Internetworking with the intelligent optical layer

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Received 14 January 2002; revised manuscript received 25 February 2002

My purpose here is to provide a general overview of the fundamental issues surrounding the interoperability of electrical-layer network devices and an intelligent optical-switched core. Included in this overview are the inter-networking models currently being debated as well as a current status report on developments within various standards initiatives.

OCIS codes: 060.0060, 060.4250.

1. Introduction

1.A. Traditional Optical Transport Network View

The provisioning of high-speed bandwidth within the traditional optical transport network (OTN) is basically static, an approach that is referred to as the provisioned bandwidth service (PBS) business model.[1] For network operators it is a slow and painstaking operation that requires considerable manual configuration and, in many cases, forces a costly redesign of optical network internals. In the PBS model, electrical devices such as Internet Protocol (IP) routers are connected to optical networks by standard OC-n/STM-n interfaces (STM, synchronous transfer mode). In general the control plane of the traditional OTN is implemented by centralized operation systems and manually intensive procedures. This approach has the following limitations[2]:

(1) It leads to relatively slow convergence following failure events—typical restoration times are measured in minutes, hours, or even days and weeks, especially in systems that require explicit manual intervention. The only way to expedite service recovery in such environments is to preprovision dedicated protection channels.

(2) It complicates the task of interworking equipment from different manufacturers, especially at the management level. Generally, a customized umbrella network management system (NMS) or operator services system (OSS) is required for integrating otherwise incompatible element management systems from different vendors.

(3) It precludes the use of distributed dynamic routing control in such environments.

(4) It complicates network growth and service provisioning.

(5) It complicates the task of internetwork provisioning (in view of the lack of an efficient communication scheme between operator network management systems).

1.B. *Intelligent Optical Transport View*

To meet the demands of today's high-speed networking applications, it is widely accepted that the automation of the optical network layer is not only practical and useful but also essential to the realization of new high-value broadband services. Recently, two simultaneous developments in networking technology have made the dynamic request of high-speed bandwidth from the optical network both feasible and desirable. First, a new generation of dynamically reconfigurable optical systems is enabling dynamic point-and-click bandwidth provisioning by network operators. These optical systems, which include optical cross connects (OXCs) and optical add–drop multiplexers (OADMs), use existing data network control protocols [e.g., multiprotocol label switching (MPLS), open shortest path first (OSPF)] to determine routing within the control channels. Second, traffic engineering[3] and constraint-based routing enhancements to IP routers[4,5] and/or asynchronous transfer mode (ATM) switches are allowing these devices to determine dynamically when and where they need to add or reduce bandwidth. This intelligent optical network view is also referred to as the bandwidth-on-demand service (BODS) business model.[1]

The benefits from automatic control and switching of optical channels include the following[6]:

(1) *Reactive traffic engineering.* This is a prime attribute, which allows the network resources to be dynamically managed according to a client's system needs.

(2) *Restoration and recovery.* These attributes can maintain graduated preservation of service in the presence of network degradation.

The ability to link optical network resources effectively to data-traffic patterns in a dynamic and automated fashion will result in a highly responsive and cost-effective transport network and will help pave the way for new types of broadband network service.

2. Internetworking Models to Accommodate Optical-Layer Intelligence

The internetworking model considered in this paper consists of electrical-layer devices (e.g., IP routers, IP edge devices, ATM switches, and the like) attached to an optical core network [e.g., synchronous optical network and synchronous digital hierarchy (SONET/SDH) transport or all-optical transport] and connected to their peers by dynamically established switched link connections.

For network architects the control plane essentially encompasses the following two functions:

- Signaling
- Routing

Signaling is the process of control-message exchange by use of a well-defined protocol to achieve communication between the controlling functional entities connected through specified communication channels. It is often used for dynamic connection setup across a network.

Routing supports adjacency discovery and ongoing health monitoring; propagation of reachability and resource information; and traffic engineering, path calculations, and the path-selection process.

