A Multi-Area MPLS/GMPLS Interoperability Trial over ROADM/OXC Network

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ABSTRACT
This article describes the first multi-area multiprotocol label switching and generalized MPLS interoperability trial over a reconfigurable optical add/drop multiplexer and optical cross-connect network. The interoperability trial demonstrated the routing of label switched paths over a multi-area GMPLS controlled ROADM/OXC network and the control of Ethernet over MPLS transport service on top of the GMPLS network. The trial was conducted using various network elements provided by 14 institutions and was carried out in Tokyo and Virginia. This article introduces the motivation for the trial, technical issues related to controlling multiarea MPLS/GMPLS networks, test network topology, and experimental results. The results show that the interior gateway routing protocol-based multi-area routing architecture is a promising solution for the nationwide deployment of GMPLS networks within a carrier domain. In addition, this article discusses the technical issues of routing constraints in ROADM/OXC networks and the limit of multiarea routing without the Path Computation Element Protocol.

INTRODUCTION
The generalized multiprotocol label switching (GMPLS) technology [1] is a framework that unifies network control of various types of network elements (NEs) across multiple network layers. This framework not only enables network operators to simplify the development of network control functionality in their network management systems, but also provides a foundation for the deployment of resilient and reliable networks. To gain such key benefits, the inter-operability of GMPLS protocols across NEs is of critical interest. Many network operators and vendors have expended significant effort and have conducted a number of MPLS/GMPLS interoperability trials since the initiation of GMPLS standardization activity in the Internet Engineering Task Force (IETF). Due to these efforts, the feasibility of the GMPLS control architecture was proven, and the interoperability of current GMPLS protocols was significantly improved with the help of the GMPLS addressing draft [2], which was created through the experience of these interoperability testing activities [3,4]. As a result,
GMPLS technology has matured to the point of more realistic deployment and operational scenarios, such as the integration of GMPLS with existing Internet Protocol (IP)/MPLS networks and GMPLS control over intra/inter-carrier multiple routing domains.

This article introduces an interoperability trial of a multi-area MPLS/GMPLS network employing the Inter-Gateway routing protocol (IGP). This functional evaluation is quite important in overcoming the scalability limitations of a single-area routing architecture and the operation of hundreds of NEs within a nationwide carrier domain. The primary motivation of this trial was to evaluate key functionalities for the control of inter-area label-switched paths (LSPs) across nationwide GMPLS networks, including an evaluation of the limit of the per-domain path calculation (PDCP) [5] solution. An additional motivation included the evaluation of the GMPLS control plane integration with several well-established optical technologies and services that use the MPLS/GMPLS infrastructure such as the Ethernet over MPLS (EoMPLS) transport service. The authors believe that this trial is unlike any previous trial because it conducts single-carrier and multi-area routing architecture in an optical network domain, which is different from the previous trials that employed single-area [3, 4], hierarchical [6], and inter-autonomous system (AS) routing architecture [7]. The testbed network, which comprised network elements from 14 institutions, including (GM)PLS test equipment, IP/MPLS routers, time-division multiplexing cross-connects (TDM-XCs), and optical network elements of reconfigurable optical add/drop multiplexer (ROADMs) and optical cross connects (OXCxs) with multi-area routing architecture, was constructed over a transpacific control network between the Toyo Corporation in Tokyo and Isocore in Virginia.

TECHNICAL ISSUES FACING MULTI-AREA MPLS/GMPLS NETWORKS

The technical difficulty related to the inter-area routing of LSPs originates from the specification of traffic engineering (TE) extensions to the existing IGPs, considering scalability limitations [8]. In the case of the Open Shortest Path First (OSPF) protocol, the advertisement of TE information is limited to the local area scope to reduce the volume of the advertised TE link information. This functional specification is quite important from the view point of operational stability. Traditionally, carriers have separated routing areas into a reasonable size or adequate operational domain, which is quite effective in preventing failure propagation across networks and in minimizing the impact on commercial networks. Consequently, a GMPLS-controlled NE is not capable of calculating a full end-to-end route for the LSPs. To cope with this issue, the current IETF proposal includes the employment of the:

