

# Signaling and Control Procedures Using Generalized MPLS Protocol for IP over an Optical Network

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**This paper reviews the existing research activities on signaling and control procedures for IP over optical networks. We focus on the IP-centric signaling and control architecture based on the generalized multi-protocol label switching (GMPLS) protocol and analyze various scenarios and technical issues for deploying the IP over an optical network.**

**We analyze the signaling and operations and administration and maintenance requirements for integrating an IP network and an optical network in order to cope with the high bandwidth and poor resource granularity of the optical network, including the optical cross-connect system. On the basis of network architecture and a reference configuration model, we investigate the GMPLS-based control architecture and interconnection model appropriate for controlling IP bandwidth and optical lambda resources. The signaling and control procedure based on GMPLS on optical user-network interface and network-network interface are comparatively investigated to provide the optical lightpath. We also study protection and restoration procedures to protect link failure when it applies to generalized MPLS signaling.**

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## I. INTRODUCTION

The rapidly increasing demand for more bandwidth, driven by the Internet, has led to a paradigm shift in the telecommunications industry to IP-centric networks. Optical networking using dense wavelength-division multiplexing (DWDM) in conjunction with optical cross-connects (OXC) presents many new opportunities for supporting faster and more flexible provisions of IP services [1]. As a network evolution strategy, IP-centric transport can give an overall solution that delivers QoS support and traffic engineering capability. Robust control is essential for the realization of the envisioned IP-centric transport for capacity expansion and cost reduction [2].

The control plane of an optical network is responsible for provisioning and maintaining optical lightpaths and managing network resources. Lightpaths Provisioning requires algorithms for route selection and signaling mechanisms to request and establish connectivity within the network along a chosen route [3]. Currently, a transport network has virtually no automatic control while it establishes, tears down, and maintains end-to-end connections. For a variety of reasons, the steps required for the provisioning process are generally very slow relative to switching speed and often inaccurate [4].

A major driving force for realizing the optical Internet is the potential ability of such networks to provide fast automatic setup and tear-down of lightpaths across the optical network and the capability of supporting diverse client signals on the lightpaths. The main focus, therefore, of today's optical network planning lies in implementing a dynamically reconfigurable optical transport

layer based on fast OXC's coupled with a suitable control and management architecture [1].

In the optical Internet, there are strong reasons for completely separating control messages from data traffic, so that the signaling is "out of band." Since all the data traffic passing through an OXC can be switched without reference to individual data packets, there is no need for the data plane part of the OXC to have any understanding of the protocol stacks that are needed for handling control messages. In particular, it may not be necessary for OXC's to electronically terminate individual links. Typically, therefore, an optical switch completely separates its control plane from its data plane [5]. On the other hand, multi-protocol label switching (MPLS) has the ability to separate routing control and forwarding. This ability allows extensions of the MPLS protocol to encompass different forwarding planes, including any type of circuit transport networks [6]. Recent work has extended and adapted the MPLS control plane, so that it can be used not only with routers and ATM switches, but also with OXC's. This is a fundamental step in the evolution and integration of data and optical network architectures [7].

The seamless integration of optical lightpaths into IP/MPLS networks allows a uniform control paradigm to span these different technologies and create a single consolidated network with lower operational expenses. It allows fast setup of lightpaths and a certain level of granularity for interoperability. For scalability, performance, and survivability requirements, IP-centric networks must be cost effective and provide control capabilities that facilitate network performance optimization. It is clear that new paradigms for control and management are needed for multi-service IP networks [8].

Following this introduction, in section II, we briefly discuss signaling and control requirements for IP over optical networks. In section III, we discuss the signaling and operations, administration and maintenance (OAM) architecture for IP over optical networks. The applications of generalized MPLS signaling for IP over optical networks is discussed in section IV. Finally, we draw our conclusions in section V.

## II. SIGNALING AND CONTROL REQUIREMENTS FOR IP OVER OPTICAL NETWORKS

Current provisioning of bandwidth in the optical network is static and takes extensive manual configuration. When it allows user devices to make requests to the optical network directly, it reduces the workload on the network operator and creates new value-added high-speed services. Intelligent optical switches which form the core of the next generation high-speed networks should have the capability of end-to-end bandwidth provisioning and distribution at the optical layer [9].

In terms of the scale and complexity of the future IP over optical networks, the following requirements on scalability and performance of optical control and management functions can be

defined [4], [6], [10], [11].

- Operation automation to discover network topology: The distributed control plane should provide carriers with enhanced automatic discovery of network topology by using a distributed routing protocol, such as the open shortest path first (OSPF) or border gateway protocol (BGP). On the other hand, the topology could also be auto-discovered in a central location as long as each node knows who its neighbors are through exchange of hello messages.
- Operation automation to setup connections: The control plane must have the capability to automatically establish, teardown, and maintain hop-by-hop connection segments and end-to-end connection between two end-points to relieve operators from unnecessary and time consuming manual operations. Switching-over time for dynamic optical lightpaths allocation should be minimized.
- Fault propagation and isolation: Quick discovery of a failure and its dissemination to the pertinent nodes must rely on distributed signaling for protection purposes as well as fault isolation.
- Automatic protection switching: The procedure to coordinate protection paths must be done in less than 50 ms. Protection and restoration from different layers should be coordinated whenever it is feasible and appropriate to provide network survivability in a flexible and cost effective manner.
- Bi-directional connection setup: Most packet-oriented connections are inherently unidirectional. However, WDM terminals, whose original applications were to transport high-speed links between SONET/SDH equipment, are usually deployed in a bi-directional arrangement.
- Scalability: The control plane should maintain a constant performance as much as possible regardless of the network scale.
- Flexibility: The control plane should have flexibility in its functionality and provide full operation control.

