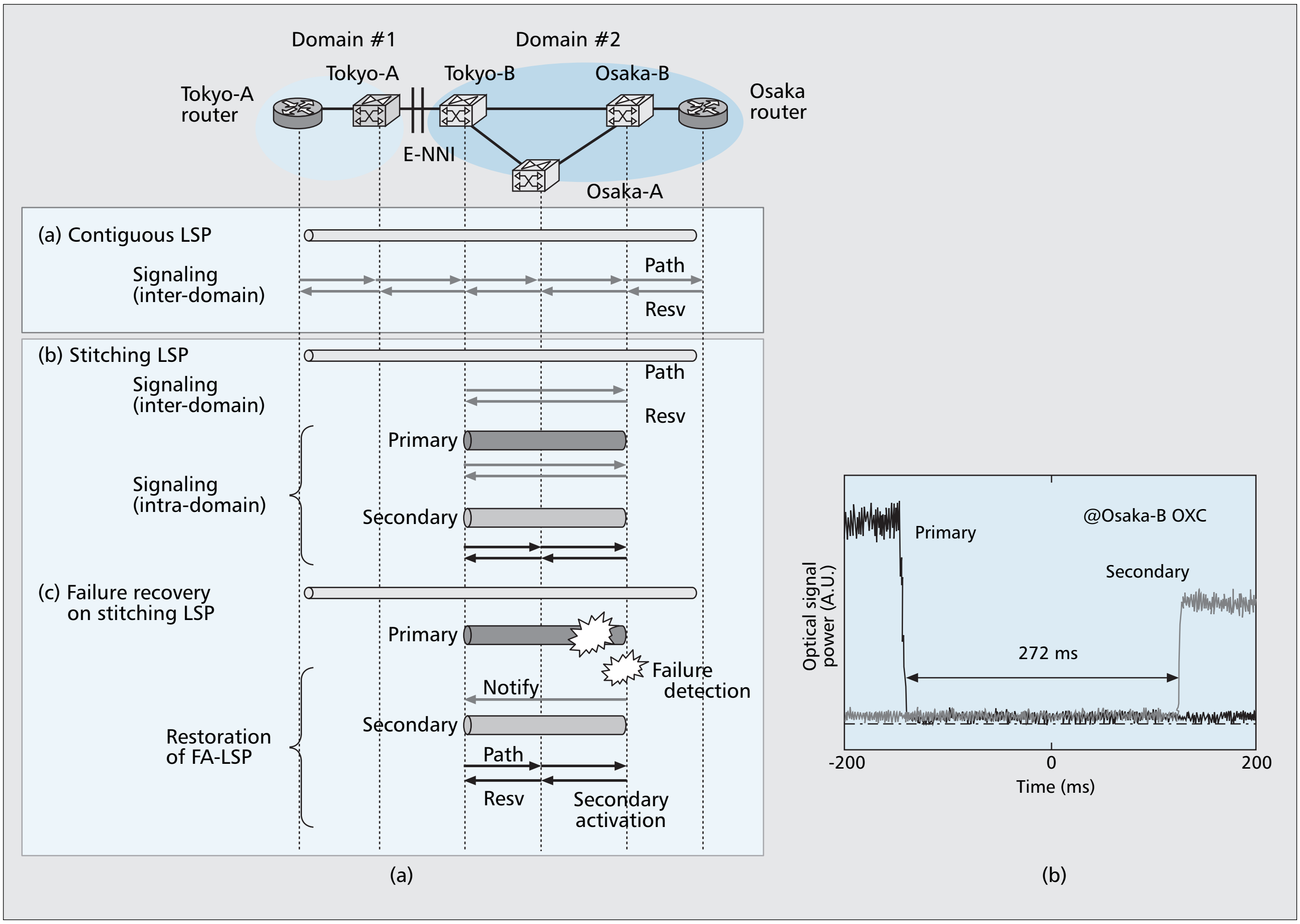


Figure 4. *a) LSP architecture and RSVP-TE signaling session of contiguous LSP and stitching LSP, and link failure recovery on stitching LSP; b) measured optical signaling power of primary and secondary paths.*

case is suitable for a single operator multi-domain environment, because only a single session must be maintained. On the other hand, in the case of a stitching LSP, to manage and control inter-carrier LSPs on a domain-to-domain basis, the end-to-end LSP is logically configured by stitching intracarrier LSPs to each other. By introducing a stitching mechanism to control the intra-carrier LSPs, even inter-carrier traffic engineering can be treated as intra-domain traffic engineering while eliminating the requirement for any LSP control messages to other domains.