To enable dynamic and rapid provisioning of an end-to-end service path across the optical network, end-system and service discovery function as described below are be provided by this model:

Service and end-system discovery is the process of information exchange between two directly connected pieces of end-system equipment: the user edge device and the network edge device. The objective is for the device to obtain essential information about the end-system or network element at the other side and thereby understand the connection between them and provide the information about available services to the other side.

The optical network essentially provides point-to-point connectivity between electrical devices in the form of fixed-bandwidth optical paths. The collection of optical paths therefore defines the topology of the virtual network interconnecting electrical-layer devices. With the intelligence (signaling and routing capabilities) built into the optical layer, not only can the interconnection topology be established rapidly; it can also be maintained in an autonomous manner and be dynamically reconfigured as triggered by either restoration or traffic-engineering needs.

Note that there are several key differences between the electrical-layer control plane (packet switching in nature) and the optical-layer control plane (circuit switching in nature) as shown in Table 1.

From the traffic-engineering perspective as shown in Table 1, we can see that although the optical-layer intelligence is different from the intelligence residing in the electrical layer, instead of competing or overlapping, these two layers complement each other. With optical-layer traffic engineering, we can dynamically create the most effective or optimized physical topology Ψ.

Table 1. Control-Plane Differences

	Electrical-Layer Control Plane	Optical-Layer Control Plane
Physical connectivity	Static physical topology	Dynamically reconfigurable physical topology
Traffic-engineering focus	Efficiently fill in the given physical connectivity; fully exploit statistical multiplexing potential.	Efficiently reconfigure (create or teardown) the physical connectivity.
Control channel (carrying signaling and routing messages)	In-band: control traffic mixed with data traffic *Implication:* Controlling the channel's health status can be used to determine the corresponding data channel's health status.	Out-of-band: because the data traffic (payload) is not processed at the optical layer, control traffic is carried separately from the payload, either by overhead bytes in the same channel or by a separated channel. *Implication:* The control channel's health status may be independent of the corresponding data channel's health status.
Internal Gateway Protocol (IGP) solution: Adjacency discovery	In-band bidirectional digital Hello mechanism is used.	Out-of-band coordination-based digital or analog Hello may be needed.
IGP solution: link representation	The main link characteristics considered in this layer is link bandwidth and/or administrative cost.	In addition to bandwidth and administrative cost, several other critical link characteristics need to be considered in this domain, including transparency level, protection level, shared-risk link group (SRLG), diversity ,[7] and so on.
Exterior Gateway Protocol (EGP) solution	Existing EGP solution in this layer such as Border Gateway Protocol (BGP) assumes preestablished physical inter-domain connectivity.	EGP solution in this layer assumes the dynamic interdomain physical connectivity.

Table 1. continued

	Electrical-Layer Control Plane	Optical-Layer Control Plane
Quality of service (QoS) differentiation	Since the processing granularity in this layer is down to the packet level, QoS differentiation can also be supported to each packet level, including weighted fair queuing (WRQ), random-early-detection- (RED-) based queue management, and so on. The delay incurred by each packet includes both deterministic transmission delay and, most of the time, nondeterministic queuing delay.	Since the processing granularity in this layer is channel level, there is no packet-level QoS differentiation. The main QoS differentiation is the protection level that differs at channel level. Since there is no mature optical-layer buffer technology, the only delay incurred in this layer is deterministic transmission delay.
Protection and restoration	Granularity: packet level In general, fault detection, fault propagation, and fault processing (rerouting, and so on) are based on layer 2 and above schemes.	Granularity: channel or path level In general, fault detection, fault propagation, and fault processing (switching, and so on) are based on layer-1 scheme.
Path computation	Physical characteristics in general need not be considered during the path computation.	In addition to SRLG diversity, other physical characteristics, such as polarization-mode dispersion (PMD), amplifier spontaneous emission (ASE), and the like,[8] also need to be considered during the path computation.

Based on Ψ, electrical-layer traffic engineering can be used to achieve load balancing, maximum-degree statistical multiplexing, and so on. So a good internetworking model should strive to marry the intelligence residing at both the optical layer and the electrical layer.