* PDCP scheme [9]
* Signaling of loosely routed paths [10]

PER-DOMAIN-PATH CALCULATION

A routing strategy of MPLS/GMPLS protocols widely employed in current vendor implementations is a "source-routing" strategy. Namely, the route calculation is performed at the ingress node of the LSP, based on the traffic engineering database (TED) and the Constraint-Based Shortest Path First (CSFP) algorithm stored in the node. In the case of route calculation of inter-area LSP, the ingress node must discover the area border node to route the LSP toward the egress node and then perform a CSFP calculation to the area border node. The application of Path Computation Element Protocol (PCEP) [5] currently discussed in the IETF PCE-working group (WG) includes automatic discovery of the area border nodes to perform full automatic inter-area calculation. This benefit also exists in the case of route calculation and discovery of autonomous system border nodes for inter-domain LSPs.

It also is possible to apply a gateway routing strategy. In this scenario, the assignment of the area border node is performed statistically or manually, based on the operational policy of network service providers. Specifically, for the service providers employing a ring-based network topology, this design, which requires a partly manual LSP establishment and assignment of area border nodes, may be an acceptable operational burden. This article assumes such an operational scenario. The target of this trial is to evaluate the PDCP solution, namely the evaluation of the PDPC function utilizing statistically or manually assigned area border node information on the route of the inter-area LSPs.

SIGNALLING OF LOOSELY ROUTED PATHS

Figure 1 outlines the procedure of signaling to create a loosely routed LSP based on the gateway routing strategy. The head-end node of the LSP performs the CSFP calculation toward the area border node and inserts the route information obtained by the CSFP calculation into the signaling message. The signaling message is transmitted node by node along the LSP. After receiving the signaling message, the area border node performs a CSFP calculation toward the destination node of the LSP to be created. If the destination node is outside of the area to which the area border node belongs, the area border node performs a CSFP calculation toward the next area border node. In the gateway routing strategy, the next-hop area border node is statically configured according to the destination node in the area border node. The area border node then sends the signaling message toward the destination node. The process iterates with the next-hop area border node performing a similar procedure to create the inter-area LSP.

Thus, the target of this testing includes the evaluation of the interoperability of ReSource reserVarion Protocol with Traffic Engineering (RSVP-TE) to create loosely routed paths and the combined operation of the RSVP-TE and the PDPC at the area border OXCs (ABR-OXCs).
The ABR-OXC performs the PDPC, based on the TE link information within the area to which it belongs. After receiving an RSVP-TE signaling message from the upstream node, the ABR-OXC processes the explicit route object (ERO) within the messages.

**Figure 1. Procedure of the per-area hop route calculation and the signaling of a “loosely routed path.”**

**MULTI-AREA MPLS/GMPLS TESTBED**

Figure 2 shows an overview of the IGP routing architecture in the MPLS/GMPLS testbed. The routing area of the MPLS and GMPLS layers were isolated. The MPLS network was constructed with an OSPF backbone area (Area 0). The GMPLS layer was comprised of a backbone area and three sub-areas making up the overall testbed network. The backbone area (Area 0) of the GMPLS domain was allocated to the OXC network area. On the other hand, the sub-area numbers area 1, 2, and 3 of the GMPLS domain were allocated to the TDM-XC network area in Virginia (Isocore site) and two ROADM network areas in Tokyo (Toyo Corporation site), respectively. All of MPLS/GMPLS border routers were located in the sub-areas of the GMPLS domain.

**Figure 2. Overview of routing area architecture.**

Table 1 shows the detailed list of network elements equipped for the interoperability trial. The network comprises mainly four types of switching capabilities, namely, IP/MPLS/GMPLS testers, MPLS routers, MPLS/GMPLS border routers as packet-switch capable (PSC), ROADMs as lambda-switch capable (LSC), and TDM-XCs and OXCs used as fiber-switch capable (FSC), and a total of 25 NEs from 14 institutions.