EXPERIMENT OVER THE JGN II NETWORK TESTBED

Figure 4a shows the network configuration over the JGN II network testbed comprising two operational domains connected by 10-Gb/s synchronous optical network (SONET)/synchronous digital hierarchy (SDH) links. We evaluated both contiguous and stitching LSPs using the testbed. During the evaluation, the open shortest path first-traffic engineering (OSPF-TE) was running in each domain, but routing information was not dynamically exchanged between carrier domains.

We evaluated the stitching LSP creation in conjunction with network restoration on a domain-to-domain basis. To create an inter-carrier end-to-end LSP, an intra-carrier LSP was initially established from Tokyo-B to Osaka-B and then, advertised as a forwarding adjacency (FA) to make the created intra-carrier LSP a virtual TE link. Subsequently, the intercarrier LSP was successfully created by stitching the intracarrier LSP.

The restoration operation of inter-carrier LSPs also was evaluated. Intra-carrier LSP failure recovery is achieved by the Resource Reservation Protocol with Traffic Engineering Extensions (RSVP-TE)-based end-to-end restoration protocol. Due to the introduction of the stitching LSP architecture, a failure along even the inter-carrier LSP affects only the stitched FA-LSP within a domain, and the session can be maintained, although the end-to-end RSVP restoration operation caused the LSP to fail during a disruption. In the experiment, optical signal failure was caused by cutting the fiber link from the Tokyo-B OXC to the Osaka-B OXC. We successfully confirmed subnetwork restoration on a domain-to-domain basis at 272 ms as shown in Fig. 4b. By introducing a hierarchical signaling mechanism, independent network operation in different domains can be achieved without affecting the end-to-end RSVP-TE session in an actual operational environment.

DISCUSSION

As discussed in the previous sections, the operational evaluations of the QoS recovery and the link failure recovery exhibit the feasibility of inter-domain traffic engineering based on the ASON/GMPLS control-plane technology. However, further operational studies are required to complete the inter-domain traffic engineering based on the ASON/GMPLS control-plane technology.

Scalability — Although the inter-domain control-plane architecture is expected to provide scalable operation, a scalability evaluation using more lambda-switching nodes is required in future studies. Specifically, the experiments reported in this article were based on statistical routing to assign the gateway node facing the reference point of the E-NNI or the OIF-UNI. Future issues include the scalability evaluation of the interdomain routing protocol to discover automatically appropriate gateway nodes.

Traffic Engineering Over A Multi-Homed Domain Border — The experiments conducted in this study do not include the inter-domain LSP control experiment over a multi-homed domain border node facing a peer domain, which is a widely employed network topology in current IP networks. In such a network, it is essential to implement a policy control mechanism in selecting the inter-domain link, as well as a discovery mechanism for node-disjoint routes for the inter- domain LSPs.

Arbitration Mechanism to Solve Resource Contention — This article described the autonomous QoS recovery of high- priority traffic within about a half minute by the combined usage of the distributed policy controller and state-of-the-art ASON/GMPLS controlled OXC technology. However, the experiments did not examine the arbitration mechanism to solve resource contention between multiple calls of cut-through OLSP requests. One choice includes the implementation of this arbitration functionality in the ASON/GMPLS control plane. However, a prudent assessment is required with the view of optimal usage of network resources, reliability of services, and manageability.

Fast Restoration Time — The optical path layer must be recovered before activating the recovery process in the upper layer. However, the restoration time of the link failure recovery that we measured took 272 ms. To satisfy the above requirement, it is necessary to improve the RSVP-TE functional block so that fast forwarding of restoration messages can be achieved, and to improve the receiver so that fast synchronization with the optical data clock can be achieved. Also, some mechanisms should be implemented to coordinate recovery functions between layers. For example, when the GMPLS-based recovery is executed in the lower layer, a signaling or alarm indication mechanism should be implemented to delay the triggering of the upper layer recovery.

CONCLUSIONS

This article evaluated the inter-domain traffic engineering capability of the ASON/GMPLS control plane. Specifically, this article addressed two primary motivations to apply the ASON/GMPLS control plane over the optical transport networks, namely, the QoS recovery by dynamically creating cut-through OLSPs and the link failure recovery of the OLSPs. The JGN II network testbed provided a valuable opportunity to evaluate such inter-domain traffic engineering functions.