Also note that the optical-layer control plane has more dependence on the physical-layer technology than does the electrical-layer control plane. We expect optical-layer technology to evolve rapidly, with a real possibility of additional disruptive advances. The analog nature of optical-layer technology compounds the problem for the corresponding control plane, because these advances are likely to be accompanied by complex technology-specific control-plane constraints. Hence an internetworking model is highly desirable if it can allow the gradual and seamless introduction of new technologies into the network without time-consuming and costly changes to the embedded control planes.

It is also worth noting that there have been instances in which people in the industry have tried to make an analogy between *electrical layer over optical layer* and *IP over ATM*. As shown in Table 1, both IP routers and ATM systems share the same control-plane characteristics as shown in column 2. And the IP router and ATM system control planes differ significantly from the optical-layer control plane as shown in column 3. From this perspective, we can see that the analogy is misleading.

Given these recognized control-plane differences, there have been several models proposed to date to internetwork the electrical layer and the intelligent optical layer. Subection 2.A describes two dominant approaches: the overlay model and the peer model. These two models differ significantly in the areas of signaling and routing.

2.A. Overlay Model

In the overlay model the electrical-layer devices operate more or less independently of the optical layer. The control-plane differences as described in Table 1 are resolved by deployment of a separate and different control plane in the electrical layer and in the optical layer. In other words, the electrical-layer address scheme, routing protocol, and signaling scheme run independently of the address scheme, routing protocol, and signaling scheme deployed in the optical layer. With this independence the overlay model can be used to support network situations in which an operator owns a multiclient OTN and each client network employs individual address, routing, and signaling schemes.

In this model, essentially the optical layer provides point-to-point connections to the electrical layer. The electrical-layer device, in this respect, acts as a client to the optical layer.

Interworking between these two layers, including control coordination, can be established through either static configuration or through dynamic procedures. On the basis of interworking (signaling) differences and whether there is exchange of routing information between these two layers, the overlay model can be further divided into two submodels: the static overlay model and the dynamic overlay model.

2.A.1. Static Overlay Model

In this model, optical-path endpoints are specified statically through the NMS. Therefore no user-to-network interface (UNI) signaling is needed in this case. Additionally, in this model there is no exchange of routing information between the client domain and the optical domain. This scheme is similar to ATM permanent virtual circuits (PVCs).[9]

2.A.2. Dynamic Overlay Model

Certain industry documents[10] also refer to the dynamic overlay model as an augmented model. In this model the path endpoints are specified through signaling by means of UNI signaling. Paths must be laid out dynamically, since they are dynamically specified by signaling, similar to ATM switched virtual circuits (SVCs). In this model, electrical-layer devices residing on the edge of the optical network can signal and request bandwidth dynamically. The resulting bandwidth connection will look like a leased line. Also in this model there may exist certain exchange of routing information between the electrical layer and the optical layer. For example, externally attached electrical end-system addresses could be carried within the optical routing protocols and further disseminated by means of the UNI signaling to allow reachability information to be passed to all the other attached electrical-layer devices.

As described below, most of the internetworking models discussed in various standards bodies can be classified into this model. And as noted in these proposals, there are several advantages of the dynamic overlay model.

First, as described in the Table 1, there are significant differences between the optical-layer control plane and the electrical-layer control plane. The dynamic overlay model allows the development of a control-plane mechanism for the optical layer independently of electrical-layer control plane. This is particularly important because the optical network is still in an evolving stage; more and more network characteristics are being discovered, and most have a direct effect on both the signaling and the routing schemes. For example, as technology advances from the opaque stage to the all-optical stage, where all the processing, including performance monitoring, channel switching, wavelength conversion, and so on is done in the optical domain, a set of physical transmission impairments will have a significant effect on wavelength routing. These physical constraints include PMD and ASE.[8] By use of the dynamic overlay model, rapidly evolving optical-layer technological advances can be contained in the optical layer itself, with the relatively mature electrical-layer control-plane scheme left intact.

