Provisioning and restoration in the next-generation optical core

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ABSTRACT
Research is underway currently to develop intelligent control planes for the next-generation optical transport networks, which can provide customers with automatic, flexible, and real-time provisioning as well as enhanced network survivability and interoperability. An intelligent optical core appears to be viable by incorporating Generalized Multiprotocol Label Switching (GMPLS) technology into the optical control plane and deploying reconfigurable optical network elements, such as reconfigurable optical crossconnects, tunable transceivers, and reconfigurable optical add-drop multiplexers. Much of the work in this area has focused on proposing network architectures, solving the dynamic RWA problem, developing distributed protection/restoration schemes, standardizing network interfaces (e.g. UNI and NNI), and extending existing Internet routing/signaling protocols for WDM optical networks. In this paper, we present an overview of the role of GMPLS in the next-generation optical core, concentrating on both the issues and the challenges in automatic lightpath provisioning and network restoration. First, we discuss the evolutionary trend and architectures of the next-generation optical network. Then, we present an overview of dynamic provisioning problems, followed by a discussion of various constraints and unique requirements for lightpath establishment in WDM optical networks. We close by discussing the challenges in optical network restoration.

1 Introduction

As today's ever-increasing IP-centric data becomes the predominant traffic in the metro/backbone networks, legacy transport networks designed for voice-predominant or leased line data traffic are facing pressures from the demands of increased bandwidth and dynamic services. WDM appears to be a promising technology to meet the bandwidth requirement in the next-generation optical networks. Research is underway to develop intelligent control planes for the metro/backbone optical WDM networks. There is an emerging consensus that incorporating GMPLS technology into the optical control plane can lead to an intelligent optical core, which provides customers with an automated and real-time service provisioning, as well as increased operational flexibility, enhanced network survivability and interoperability.

In WDM optical networks, data can be transmitted over hundreds of fibers, each of which is capable of carrying up to tens of different wavelengths (frequencies) with bit rates from 2.5 Gbps to 10 Gbps simultaneously [1]. A lightpath in a WDM optical network is an end-to-end tunnel, usually along a single wavelength (maybe several wavelengths), spanning several links, which are connected along the way from the source to the destination. Optical crossconnects (OXCs) are able to switch a wavelength from an input to an output. In this paper, we use OXC to specify all the categories of optical crossconnects, irrespective of the internal architecture. Reconfigurable equipments, such as programmable OXCs, tunable optical transceivers, tunable filters, reconfigurable optical add-drop multiplexers (OADMs) and so on, allow optical transport networks to be automatically manageable, in contrast to the current statically configured transport networks. With those equipments available for use, an intelligent control plane is necessary to coordinate the operation of the network.

Multiprotocol Label Switching (MPLS) technology evolved from tag switching with the original aim to improve packet-forwarding efficiency of the switching routers [2]. Its capability for implementing traffic engineering was found later. In an MPLS-based network, the explicitly routed point-to-point paths can be accomplished and are referred to as explicitly routed label switched paths (LSPs). The detailed specifications of MPLS are beyond the scope of this paper and can be found in recently published books [2], papers, and IETF drafts. Generalized Multiprotocol Label Switching (GMPLS) is formulated by extending MPLS to encompass time-division (e.g. SONET ADMs), wavelength-division (e.g., optical wavelength or lambda), and spatial switching (e.g., incoming port or fiber). For WDM optical networks, the label operation becomes the operation for optical wavelengths by implicitly using wavelengths as labels at OXCs. Substantial efforts have been expended on extending MPLS protocols to support the integration of GMPLS into optical control plane [3-8]. The solutions discussed in those papers are leveraging the existing MPLS protocol suite. Explicit lightpath computation is implemented at source node, with the aid of extended IP link state routing (e.g. OSPF or IS-IS) and constraint-based RWA algorithms. The lightpath establishment and teardown can be achieved by signaling protocols, such as extensions to RSVP-TE or CR-LDP [9,10].