The control plane of the optical Internet also requires traffic engineering algorithms to efficiently utilize network resources and maximize the number of lightpaths established. It encompasses measurement, modeling, characterization, and control of Internet traffic. To achieve specific performance objectives, techniques including reliable and expeditious movement of traffic between lightpaths, planning of network capacity, and selection of the explicit routes should be considered. However, in this paper, we focus on the control plane and OAM architecture and the signaling procedure, so we do not discuss these other factors [13].

The control channel, which conveys control and signaling messages, is of crucial importance in optical networks. Such signaling channels must be defined both for the user-network interface (UNI) and network-network interface (NNI) within the network. These channels may be either in-band or out-of-band.

Out-of-band signaling is attractive in networks where large numbers of channels are managed, and the control information associated with different connections can be aggregated [3].

### III. SIGNALING AND OAM ARCHITECTURE OF OPTICAL IP NETWORK

#### 1. Control Structure

Figure 1 shows the architectural model for the IP over an optical network with special attention on the control interface among administrative domains. This figure shows three interfaces according to the overlay model and the peer/integrated model: the user-network interface (UNI), the internal node-to-node interface (I-NNI) within a single sub-network, and the external node-to-node interface (E-NNI) between different sub-networks [3], [14]. These interfaces require the implementation of a signaling protocol with sufficient capabilities. New messages are being defined by extension of the signaling protocols (i.e., the label distribution protocol (LDP) and resource reservation protocol – traffic engineering (RSVP-TE)) in the standardization bodies, such as the Internet Engineering Task Force (IETF) and Optical Internet-

working Forum (OIF).

According to the administrative domain, the I-NNI is an interface within a given network under a single technical administration, while the E-NNI indicates an interface at the administrative boundary between optical networks. The I-NNI and E-NNI may thus differ in their policies on signaling and routing. In the I-NNI, path selection and setup through the optical network requires a signaling protocol. Transport networks typically use explicit routing, where path selection can be done by management systems. In the E-NNI, which is similar to the UNI interface, there are some concerns about the exchange of reachability and security information which may need to be hidden from other administrative domains. Some routing functions, like BGP, could be used to summarize reachability information between different domains in the same manner as IP networks. However, in principle, the control flows across the UNI and the NNI should be harmonized to eliminate the unnecessary overhead between them [14], [15].

Figure 2 shows the reference configuration model for the IP over an optical network; it indicates various ways in which the control messages may be delivered via the UNI or NNI. There are two invocation models of direct invocation and indirect invocation. Under both models, the client-side and network-side UNI sig-

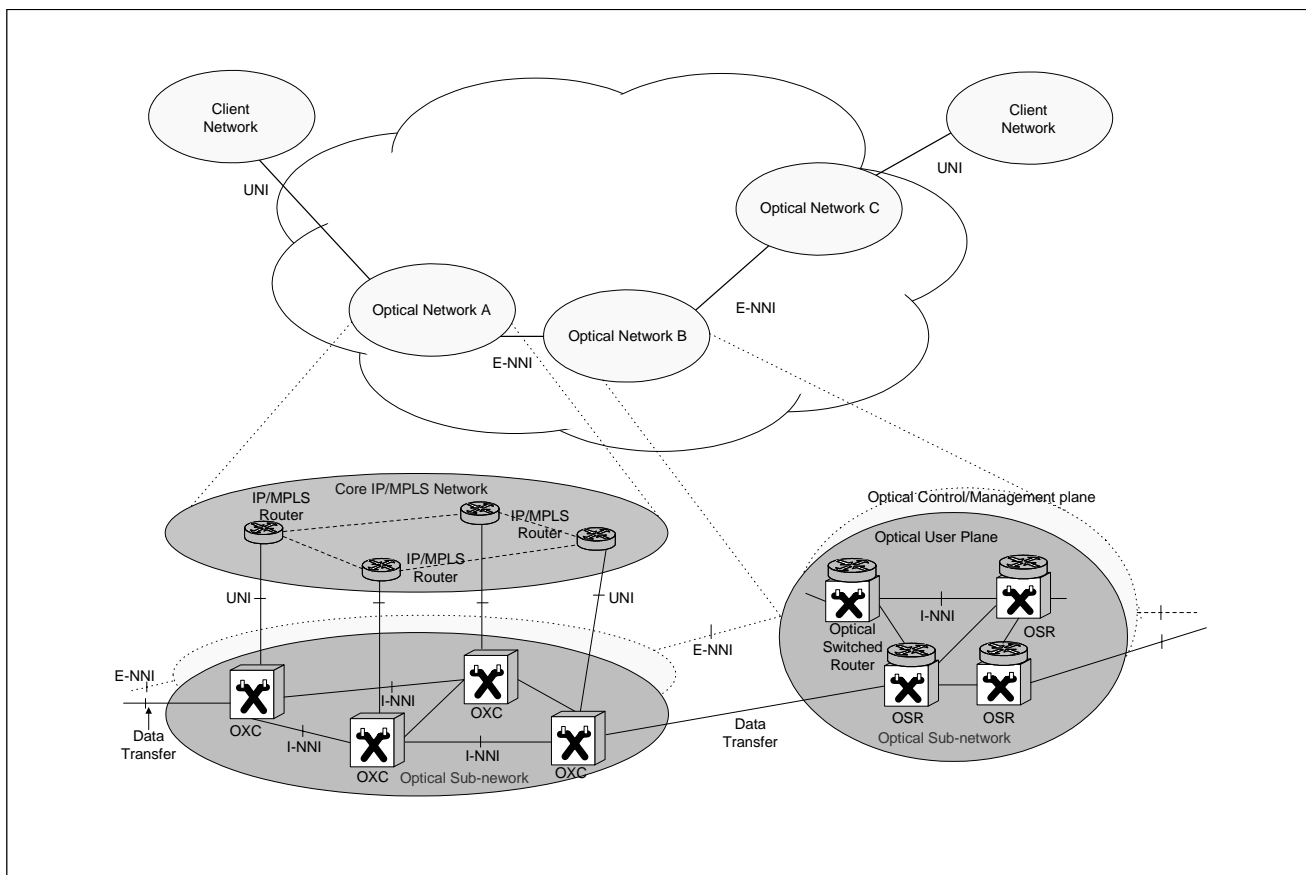


Fig. 1. Architectural model for the IP over optical networks.