The QoS recovery successfully achieved the migration of high-priority video traffic with no confusion from the MPLS-LSP to the cut-through OLSP and vice versa over the JGN II network testbed within about a half minute. There was no packet loss for high-priority traffic flows when migrating traffic between MPLS-LSP and optical LSPs. This indicates that the proposed distributed traffic control scheme is applicable to data transport services that require low packet-loss rates such as content delivery service of video. In addition, link failure recovery also was confirmed by using hierarchal LSP over the JGN II network testbed. These results show that the hierarchical LSP can perform link failure recovery without the outflow of any control packets to an outside domain and is effective as an actual operational requirement. Although these operational evaluations of the ASON/GMPLS inter-domain traffic engineering capability are primitive compared to the expected operational scenarios in future networks, the authors believe that the achievement of this activity provides a valuable first example to understand the performance of the inter-domain traffic engineering capability using state-of-the art software technologies; namely, the ASON/GMPLS control-plane technology and hardware technologies; namely, optical switching and transport technologies.

The authors believe that the achievement of this activity provides a valuable first example to understand the performance of the inter-domain traffic engineering capability using state-of-the art software technologies.

REFERENCES

[1] ITU Rec. G.872, "Architecture of Optical Transport Networks," (ITU 2001).

[2] ITU Rec. G.8080/Y.1304, "Architecture of Automatically Switched Optical Network (ASON)," (ITU 2006).

[3] E. Mannie, Ed., "Generalized Multi-Protocol Label Switching (GMPLS) Architecture," IETF RFC3945, 2004.

[4] OIF-UNI 1.0 Rel. 2 "OIF-UNI-01.0-Common-User Network Interface (UNI) 1.0 Signaling Specification, Release 2: Common Part" (OIF 2004)

[5] T. Otani *et al.*, "GMPLS/OXC Network Testbed of JGN II," *Proc. Int'l. Conf. Testbeds and Research Infrastructures for the Development of Networks and Communities (TRIDENTCOM)*, CD-ROM, 2006.

[6] Y. Sameshima *et al.*, "Nation-Wide GMPLS/OXC Networking Experiments over JGN II Testbed," *Proc. SPIE 6388-01*, 2006.

[7] ITU Rec. G.709/Y.1331, "Interfaces for the Optical Transport Network (OTN)," (ITU 2003).

[8] Y. Koike *et al.*, "Intelligent and Reliable Photonic Cross-Connect System Based on Overlay Model," *J. Lightwave Tech.*, vol. 25 no. 6, June 2007, pp. 1356–71.

[9] J. Murayama *et al.*, "Traffic-Driven Optical IP Networking Architecture," *IEICE Trans. Commun.*, vol. E86-B, no. 8, Aug. 2003, pp. 2294–2301.

[10] Y. Nakahira *et al.*, "Traffic Driven IP Optical Path Rearrange Network System Using PSC/LSC Multi-Layer GMPLS," *Proc. European Conf. and Exhibition on Optical Commun. (ECOC)*, WE4, 147, 2004.

[11] T. Yamaguchi *et al.*, "SHD Movie Distribution System Using Image Container with 4096 × 2160 Pixel Resolution and 36 Bit Color," *Proc. IEEE Int'l. Symp. Circuits and Systems*, May 2005, pp. 5918–21.
[12] Y. Tsukishima *et al.*, "The First Application-driven Lambda-on-Demand Field Trial over a U.S. Nationwide Network," *Proc. Optical Fiber Commun. Conf. (OFC)*, PDP48, Mar. 2006.
[13] A. Farrel *et al.*, "A Framework for Inter-Domain Multiprotocol Label Switching Traffic Engineering," IETF RFC4726, Nov. 2006.

BIOGRAPHIES

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YASUNORI SAMESHIMA received his B.E. degree in mathematics from Keio University, Kanagawa, in 1988. He joined NTT in 1988. Until 1999, he was engaged in the R&D of designs for tests for LSIs. He worked in establishing the global IP-VPN service in NTT communications from 2000 to 2003. Since 2004 he has studied optical transport networking technologies, such as GMPLS. He also has been working as a research fellow at the NICT Tsukuba Research Center since 2004.

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WATARU IMAJUKU [M'98] has been consistently engaged in R&D activities on optical amplifiers, high-speed photonic transmission, and photonic IP networking since assuming a position at the NTT laboratories in 1994. Currently, he is a senior research engineer at the NTT Network Innovation Laboratories. He led the development and deployment of the project on generalized MPLS in the NTT laboratories, authored or coauthored more than 70 publications, and holds about 30 patents in his research field.