Due to the inherent difference between packet-switched Internet and wavelength-routed optical transport networks, however, GMPLS can only subsume a subset of functionality of MPLS. Furthermore, the physical constraints, some peculiarities of routing and wavelength assignment algorithm (RWA), and the special requirements of protection/restoration in optical networks impose additional challenges in designing GMPLS-based optical networks. Many issues and challenges arise from the unique characteristics of optical transport networks. Some of them appear to be solvable. For example, link bundling is proposed to enhance the scalability of routing and signaling in optical networks [30]. And, link management protocol (LMP) is proposed to maintain connectivity status of links and channels between two adjacent nodes [35]. Some issues are still not clearly understood; for instance how to detect and localize fault in all-optical networks is still unclear. In this paper, we mainly concentrate on the issues and challenges in integrating GMPLS into an intelligent optical core. We only consider the non-packet (i.e., circuit switching) forms of optical switching in mesh networks.

The remainder of this paper is organized as follows: Section 2 describes the evolutionary trend and architectural alternatives of the next-generation optical transport networks. Section 3 presents an overview of automatic provisioning in optical networks, taking into account the RWA problem, physical layer impairment constraints, wavelength conversion capability, link bundling and link management protocol, inter-domain routing and signaling, bi-directional lightpath establishment, and crankback routing. Section 4 presents issues and challenges in network survivability. Section 5 concludes this paper.

2 Architecture

Dramatic increase in data traffic, driven primarily by the explosive growth of the Internet, is challenging today's transport networks, which are essentially statically configured and voice-optimized. In addition to the bandwidth problem, the slow provisioning time provided by current transport networks cannot meet the demand from the frequently changing IP services. Today's transport networks consist of SONET ring and are widely deployed in the metro networks, which are connected by backbone networks. Data traffic in such networks is carried on leased circuit through TDM channels. Given the inherently bursty nature of IP data traffic, the fixed-bandwidth pipes of TDM transport may not be an efficient solution. As indicated in [12], the traditional approach of building SONET-based ring networks fails to handle current traffic growth because of its long deployment time, difficulty of equipment scaling, and high operational costs. In contrast, making use of GMPLS in WDM optical networks has the potential to provide ATM-like QoS capability and SONET-competitive restoration time, resulting in an efficient optical core with unlimited bandwidth. Figure 1 shows the expected evolution of transport networks from a layered perspective. Figure 1(a) is the current status of layered transport networks. Although various approaches can be chosen to meet the requirements for different types of traffic, multi-layering becomes an overhead for the transport networks. For example, a low efficiency is introduced by layering best-effort IP data over ATM or SONET (or both), because the ATM layer brings in significant overhead to meet QoS requirements and SONET is voice-optimized. In the next-

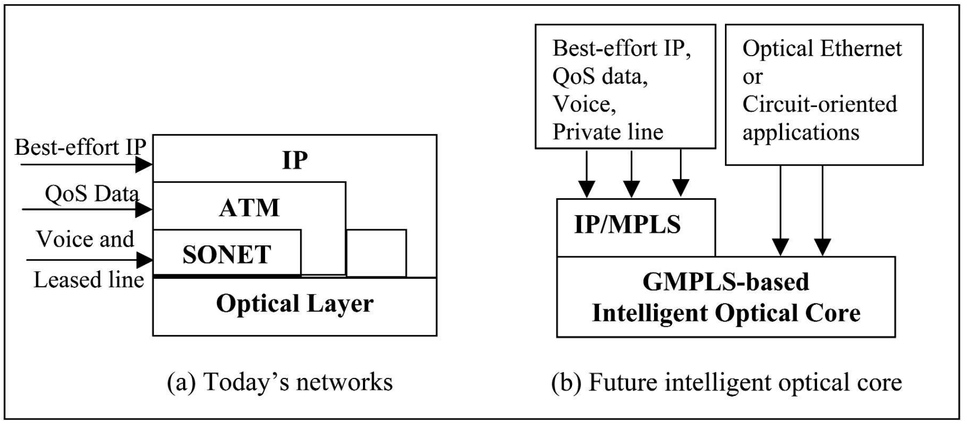

Figure 1: The evolution of transport networks — a layered perspective.

generation networks, as shown in Figure 1(b), a simpler, lower cost, and more responsive network with two layers (MPLS-based IP layer and smart GMPLS-based optical layer) is likely to replace the four layered transport networks. In the expected future network architecture as shown in Figure 1(b), the ATM-like QoS can be implemented at IP/MPLS layer and SONET-competitive restoration capability can be achieved at the GMPLS-based optical layer.