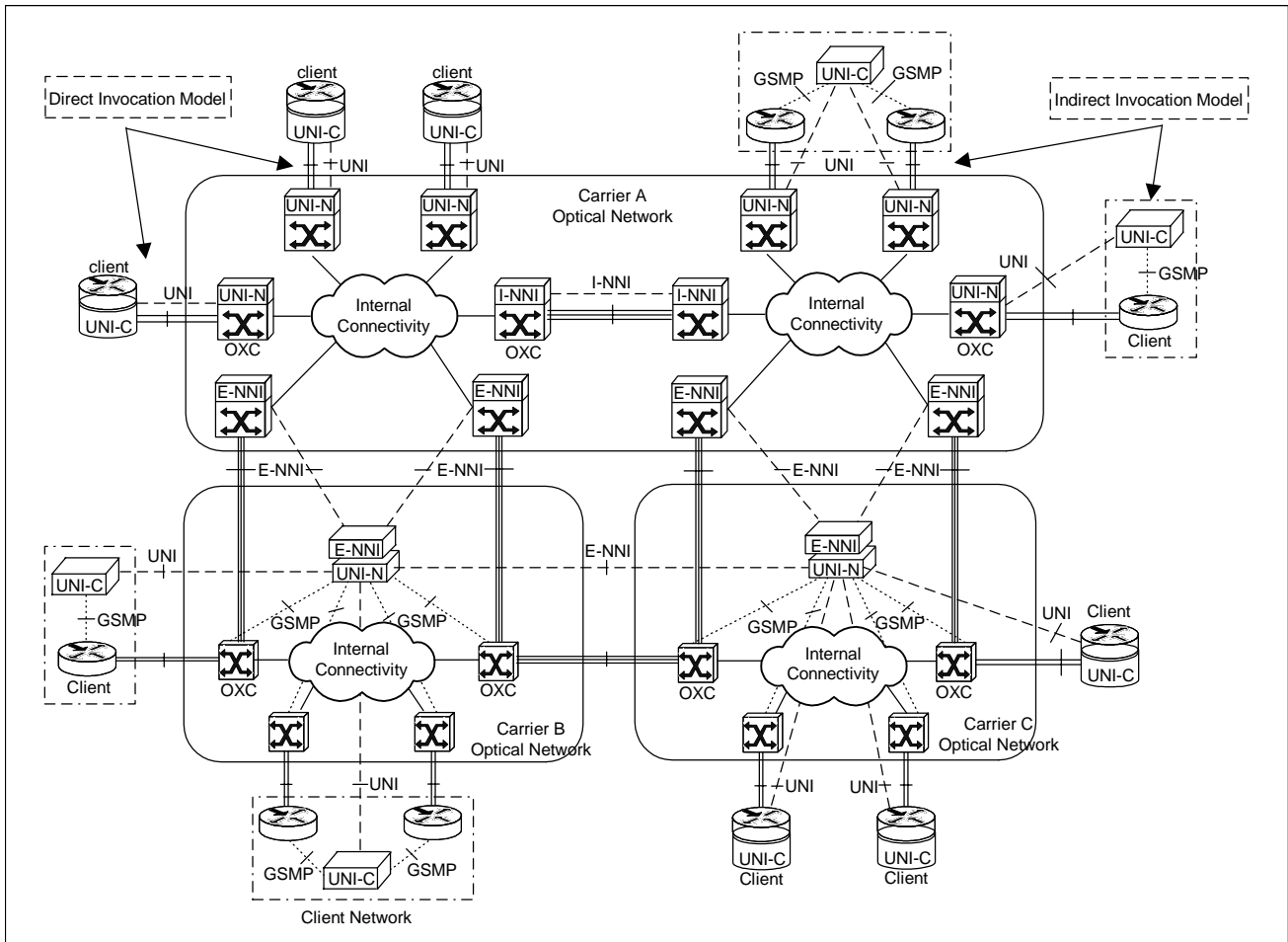


Fig. 2. Reference configuration model for the IP over optical networks.

naling agents are referred to as UNI-C and UNI-N, respectively.

In the direct invocation model, the client invokes optical network services directly over the UNI. The UNI-C functionality is implemented in the client itself (Fig. 2). In the indirect invocation model, clients invoke transport network services using proxy signaling. An entity called the Proxy UNI-C performs UNI functions on behalf of one or more clients. A General Switch Management Protocol (GSMP) within the optical transport network is used to carry out signaling among the UNI-C, the UNI-N and the OXC (Fig. 3). The request to set-up a lightpath may be initiated from the UNI-C [19].

## 2. Interconnection Model

The interconnection of the IP network and optical network can be realized in a number of ways depending on the invocation model as mentioned above. It can be classified into a loosely-coupled model and a tightly-coupled model according to the exchange of routing information between the IP network and optical network. The loosely-coupled model is generally referred to as the overlay model and the tightly-coupled model is referred to

as the peer model.

- Loosely-coupled model (Overlay model)

Under the loosely-coupled model, routing, topology, and signaling information for the IP network are independent of those for the optical network. Even though it is assumed to be independent, the optical network can re-use IP-based protocols to perform routing and signaling functions. The overlay model can provide proper signaling to client networks when clients request to add, delete, or modify their connections.