Figure 3 shows a detailed configuration of the network, constructed in Tokyo and Virginia. The network comprises synchronous transport module (STM)-16, optical Gigabit Ethernet (GbE), and STM-16/GbE multirate optical links. Here, the STM-16/GbE multirate links were constructed in the section between peer OXCs. Dataplane links between the ABR-OXCs in Tokyo and the area 1 network in Virginia were configured using virtual STM-16 links. Namely, the synchronous digital hierarchy/synchronous optical network (SDH/SONET) interfaces between them set loopback to virtually activate the transpacific data link. Additionally, four out-of-fiber signaling control networks (SCNs) were constructed according to routing area separation. A transpacific Internet Protocol security (IPSec) tunnel also was established over the public Internet to connect the ABR-OXCs at the Tokyo site into the SCN in Virginia. Generic routing encapsulation (GRE) tunnels also were created over some SCNs to form virtual point-to-point control channels between peer GMPLS capable nodes.

**AREA BORDER OXC**

The ABR-OXC performs the PDPC, based on the TE link information within the area to which it belongs. After receiving an RSVP-TE signaling message from the upstream node, the ABR-OXC processes the explicit route object (ERO) within the messages. The RSVP-TE signaling...
instance in the ABR-OXC requests the CSPF instance to execute a route calculation toward the next-hop area border node considering the destination node of the LSP. The RSVP-TE signaling instance then inserts a new ERO into the RSVP-TE message to assign a detailed LSP route within the area, based on the result of the CSPF calculation. In other words, the ABR-OXC executes a so-called ERO expansion, taking responsibility to determine the route of the inter-area LSP downstream of the routing area to which the ABR-OXC belongs. The ABR-OXCs are designed to search next-hop ABR-OXCs dynamically by using the "Summary link state attribute (LSA)" of the OSPF-TE protocol as a temporal solution if there is no next-hop ABR-OXC node in its static routing tables. Each ingress node selects the default ABR-OXC in its sub-area to create the inter-area LSPs.

**MPLS/GMPLS BORDER ROUTER**

The MPLS/GMPLS border router also acts as an area border node. MPLS/GMPLS border routers support MPLS LSP hierarchy and virtualize the LSPs created in the GMPLS domain as forwarding adjacencies in the MPLS domain, which enables autonomous routing of MPLS LSPs within the MPLS domain. In the MPLS domain, the interoperability test of MPLS RSVP-TE also was conducted using four routers from two vendors to evaluate the functionality of Ethernet over MPLS (EoMPLS) transport over the GMPLS network. A video stream was transported over the Ethernet pseudo-wire established among MPLS routers and MPLS/GMPLS border routers.

**EXPERIMENTS AND RESULTS**

In the first step of this testing, the interoperability of the OSPF-TE protocol was evaluated. At the initial stage of the testing, the ABR-OXC did not have the capability to advertise router address type-length-value (TLV) [8] for the multiple routing areas to which the ABR-OXC belonged. After resolving this problem, we successfully achieved multi-area operation of the OSPF-TE protocol. The ABR-OXCs communicated with each other to establish dynamic OSPF-TE area LSA of the ABR-OXC protocol; however, the ABR-OXCs failed to create the routing table to assign next-hop ABR-OXCs to reach destination nodes outside their area. This was because some GMPLS routers inactivate advertising functionality of reachability information toward their node IDs (node ID advertisement as stub area in router LSAs). Therefore, for this experiment, we manually set next-hop ABR-OXCs to reach destination nodes in the static routing tables of the CSPF instance within each ABR-OXC. Hereafter, this article explains the results of:

- GMPLS signaling interoperability to control strictly routed inter-area LSPs
- GMPLS signaling interoperability to control loosely routed inter-area LSPs
- MPLS signaling interoperability to initiate Ethernet transport service over the MPLS/GMPLS network