Note that in the dynamic overlay model, unlike with most conventional IP-over-ATM overlay models, we need not assume that any electrical attaching device is connected to all the other electrical devices attached to the optical network. In fact, from a routing perspective, the electrical-layer-attaching device is interested only in the electrical-level reachability, which can be achieved in this model by the exchange of routing information between the electrical layer and the optical layer, facilitated by enhancement of the optical-layer internal topology dissemination mechanism (piggyback) and UNI interface. This method eliminates the need to expose the client layer to the full optical-layer topological details; hence no N^2 scalability issue is assumed for the conventional IP-over-ATM overlay model.

Requiring the electrical-layer system to store only the electrical-layer topological reachability information significantly improves the overall scalability of the network. In addition, any optical-layer topology change, such as a change triggered by either the addition or the removal of optical elements or a breakdown of certain optical-layer node, fiber, wavelengths, and the like, will not have any effect on the electrical layer unless it affects the corresponding electrical-layer connectivity. This benefit contributes significantly to network stability and performance.

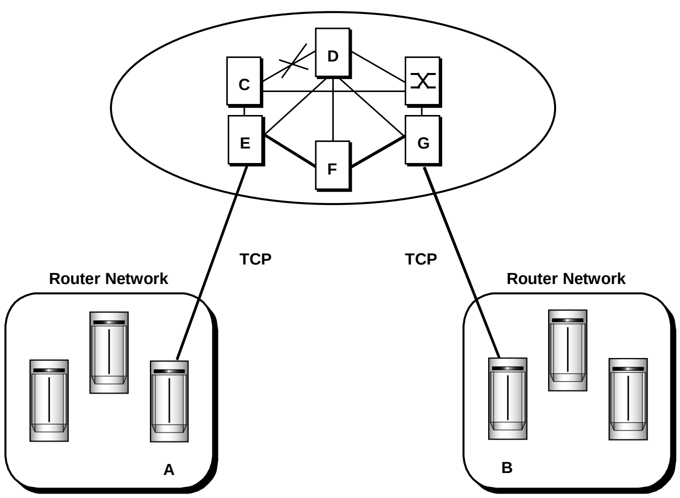

Fig. 1. Network example. TCP, Transmission Control Protocol.

Take Fig. 1 as an example. In this case, after Router A and Router B have formed the physical connectivity, the primary concern is this physical connectivity. With this model, as long as optical systems E, F, and G and all the related links, A↔E, E↔F, F↔G, and G↔B, are functioning normally, all the other optical network details should be irrelevant from the router network's perspective. When the number of optical systems in the optical network increases from 6 to 100, or the number of optical links increases from 10 to 350, or the link between optical systems C and D is down, will have an effect only on the optical-layer internal topology and will have no effect on the router network topology.

With this dynamic overlay model, independent protection and restoration schemes can be deployed in both layers. This addresses the difference in the protection-level requirements of the two layers, including protection granularity, diversity, and so on, as described in Table 1. In addition, a multilayer survivability scheme can also be developed based on the enhancement of the UNI interaction between these two layers if needed.

From the operator's perspective this model addresses a critical business requirement common to network deployment: Operators typically run the operator network independently. The dynamic overlay model fits well with the distrusted domain interconnection situation, or intercarrier model.[1]

Note that service operators are sensitive to the routing policy that determines how the routing functions are performed and to what extent the routing information should be exchanged between networks or between the optical network and user network. With the exception of specific cases or architectural requirements, topology information of the optical network in general shall *not* be advertised to the user network.[10]

2.B. Peer Model

In the peer model the electrical-layer systems, such as IP-over-ATM devices, and the optical-layer systems act as peers. This model assumes a uniform control plane for both the optical and the electrical layers, driven by the consideration to exploit the existing control-plane technology deployed in the electrical layer to foster the rapid development and deployment of the control plane in the optical domain. The main leveraging target is the electrical-layer control-plane technology developed for MPLS traffic engineering.[2] The control-plane differences between these two layers, as described in Table 1, are addressed in this model by the extension of the existing electrical-layer control plane. One proposal of such an extension is described in Refs. 2 and 11. Note that with the uniform control plane deployed across both the electrical layer and the optical layer, no special boundary-layer scheme such as UNI interaction is needed.