- Tightly-coupled model (Peer model)

Under the tightly-coupled model, the IP router acts as a peer of the optical transport network, such that a single routing protocol instance runs over both the IP and optical domains. The peer model, although not strictly an internal NNI, behaves as if there is sharing of resource and topology information. A common interior gateway protocol (IGP), such as the OSPF or intermediate

system–intermediate system (IS-IS) protocols, with appropriate extensions, will be used to distribute topology information. A common address scheme based on IP addresses can be realized in both IP and optical domains. The obvious advantage of the peer model is the seamless interconnection between the IP network and optical transport networks.

On the other hand, there are actually separate routing instances in the IP and optical domains, but information from one routing instance is passed through the other routing instance. This model is called the augmented model, which although not strictly an external NNI, behaves like an E-NNI in that there is limited sharing of information. For example, external IP addresses could be carried within the optical routing protocols to allow reachability information to be passed to IP clients. A typical implementation would use BGP between the IP client and the optical network [6].

The main architectural principles of the interconnection model that has recently been approved by the IETF and OIF are described in [6], [19].

### 3. A Scenario Using OXCs Controlled by an IP Router

In this section, we illustrate a scenario to initially deploy an optical Internet as an example of a control structure and an interconnection model. Figure 3 shows an optical network with reconfigurable OXCs controlled by an IP router. Each node consists of an IP router and a dynamically-reconfigurable OXC. In this model, IP routers play the role of UNI-C, and the UNI-N function is located in the OXC; this is a direct invocation model, and the control plane architecture is a domain service model. We

predict that the control plane architecture for initial deployment of the optical Internet is the domain service model that is shown in Fig. 3. In this model, the IP router is responsible for the management of optical resources, configuration and capacity management, addressing, routing, traffic engineering, topology discovery, exception handling, and restoration. In general, the IP router may be traffic bearing. However, it may function purely as a controller for the optical network and carry no user traffic from clients. The IP router implements the necessary signaling protocols to establish lightpaths as proposed in [16].

Within the network, the routed lightpath can provide router to router connectivity. All traffic using this lightpath is forwarded by the IP router. All control messages are sent via the control channel.

In Fig. 3, the Generic Switch Management Protocol (GSMP) master of the IP router communicates with the GSMP slave located in the OXC system. The interface defines a set of basic primitives to configure the OXC and to enable the OXC to convey information to the router. The GSMP translates the logical primitives to and from the system controls of the OXC.

To illustrate the provisioning of an end-to-end route at the optical layer in Fig. 3, the ingress router receives a lightpath request from a source. The ingress router creates a lightpath request message and sends it towards the destination of the lightpath where it is received by the egress router. The lightpath is created when the ingress router receives the lightpath allocation message. If all routers are MPLS-capable, the appropriate constraint-based label distribution protocol (CR-LDP) or RSVP-TE messages can be used. If no channel is available on any link, the setup fails, and a message is

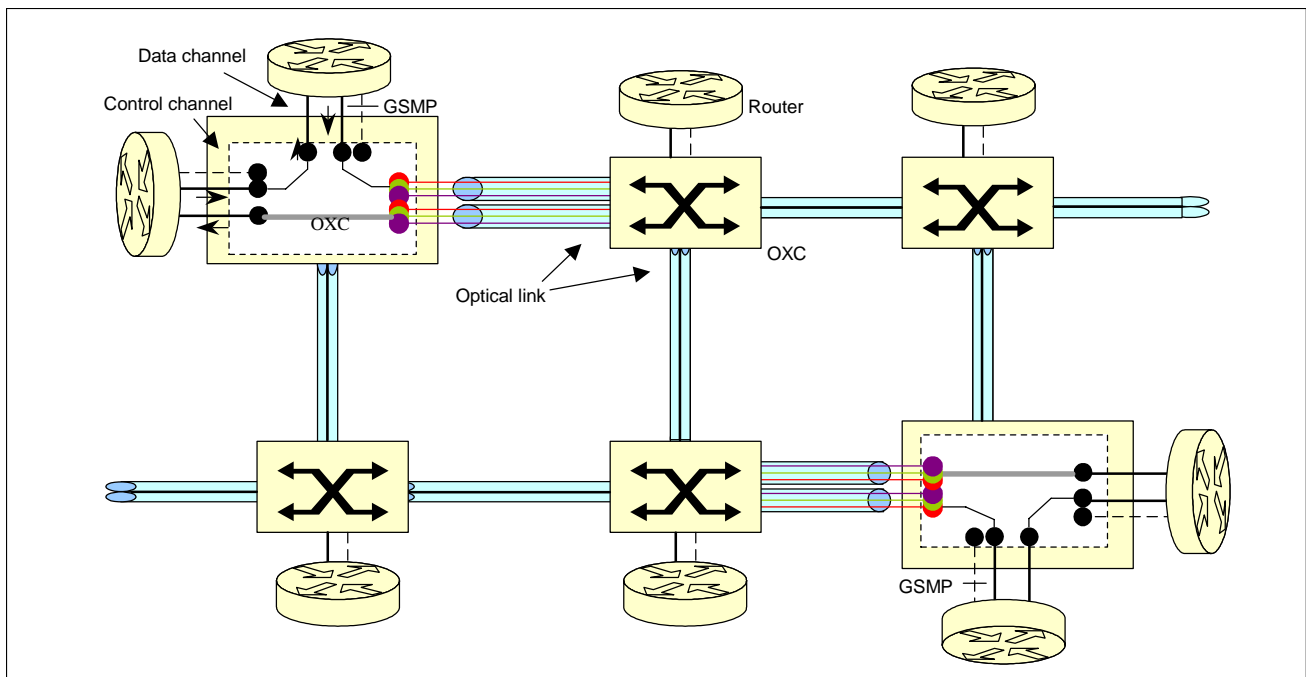


Fig. 3. Optical network model with reconfigurable OXC controlled by IP router.

returned to the ingress router informing it that the lightpath cannot be established. When the setup fails, the ingress router issues a release message to release resources allocated for the partially constructed lightpath; it may attempt to establish the lightpath over an alternate route before giving up on satisfying the original user request. After processing the setup, the egress router returns an acknowledgement to the source [16]. Ref. [16] gives details on the control of lightpaths in an optical network. In this section, we focused on a scenario using OXCs controlled by an IP router in the direct invocation and domain service model.