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Network element type</th>
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<tbody>
<tr>
<td>A</td>
<td>IP/MPLS routers</td>
</tr>
<tr>
<td>B</td>
<td>IP/MPLS/GMPLS routers</td>
</tr>
<tr>
<td>C</td>
<td>IP/MPLS/GMPLS routers</td>
</tr>
<tr>
<td>D</td>
<td>IP/GMPLS routers</td>
</tr>
<tr>
<td>E</td>
<td>IP/MPLS/GMPLS testers</td>
</tr>
<tr>
<td>F</td>
<td>IP/MPLS/GMPLS testers</td>
</tr>
<tr>
<td>G</td>
<td>TDM-4C(STM-16xOC-48c Xc)</td>
</tr>
<tr>
<td>H</td>
<td>TDM-4C (STM-16xOC-48c Xc)</td>
</tr>
<tr>
<td>I</td>
<td>OXC</td>
</tr>
<tr>
<td>J</td>
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</tr>
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<td>L</td>
<td>OXC</td>
</tr>
<tr>
<td>M</td>
<td>ROADM</td>
</tr>
<tr>
<td>N</td>
<td>ROADM</td>
</tr>
</tbody>
</table>

Table 1. List of evaluated NEs.

**GMPLS SIGNALING INTEROPERABILITY OF STRICTLY Routed PATHS**

The interoperability testing of the GMPLS RSVP-TE signaling was conducted assuming a scenario where the operators manually design the route of inter-area LSPs. In this operational scenario, the RSVP-TE signaling message includes the ERO to strictly assign the route of LSPs. The interoperability testing evaluated two types of LSPs:

- SDH
- Ethernet encoding

Type was assigned in the generalized label request object of the Path message to create STM-16 and GbE LSPs, respectively. Some OXCs accommodating STM-16/GbE multirate links inactivated the encoding type check and generalized payload identifier (G-PID) in the generalized label request object assigning the type of LSPs and SENDER traffic specification (TSPEC)/FLOW SPEC objects assigning bandwidth of LSPs.

Table 2 describes the LSP routes and the round trip time (RTT) of RSVP PATH/RESV two-way signaling messages to create each LSP. The RTT of the RSVP PATH/RESV message ranged from 64 msec to 11.6 sec—performance that is good enough to realize fast provisioning in service providers' networks. Most scenarios that exceeded a one-second RTT included transit NEs that control the STM-16 interfaces. The time to initiate IP packet forwarding typically requires eight to nine seconds in addition to the...
RTT. This includes the processing time for changing IP forwarding tables in the MPLS/GMPLS border routers. In the case of GbE interface, the negotiation of Address Resolution Protocol (ARP) also is executed between the pair of the MPLS/GMPLS border routers before initiating IP-packet forwarding. The IP-packet forwarding time was 17.8 sec after transmitting the RSVP PATH message from the ingress node, when the LSP traversed seven switches in two ROADM sub-areas and the backbone OXC area (scenario 1 in Table 2).

**GMPLS Signaling Interoperability of Loosely Routed Paths**

Next, the interoperability testing of the GMPLS RSVP-TE signaling was conducted assuming the scenario that the operators manually assign only node IDs of the ABR-OXC attached to the source area and destination node of inter-area LSPs. In this operational scenario, the RSVP-TE signaling message includes an ERO that loosely assigns these two nodes. Specifically, we evaluated the PDPC function of the ABR-OXCs that belonged to the backbone area or destination area.

Table 2 also describes the LSP routes and the RTT of RSVP PATH/RESV two-way signaling messages in this operational scenario. The dominant factor of the inter-area LSP is not the route calculation time in each ABR-OXC, but the interface control of the NEs. The PDPC function was successfully performed in less than 50 to 100 milliseconds in the ABR-OXCs in three LSP creation scenarios. Each ABR-OXC successfully inserted a new ERO into the RSVP-TE message to assign a detailed route in the transit area and destination area. For example, node L1 inserts node K and L2 into the ERO to assign a detailed route of the transit area, and node L2 inserts node I to assign a detailed route of the destination area in the case that an inter-area LSP is created between node B1 and B2.

On the other hand, we must comment on failed scenarios — specifically, the LSP creation scenarios wherein the LSP traverses a ROADM ring in the destination area. Because the ABR-OXCs do not have the ability to understand constraints such as the asymmetric switch architecture of ROADMbs, the ABR-OXC failed to calculate a precise route for inter-area LSPs in the ROADM/OXC hybrid destination area. These issues are addressed in the Discussion section below.