There are several advantages to this approach[2]:

(1) It exploits recent advances such as MPLS control-plane technology and leverages accumulated operational experience with IP distributed routing control.

(2) It obviates the need to reinvent a completely new class of control protocols for OTNs and allows reuse of software artifacts originally developed for the MPLS traffic-engineering applications. Subsequently, it fosters the rapid development and deployment of a new class of versatile OXCs.

(3) It simplifies network administration in facilities-based service-provider networks by providing uniform semantics for network management and control in both the data and the optical domains.

With the same control plane deployed in both electrical and optical layers, this approach implies the following:

Implication 1. The same routing scheme must be used in both layers.

We know that the routing scheme can be further broken down into addressing scheme, Interior Gateway Protocol (IGP) scheme, Exterior Gateway Protocol (EGP) scheme, path-computation scheme, and traffic-engineering scheme. Hence one tacit peer-approach assumption is that a common addressing scheme, a common IGP and EGP mechanism, a common-path computation scheme, and a common traffic-engineering scheme should be used for both optical and electrical layers.

A common address space can be realized by use of the same addressing scheme such as the IP addressing scheme in both the electrical and the optical layers. In this case, optical-layer elements become IP-addressable entities.[10] This common address scheme assumption implies that the peer model is impractical for the network situation in which an operator owns a multiclient, heterogeneous address-scheme-based OTN.

To resolve the control-plane differences as specified in Table 1, the following routing scheme extensions are also needed to apply to both layers:

(1) IGP extensions include the following:

a. The existing adjacency discovery protocol, such as the OSPF Hello Protocol, needs to be expanded to deal with adjacency discovery situations in which the in-band bidirectional digital communication may not be feasible.

b. The link representation needs to be further expanded to represent different link physical characteristics and adjacency types. For example, consider that one optical switching system could have many ports, each of which may terminate many optical channels, each of which may contain many subchannels, and so on. It may not be reasonable to assume that every subchannel or channel termination, or even optical switching port, could be assigned a unique address,[10] so a specific link level abstraction mechanism such as link bundling[12] needs to be introduced to help improve the network scalability.

c. The existing topology distribution mechanism needs to be expanded. In the case of OSPF, additional opaque link state advertisements (LSAs) need to be defined to advertise topology state information. In the case of intermediate system to intermediate system (IS–IS), extended type length values (TLVs) will have to be defined to propagate topology state information.[10] Note that unless a certain filtering mechanism is developed during the flooding stage, not only will the optical-layer topology be flooded to the electrical-layer systems; in addition, the electrical-layer topology will be disseminated into the optical-layer systems, which is usually not necessary.

(2) EGP mechanisms such as the Border Gateway Protocol (BGP) need to be enhanced to deal with the dynamic interdomain physical topological re-configuration case.

(3) The existing explicit routing-based path-computation mechanism needs to be enhanced to consider optical-layer diversity constraints, such as SRLG diversity, for example, and various physical impairment constraints including optical signal-to-noise ratio (OSNR), ASE, and PMD.

(4) The existing electrical-layer traffic-engineering solution needs to be enhanced so that the dynamic physical topological reconfiguration capability can be fully exploited.

With the peer-model approach, an electrical-layer device, such as an IP router, obtains both the electrical- and the optical-layer topologies. Although this permits an electrical-layer device to compute one complete end-to-end path to another electrical-layer system across the optical network, this is at the cost of sacrificing network scalability. Although the topology summary scheme can be used here, overall network scalability is still affected, since some of the optical-layer link state information may potentially have no meaning in the electrical layer. In addition, any optical network outage that may be irrelevant to the electrical-layer system may also need to be “leaked” to the client layer, introducing unnecessary topological instability.