#### 4. GSMP Interface between IP Router and OXC

We present the GSMP interface to support the reconfigurable OXC system as in Fig. 4. The GSMP defines the interface between the signaling element and the transport network elements. The GSMP is a general-purpose protocol that allows a controller to establish and release connections across a switch. The GSMP is well suited for network architectures for applying label swapping in the forwarding plane, e.g., ATM, FR, and MPLS. This property makes the GSMP a good fit for a generalized label as defined by the GMPLS. Connection control information is passed over this interface to establish connections between the ports of the OXCs. The GSMP must support two essential functions: adding and deletion of lightpaths and query of the port status of the switch [16].

#### 5. Multi-Layer Protection and Restoration

The ingress router or OXC selects the restoration route(s) and is responsible for reserving restoration capacity. The choice

of restoration policy is in tradeoffs between simplicity, utilization, and restoration speed. Numerous policies may be used for determining the lightpath restoration routes. An overview of multi-layer protection and restoration concept was presented in [18]. In this section, we illustrate protection and restoration of the optical layer, GMPLS layer and IP layer in particular.

From the point of view of the layer, the protection and restoration could be triggered at multiple layers as shown in Table 1. Because any layer in this table may be involved in control and transmission, it is necessary that notice of a fault in one layer be passed to the adjacent higher and lower layers. However, due to the nature of these many layers, it is possible and even probable that hundreds or even thousands of notifications between layers will be needed [18]. This necessitates setting up recovery mechanisms at multiple layers in the network.

Although failures at the physical layer and optical transport network (OTN) equipment failures can be recovered at both the GMPLS or IP layer, it seems more sensible to provide “bulk recovery” of these failures at the OTN network layer. In the optical layer fewer recovery actions are needed, because the recovery operates at a coarser granularity. The failure scenarios are less complex, which enable simpler recovery [26].

In general, successful lower layer protection should circumvent activation of higher layer mechanisms. On the hand, in the absence of a lower layer mechanism, or in case of multiple failures, activation of a higher layer protocol may be expedited. At times the higher layer mechanism may be the only remaining recovery option [18].

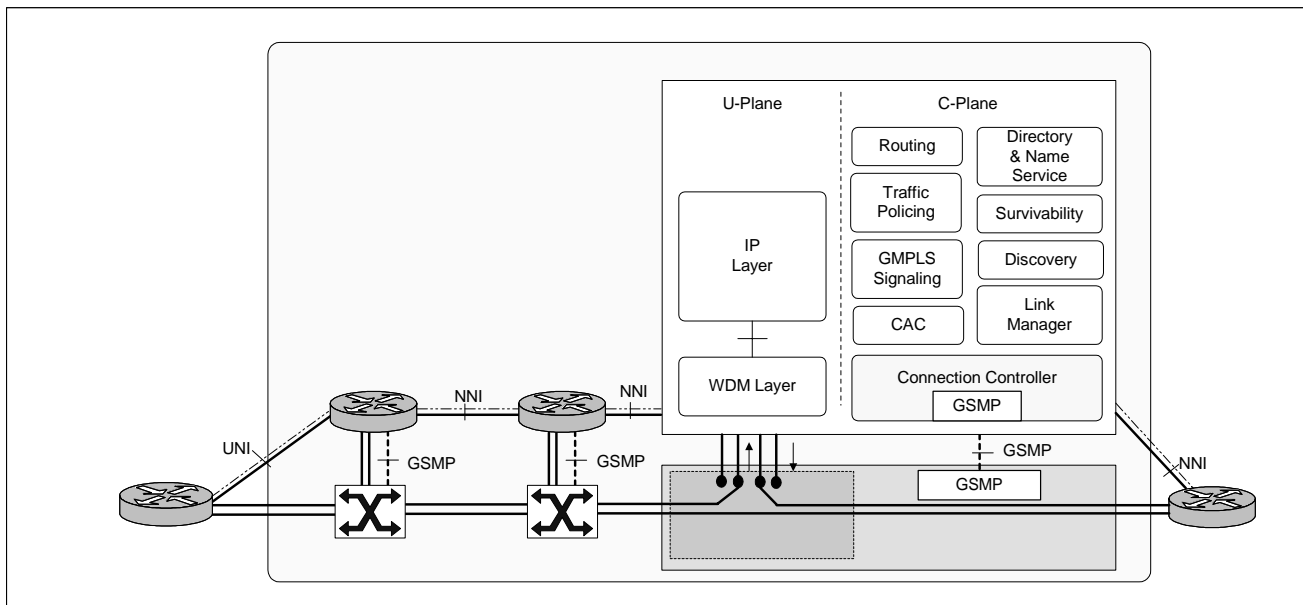


Fig. 4. GSMP Interface to support the reconfigurable OXC system.

Table 1. Hierarchical views of protection and restoration for IP over optical network. Based on source: "Dynamic protection & restoration in multi layer networks," 2001, OIF.