**Ethernet Pseudo-Wire Over MPLS/GMPLS Network**

On top of the GMPLS layer, an Ethernet pseudo-wire also was established by employing MPLS LSP hierarchy. The MPLS domain consists of three layers in this trial as depicted in

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**Table 2. Ten successful scenarios and round-trip time of RSVP PATH/RESV messages to create LSPs.**

<table>
<thead>
<tr>
<th>Type</th>
<th>LSP route</th>
<th>Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OC48 E1-N1-N2-L1-L2-I-M1-M2-E2</td>
<td>9,209</td>
</tr>
<tr>
<td>2</td>
<td>OC48 E2-M2-M1-L1-L1-I-N2-N1-E1</td>
<td>6,928</td>
</tr>
<tr>
<td>3</td>
<td>OC48 D3-N3-N2-L1-K-L2-M1-M2-D2</td>
<td>11,653</td>
</tr>
<tr>
<td>4</td>
<td>OC48 B1-L1-C</td>
<td>64</td>
</tr>
<tr>
<td>5</td>
<td>OC48 B1-L1-G-B3 (Transpacific)</td>
<td>890</td>
</tr>
<tr>
<td>6</td>
<td>OC48 D2-M2-M1-L2-H-F (Transpacific)</td>
<td>7,027</td>
</tr>
<tr>
<td>7</td>
<td>GbE B1-N1-N2-L1-I-L3-I-B2 (per area route calc.)</td>
<td>5,216</td>
</tr>
<tr>
<td>8</td>
<td>GbE B1-L1-L2-I-B2 (per area route calc.)</td>
<td>583</td>
</tr>
<tr>
<td>9</td>
<td>GbE B1-L1-K-L2-I-B2 (per area route calc.)</td>
<td>694</td>
</tr>
<tr>
<td>10</td>
<td>MPLS A1-B2-(LSP 7 or LSP 8) B1-A2</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 4. The lowest MPLS layer acts as an FA-LSP between the MPLS/GMPLS border routers. The FA-LSP can provide a protection capability to cope with the failures in the GMPLS domain, if the MPLS FA-LSP is established with a primary and secondary path. The FA-LSP is advertised into the MPLS domains as a TE link by the MPLS/GMPLS border router. The middle MPLS layer is an LSP controlled by the RSVP-TE protocol session between provider edge (PE) routers. Finally, the upper MPLS layer acts as a virtual private LAN service (VPLS) layer, which is controlled by a Label Distribution Protocol (LDP) session. The PE routers build a medium access control (MAC) address table from the Ethernet traffic transiting through those devices and destined to the remote computation elements (CEs).

In the experiment, we connected a movie camera and two personal computers with IP addresses of 10.10.10.24 and 10.10.10.24 to the PE routers. It took 58.9 sec before the first Ethernet frames were forwarded and available on the edge MPLS routers after transmitting the RSVP-TE PATH message from the GMPLS routers to create an LSP in the lowest GMPLS layer. This time includes the process of the GMPLS LSP creation, the MPLS base FA-LSP creation, the re-estabishment of MPLS LSP between the PE routers, and the ARP process to associate IP/MAC addresses pairs. After investigation, it appeared that advertising the FA into the IP/MPLS network required some cycle. This cycle is expected performance in re-optimizing the routes of MPLS LSPs to transit over the newly created GMPLS LSP. At this stage, this performance seems sufficient for the purpose of MPLS LSP re-optimization, although it is necessary to conduct further evaluation and assess the dependency on number of nodes, MPLS LSPs, and so on.

**DISCUSSION**

The results of the experiment demonstrate that the interoperability of basic GMPLS protocol suites has become almost stable. We encountered only a few problems in the experiment related to the interpretation and implementation of basic GMPLS extensions in the IETF RSVP-TE protocol documents. We encountered problems of routing mainly related to two aspects:

- Routing signaling packets in the control plane
- Routing LSPs, considering constraints in the data plane

Through the experiment, we found that the stability and performance of the control plane functionality of ABR-OXCs greatly impacts the overall operability of GMPLS networks. With the routing architecture established in this experiment, all end-to-end signaling packets such as RSVP-TE notify messages or RSVP-TE signaling messages stitched or nested to the optical LSPs transit the control plane module of the ABR-OXCs. Also, explicit requirements to advertise IP reachability information are quite important for exchanging such end-to-end signaling packets, which is also valid for the PCE architecture [5] in discovering “next-hop PCE” in the route calculation of inter-area/AS LSPs.