Take Fig. 1 as an example. In this case, with the peer model, after Routers A and B have formed the physical connectivity, any optical network internal topology changes, such as optical systems C and D losing their connectivity, or the number of optical systems increasing from 6 to 100, and the number of optical links increasing from 200 to

350, and so on, will cause all the routers to update their topology, although none of these changes have any effect on the interconnectivity between this pair of routers. From this example, we can see that this would have a significant effect on the overall network scalability and stability.

From the analysis above we can see that with the peer model the existing control plane needs to be updated. Although these updates are introduced purely to accommodate optical-layer intelligence, this common control plane also needs to be applied to the electrical layer. There also exists the potential that, later on, any control-plane update triggered by advances in either optical- or electrical-layer technology will always have implications for both domains. Although the control-plane solution in the electrical layer so far is relatively mature, with this approach it needs to be frequently updated, since the optical-layer control-plane scheme is still in its early state of evolution. Although there are several advantages to using one common control plane instead of two for both the optical and the electrical layer, from the perspective of electrical-layer control-plane stability, the peer-model approach is best viewed as a long-term rather than short-term solution.

It should also be noted that sharing the same address space and the same topological view as implied in the peer-model approach is feasible only when both the optical and the electrical networks are administered by the same entity. One potential deployment situation is an Internet service provider (ISP) owned by a carrier, such as the intracarrier model as defined in Ref. 1.

Implication 2. The same signaling scheme must be used in both layers.

Since it is possible to model wavelengths, and potentially TDM channels within a wavelength, as labels, one generalized MPLS (GMPLS) signaling scheme as specified in Refs. 13–15 can be used to encompass both (1) the optical level, including time-division systems [e.g., SONET add–drop multiplexers (ADM)], wavelength-switching systems (e.g., OXCs), and spatial switching systems (e.g., incoming port or fiber to outgoing port or fiber), and (2) the electrical level mainly consisting of packet-switching systems.

Although it might seem straightforward to assume using one uniform MPLS signaling scheme across both layers, this assumption is complicated by the fact that currently under MPLS, both the Label Distribution Protocol with extensions for constrained routing (CR-LDP) and the Resource Reservation Protocol with extensions for traffic engineering (RSVP-TE) are simultaneously evolving. It is likely that a signaling interworking function as proposed in Ref. 16 will be required, since both CR-LDP and RSVP-TE will continue to coexist. As studied in Ref. 16, the interworking function is complicated in that the mapping between these two protocols is not one to one.

3. Standards Activities: Status Report

To achieve automatic optical level switching, a certain degree of global standardization is required, because neither rapid provisioning nor the operational improvements desired are likely if each vendor generates a proprietary control plane. As a consequence, a wide range of standards organizations and industry forums have begun to address various aspects of the intelligent optical network with a goal of creating open interfaces. Included below are summaries of activities from three groups that are currently developing proposals for internetworking schemes. This summary of activity reflects a status concurrent with the date of this document.

3.A. International Telecommunication Union

During the year 2000 February/March Q19/13 meeting, contributions from the United States[17] and British Telecom[18] were presented on the automatic switched optical network (ASON). From discussion of these two contributions, Q19/13 agreed to begin work on the development of a new recommendation, G.ASON.[19]

The G.ASON model can be categorized as belonging to the dynamic overlay model described above. Figure 2 illustrates a general ASON architecture[6]:

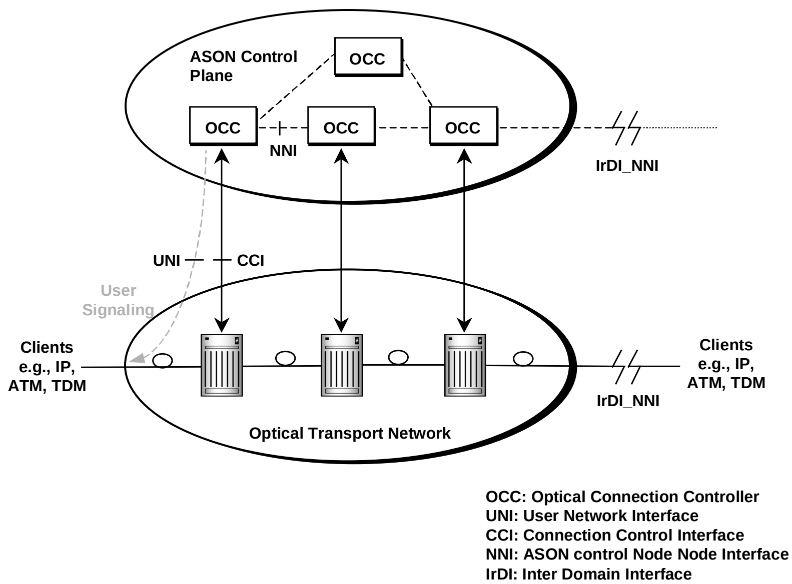

Fig. 2. Logical view of automatic switched optical network (ASON) architecture.

During 2001, The International Telecommunication Union (ITU) made significant progress in this area. In addition to finishing the architecture recommendation for ASON,[20] it also finished the following three related recommendations:

1. Architecture and specification of data communication network[21]
2. Distributed call and connection management (DCM)[22]
3. Generalized automatic discovery techniques[23]

From the network requirement perspective, the ITU-T has established a solid basis for the wide deployment of the intelligent optical network. At the current stage, the ITU-T is still working on ASON NNI and UNI protocol requirements.

3.B. Internet Engineering Task Force

Generally the Internet Engineering Task Force (IETF) is viewed as a home for protocol development. One of the ongoing IETF protocol efforts related to the optical network interworking issue is the development of GMPLS, which extends the MPLS protocol family to encompass time-division systems (e.g., SONET ADMs), wavelength switching (e.g., optical lambdas), and spatial switching (e.g., incoming port or fiber to outgoing port or fiber).[14] GMPLS is expected to cover both the peer model and the dynamic overlay model as described above. This approach proposes constructing an optical network control plane based on the IGP extensions for MPLS traffic engineering with additional enhancements to distribute relevant OTN state information, including topology state information. In the peer-model case, the full optical-layer internal topology is disseminated to the electrical layer. This state information is subsequently used by a constraint-based routing system to compute paths for point-to-point optical channels. The proposed optical network control plane also uses a MPLS signaling protocol to establish point-to-point optical channels between access points in the OTN. Note that in the peer-model case of the GMPLS approach, no specific UNI signaling is needed; whereas in the dynamic overlay model case, UNI signaling is required.

Figure 3 illustrates the peer-model case of the GMPLS-based network architecture.

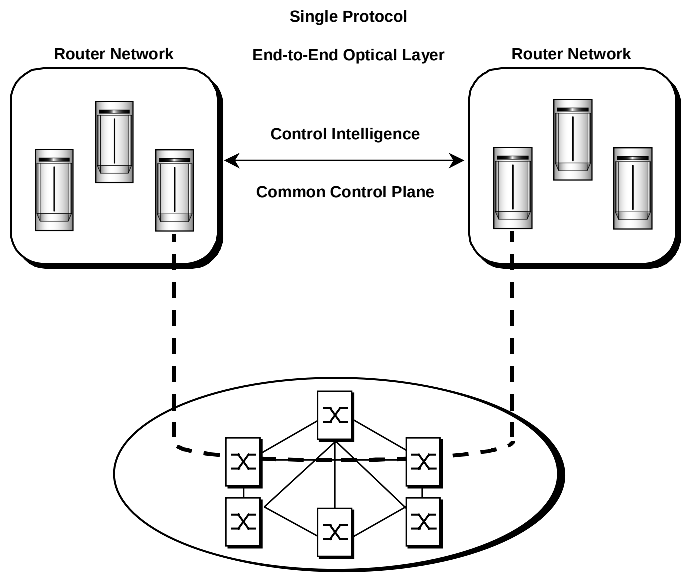

Fig. 3. GMPLS control plane for provisioning end-to-end paths.

Currently IETF MPLS and CCAMP (common control and measurement plane) workgroups have a baseline GMPLS signaling document that covers both SONET and SDH.[13] In addition to GMPLS signaling, other protocol developments such as routing extension (e.g., OSPF extensions) in support of GMPLS[24] and the Link Management Protocol[25] are also in progress.