	Optical Transmission Network	GMPLS	IP
Recovery domain	Optical trail, sub network connection	Node/links between OXCs and LSRs	Entire Internet
Granularity of protection	Fiber, optical channel	Per LSP	IP routes
Recovery objectives	1-10 [ms] detection 10-40 [ms] recovery	Needed further study.	Time out, flooding Few [s] recovery
Driving applications	SONET, IP, Ethernet, ATM, etc.	IP VPN, Network Engineering, potentially voice & mission critical	Data
Recovery initiation criteria	LoS (or LoL)	Keep alive, lower layers	Loss of Hello PDU or lower layers
Recovery resource mapping algorithms	To be defined	To be defined	Based on packet type of service (TOS)

#### IV. APPLICATIONS OF GENERALIZED MPLS SIGNALING FOR OPTICAL IP NETWORK

##### 1. Signaling for Optical Label Switched Path

The reference configuration mentioned in the previous section indicates the different ways in which transport network service may be invoked. In these different models, a signaling channel is the communication path for transporting signaling messages between network nodes and over the UNI and NNI. There are three different types of signaling methods depending on the way the signaling channel is constructed as described in [3], [6]:

- In-band signaling: The signaling messages are carried over a logical communication channel embedded in the data-carrying optical link or channel.
- In-fiber and Out-of-band signaling: The signaling messages are carried over a dedicated communication channel separate from the optical data-bearing channels, but within the same fiber.
- Out-of-fiber signaling: The signaling messages are carried over a dedicated communication channel or path within different fibers to those used by the optical data-bearing channels.

In-band signaling is particularly important over a UNI interface where there are relatively few data channels. Proxy signaling is also important over the UNI interface, as it is useful to support users unable to signal to the optical network via a direct communication channel [6]. Out-of-band signaling is attractive within the network where large numbers of channels are managed and the control information associated with different connections can be aggregated. However, dedicating a complete channel for signaling over the UNI for each individual client appears impractical from a carrier's perspective [3]. In-fiber, out-of-band and out-of-fiber signaling channel alternatives are particularly

important for NNI interfaces, which generally have significant numbers of channels per link. Signaling messages relating to all of the different channels can then be aggregated over a single or small number of signaling channels [6].

The signaling network forms the basis of the optical transport network control plane. To achieve reliable signaling, the control plane needs to provide reliable transfer of signaling messages, its own OAM mechanisms, and flow control mechanisms for restricting the transmission of signaling packets where appropriate [6].

In the GMPLS control plane, the basic functions include lightpath handling, such as creation, deletion, modification, error reporting and handling, as well as lightpath restoration. Because the optical network carries a huge bandwidth, fast failure detection and fast lightpath restoration become basic requirements that support high reliability and availability for application.

##### A. Lightpath Creation Operation

The lightpath creation is initiated by the control/management plane on behalf of an end-user or by the end-user signaling device. The ingress OXC, which receives a lightpath request from the client network, usually performs certain processes of authorization including admission control and resource verification. If the authorization is confirmed, it selects a path and starts the lightpath creation operation. If the lightpath creation is successful, then the optical circuit, resources, and required bandwidth is dedicated to associated end-points. Dedicated resources may include active resources as well as protection or restoration resources in accordance with the class of service indicated by the user. If the lightpath creation is not successful, a negative response is returned to the ingress OXC and any partial allocation of resources is de-allocated.

Figure 5 shows the lightpath creation procedure using the LDP. In the lightpath request message, the initiating UNI-C identifies the two lightpath termination points source and destination addresses.

Upon the reception of the lightpath request message, the UNI-N verifies that the signaled attributes can be supported. The network delivers the assigned lightpath identifier to the calling client in the lightpath mapping message [19].

### B. Lightpath Deletion Operation

When a lightpath is not needed anymore or a lightpath has been given up by the optical network, the resources occupied by this lightpath are released. A deletion request message is provided in the signaling protocol. The deletion operation may start from the ingress OXC, the egress OXC, or any middle OXC of the lightpath [6].

Figure 6 shows the lightpath deletion procedure using the LDP, in which the lightpath release message is used for lightpath deletion in the downstream direction. the receiver of this message must respond with a notification message with the appropriate status code [19].

## 2. Routing and Provisioning of Optical Routes Based on GMPLS

Routing is an important component of the control plane. It inclu-

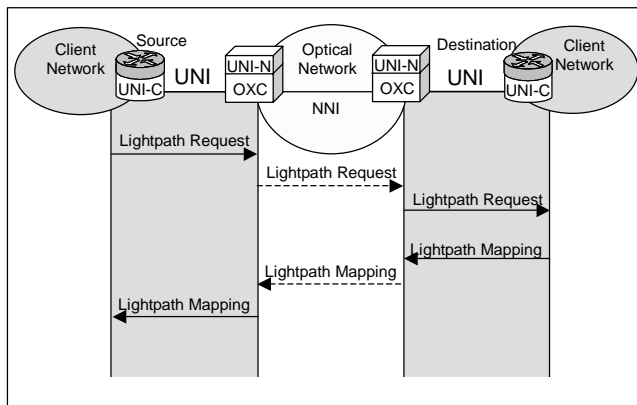


Fig. 5. Lightpath creation procedure using LDP.

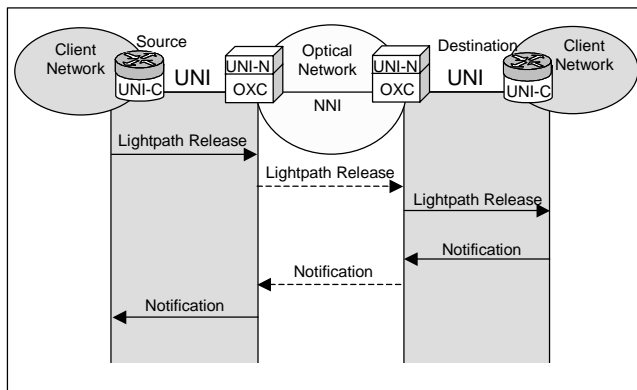


Fig. 6. Lightpath deletion procedure using LDP.

des neighbor discovery, reachability information propagation, network topology information dissemination, and service capability discovery. Automatic discovery of optical network topology should be provided by routing functions based on GMPLS. The objective of neighbor discovery is to provide the information needed to identify the relationship and connectivity of neighbor nodes. Neighbor discovery may be realized via manual configuration or protocol automatic identification, such as Link Management Protocol (LMP).

In this section, we investigate the selection of a lightpath by the edge node. An edge node can participate more or less deeply in the GMPLS routing. Four different routing models can be supported at the UNI as described in [17]: configuration based, partial peering, silent listening, and full peering.