Furthermore, the extension of the GMPLS traffic engineering specification is required to cope with the advent of new optical switches such as ROADMs and transparent OXCs. In the transparent optical network with the ROADMs and OXCs, each LSP traverses in single wavelength over optical multiplex sections (OMSs) to satisfy so-called wavelength continuity constraint. Namely, the GMPLS traffic engineering specification must incorporate the information of the resource status of wavelength space in fibers forming OMSs so as to take into account the wavelength continuity constraint. In other words, the information should include transparent opti-
cal network domain-wide unique encoding to represent the wavelength space over each OMS. In addition, the traffic engineering information should properly represent not only the asymmetric selectivity of optical switches but also the capability of wavelength conversion in ROADM and OXC.

Furthermore, the optical transport network can accommodate various types of optical LSPs having different data rates. We employed commercially available regenerators capable of regenerating optical signals with an intensity modulation and direct detection (IM-DD) format of up to 2.4 Gb/sec data rate. However, there is no adequate specification to advertise the status and capability of the fiber links, taking into account the bandwidth of optical band-pass filters inserted at both ends of the fiber links, the range of the supportable data range, and the modulation format of transmitter and receivers attached to both ends of the fiber links, and so on.

Currently, these problems are addressed in the IETF draft of [11]. The representation called lambda labels provides an effective way to understand the resource status of wavelength space in each OMS. Also, this IETF draft proposes the incorporation of connection matrix and new link attributes to represent constraints in the optical domain, which provides a solution to perform the CSPF calculation to create LSPs over the transparent optical network. Thus, continuous-standardization activity and evaluation processes are still required to realize worldwide deployment of the GMPLS control plane technology. Specifically for incumbent service providers employing photonic backbone networks, the transparent optical network is expected to be a unique service platform to support both legacy services, such as SDH/SONET-based private line services, and IP/Ethernet services with various types of maintenance, grades, reliability, quality of service, and so on. The PCE architecture for transparent optical network that is discussed in [11] also is helpful not only to overcome the IGP limitation on more optical information required for end-to-end path computation, but also to realize carrier-specific policy-based control in conformance to the policies of these services.

CONCLUSIONS
This article discussed the evaluation of MPLS/GMPLS control-plane technology mainly from three view points:
• The key functionality to control inter-area LSPs, namely, the PDPC function and the signaling to control loosely routed paths
• The integrity of the GMPLS control plane with state-of-the-art wavelength switching technologies
• The feasibility evaluation of services making use of the MPLS/GMPLS infrastructure such as Ethernet transport service

Due to the standardized definition of GMPLS, GMPLS-based networks are certain to be configured in a multi-vendor fashion. This article demonstrated a multi-area MPLS/GMPLS interoperability trial using various types of NEs from 14 institutions, that is, IP/MPLS/GMPLS testbeds from two vendors; an MPLS router from one vendor; MPLS/GMPLS border routers from two institutions, a LSR router from one institution; TDM-VCs and ROADM, respectively, from two institutions; and OXC from four vendors and institutions. To our knowledge, this trial was the largest interoperability trial based on a homogeneous GMPLS control-plane architecture, based on the number of participant vendors. The authors also discussed technical issues related to the control of transparent optical networks with ROADM and OXCs. On top of the GMPLS layer, we successfully confirmed service activation of the Ethernet transport service over a multi-vendor MPLS network. We successfully demonstrated sophisticated Ethernet transport service activation over a multi-area GMPLS network.

Finally, the authors note that this activity did not address interworking among various types of control-plane technologies other than IETF GMPLS although the authors believe that this activity can help enhance the scalability and an automatically switched optical network (ASON). Currently, the interworking among heterogeneous control planes is addressed actively by the Optical Interworking Forum (OIF) [6], and the OIF specifications are the most feasible solution for that case.

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