3.C. Optical Internetworking Forum

By definition the Optical Internetworking Forum (OIF) has a charter of developing interoperability agreements between the emerging optical layer of the network and other layers already defined in the open systems interconnection (OSI) model. The OIF is also responsible for developing interoperability agreements between different vendors within the optical network layer.

The initial focus of the OIF is to define the requirements of the UNI and the network services offered across the UNI, particularly with respect to the requirements of internetworking IP with the optical network layer through SONET framed and rate circuits. Although the group needs to create an open architecture that can internetwork with a variety of clients, such as IP, SONET, Gigabit Ethernet, Frame Relay, and so on, the working group must also prioritize which clients will be defined first. It has been decided that the initial focus should be on IP as a client to the optical network.[26]

Figure 4 shows an optical network as a collection of connected optical subnetworks. The UNI and NNIs may be electro-optical or all optical. This figure shows that the OIF reference diagram in nature can also be categorized into the dynamic overlay model.

Currently OIF has finished the UNI 1.0 specification[27]; UNI signaling is based on GMPLS extension of both RSVP and CR-LDP. During Supercomm 2001,[28] OIF successfully demonstrated UNI interoperability among over 20 system vendors. As the next step, OIF is going to expand UNI features, meanwhile resolving intradomain and interdomain NNI issues.

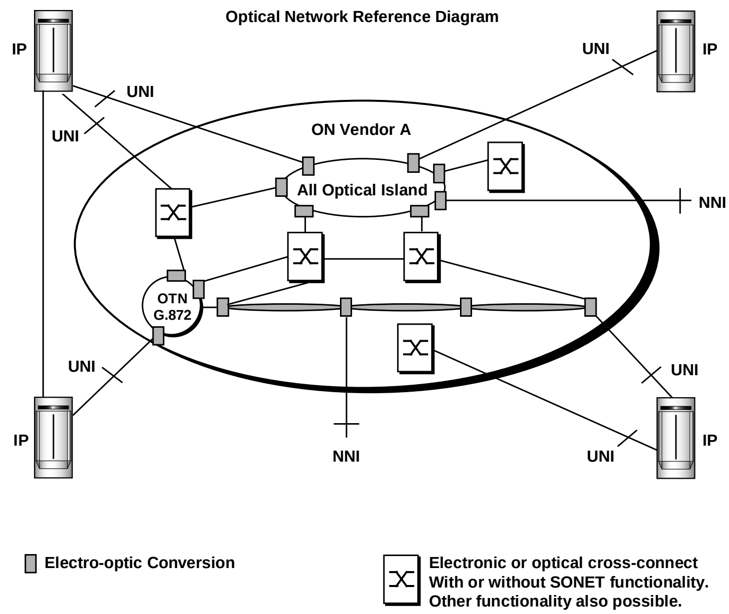

Fig. 4. Optical network reference diagram (see Ref. 26).

4. Conclusions

Enabled by a new generation of elements, the optical network is transitioning from a static, dumb, unaware transport layer to a more dynamic, flexible, self-aware layer. The emergence of intelligence at the optical layer has introduced new features and functionality to next-generation networks. It has also forced the network operators to reevaluate some fundamental assumptions. One of the biggest challenges for network operators today is to understand how to exploit and couple the intelligence residing at both the electrical layer and the optical layer so that they can optimize their network resources and deploy the most advanced services to their end-user customers. The two internetworking models described above—overlay and peer models—are examples of efforts underway within the industry to harness the powerful features and functionality that emerging optical-layer intelligence brings to the next-generation networks. Table 2 summarizes the status of these standard activities in the beginning of 2002.

Table 2. Standard Status Summary

	Internetworking Model	Focus	Status
ITU-T: G.ASON	Dynamic overlay	Architecture requirement	Requirement document finished
IETF: GMPLS	Peer Dynamic overlay	Protocol development	Ongoing
OIF: UNI/NNI	Dynamic overlay	Interoperability	UNI 1.0 document finished

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