The configuration based routing model requires manual or automatic configuration of an edge node with a list of neighbor OXCs sorted by preference. In the partial peering routing model, limited routing information can be exchanged across the UNI using some extensions of the signaling plane. The reachability information exchanged at the UNI may be used to initiate edge node specific routing decisions over the network. In the silent listening model, the edge node can silently listen to routing protocols and compute a complete explicit route taking into consideration all the end-to-end routing information. Finally, in the full peering routing model, the edge node participates in the routing, establishes adjacencies with its neighbors, and advertises link state advertisements (LSAs).

Different from routing of a UNI, lightpaths inside an optical network mostly uses an explicit route. A lightpath across multiple I-NNIs is normally computed in the first node accepting the connection request from the UNI. The selected path may be either a loose explicit route or a strict explicit route. If the lightpath computation node has all the network topology and resource information, it is able to select a strict explicit route. Otherwise, if the path computation node only has abstract network topology with summarized resource information, it can only select a loose explicit route. The detailed routes inside other domains are left for other domain nodes [25].

A routing protocol must run across the NNI between sub-networks. It is desirable that such a protocol allows the separation of routing algorithms between sub-networks. This allows proprietary provisioning to be implemented within sub-networks while end-to-end provisioning is performed. These objectives may be satisfied by running a version of BGP between border OXCs. Using an exterior BGP, adjacent border OXCs in different sub-networks can exchange reachability of OXCs and border routers. Using an interior BGP, the same information is propagated from one border OXC to others in the same sub-network.

Once border OXCs acquire reachability information regarding remote destinations, this information may be shared with other



OXC's within the sub-network to enable end-to-end path provisioning. A source OXC within a sub-network must determine the border OXC through which the ultimate destination can be reached [20].

### 3. Signaling for Protection and Restoration

Once the route of a lightpath is decided, the ingress OXC sends a Lightpath Create Request message to the next intermediate OXC through the control channel (Fig. 7). The intermediate OXC receives the messages to configure the OXC switch fabric and then sends the message to its downstream intermediate OXC for that route. If it successfully reaches the egress OXC, the OXC returns the lightpath create response message through the ingress OXC. Upon receiving it, each OXC updates the link state database. When the message reaches the ingress OXC, it advertises the available bandwidth capacity by flooding the link-state IGP routing protocol advertisement at the client IP network.

On failure of a fiber link, the OXC generates a Notification message in both the downstream and upstream direction (Fig. 8). If the upstream (or the downstream) OXC has detected a loss of light (LoL) or loss of signal (LoS) alarm, then it sends back a notification message to the downstream (or upstream) OXC. In unidirectional link failure detection the upstream (or the downstream) OXC forwards the notification toward the ingress (or the egress) OXC. Since the failure notification message is sent simultaneously from the OXC detecting the failure to the ingress and the egress OXC, this notification message is also received by the egress OXC's.

If the provisioned restoration policy has been previously configured, the ingress OXC replaces the damaged primary lightpath with the backup lightpath shared by the same restoration group. If it has not been previously configured, the ingress OXC

initiates a lightpath create procedure for the backup lightpath for the same setup procedure as the primary lightpath.

There are two types of modes, the revertive mode and the non-revertive mode. In the revertive mode, traffic is automatically switched back from the recovery path to the original working path upon the restoration of the working path to a fault-free condition. However, in the non-revertive mode, traffic is not automatically switched back to the original working path after this path is restored to a fault-free condition. The choice to switch or not to switch will typically depend on the relative costs of the working and protection paths and the tolerance of the service to the effects of switching paths. [21], [22], [24].

### 4. Relation with Network Management

Network management functions of an optical network should extensively support configuring, monitoring, and provisioning various devices. Therefore, the service provider should utilize a network management system (NMS) and standard management protocols such as the simple network management protocol (SNMP) and its associated management information bases (MIBs) as interfaces to configure, monitor, and provision devices at various locations. Since GMPLS comprises many different layers of control-plane and data-plane technology, it is important for management interfaces to be flexible as described in [17]. Therefore, control of parts of GMPLS should be achieved through the MIB interfaces by using the SNMP. Standard tools such as traceroute and ping should be also studied for debugging and performance monitoring of GMPLS networks.

## V. CONCLUSIONS

One of the challenges involved in designing the optical Internet

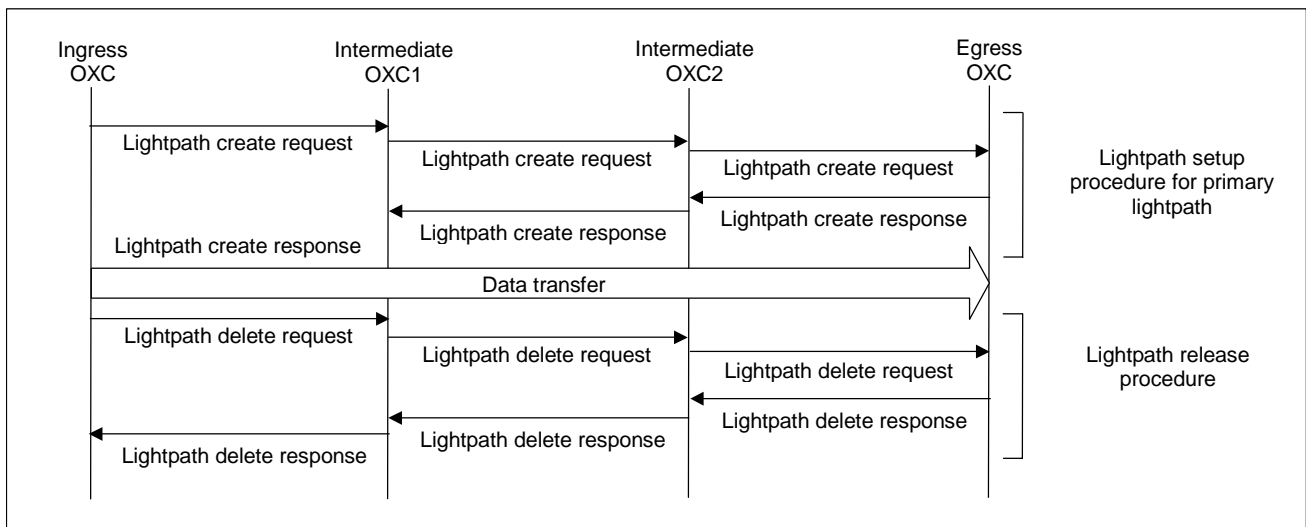


Fig. 7. Procedure of normal lightpath create and delete operation.

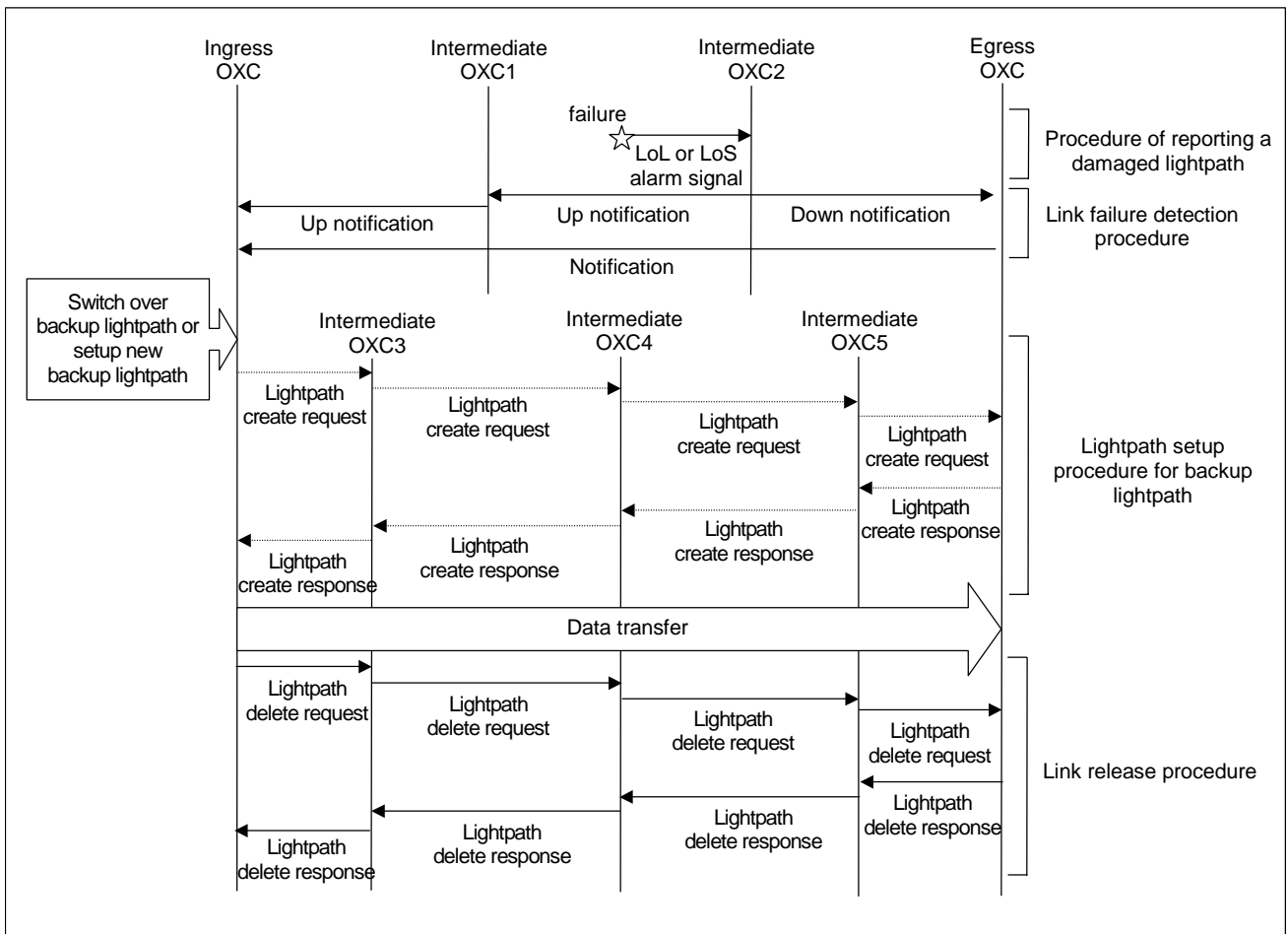


Fig. 8. Lightpath protection/restoration procedure after failure detection.

is to develop a control plane and efficient control procedures for establishing lightpaths. In this paper, we reviewed various research activities to develop the IP for optical networks, especially signaling and control procedures. First, we analyzed the signaling and OAM requirements to support IP service with the limitations of optical networks, including the optical cross-connect system. We focused on whether IP-centric control using generalized MPLS signaling is suitable to meet the control requirements of optical networks.

With attention on the reference configuration model and network architectural model, we analyzed the proper signaling and control architecture for the IP over optical networks and concluded that generalized MPLS signaling was appropriate for controlling bandwidth and optical lambda resources. The control structure using optical UNI, NNI, and GSMP interfaces were comparatively investigated for the IP over optical networks. We also studied signaling for protection and restoration procedures to protect link failure.

The control plane of the optical Internet will allow faster service provisioning and create opportunities for new network service.

However, it will still require control algorithms to efficiently use network resources and maximize the number of lightpaths. We expect that the initial deployment of the optical Internet will use the control plane architecture of the domain service model based on UNI signaling and it will evolve and extend to the peer model based on NNI signaling.

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