Hence, the transport infrastructure is moving towards a model of high-speed routers interconnected by intelligent optical core networks. The next step is to interconnect these two layers, resulting in automatic end-to-end connectivity via standardized routing and signaling methods. Three interconnection models, i.e. peer model, overlay model, and augmented model, were first proposed in [11]. Under the peer model [11], the IP/MPLS layer nodes act as peers of the nodes in optical transport networks, such that a single routing protocol instance runs over both IP/MPLS and optical domains. The interior gateway protocol, such as OSPF or IS-IS, with appropriate extensions, can be used to distribute topology information. Under the overlay model [11], the IP/MPLS routing, topology distribution, and signaling protocols are independent of those at the optical layer. Each layer defines its own approaches for routing and signaling. Under the augmented model [11], although IP and optical domain use separate routing instances, information from one routing instance is passed through to the other, depending on the administration policies and other factors. This is analogous to the routing approach in today's Internet, where different interior gateway routing protocols may be used in different autonomous systems (ASs), while interdomain routing is used to exchange reachability information between ASs, such that each AS can have summary information about others.

The peer model is not practical for implementation due to its poor scalability and high complexity. The overlay model imposes administrative control boundaries between core and edge, strictly limiting the network information within each domain. As a result, explicit routing across several domains is difficult to implement. One point of view is that the augmented model appears to meet the requirement to achieve a simple, effective, and scalable transport network. However, as discussed in [13], diversity of protocol stacks, architecture choices, and network applications in the transport networks will continue to exist in the near future. So, although the augmented model would seem superior architecturally, the overlay model will prevail in practical networks for many years due to the existence of these diversities.

3 Issues and Challenges in Automatic Provisioning

Provisioning of new services in today's transport networks involves activities, such as adding new access devices and ADMs, mapping new paths, verifying link connectivity, signing up Service Level Agreement (SLA) and so on. These processes are extremely manual and generally take several weeks (or months) to accomplish. By employing distributed GMPLS optical control planes, all of these processes (or part of them) can be automatically implemented, resulting in faster provisioning, lowered operating cost, and improved network resource management.

However, some unique characteristics and requirements are critical for the implementation of automatic provisioning in the GMPLS-based optical core and will cause vital problems if they are not adequately addressed. We will review issues and challenges in automatic provisioning in this section: we give an introduction to the routing and wavelength assignment problem in Section 3.1; we introduce physical layer impairment constraint in WDM optical networks in Section 3.2; we present the issues regarding wavelength conversion in Section 3.3; we discuss the routing scalability and link bundling in Section 3.4; we introduce the link management protocol in Section 3.5; we present the issues in bi-directional lightpath establishment and crankback routing in Section 3.6 and Section 3.7 respectively; we discuss the challenges in inter-domain routing and signaling in Section 3.8.

3.1 Routing and wavelength assignment (RWA)

3.1.1 Background

In order to implement automatic provisioning, the routing and wavelength assignment (RWA) problem must be solved for each lightpath connection request either in an on-line or in an off-line manner. RWA is referred to as the scheme/algorithm to determine a route and corresponding wavelength on each fiber along the route for the lightpath. The objective of a RWA problem is to optimize the network performance, in terms of network blocking probability or network utilization. The RWA problem for static traffic is known as the static lightpath establishment (SLE) problem. For dynamic traffic, the RWA problem is referred to as the dynamic lightpath establishment (DLE) problem, which is aimed at setting up a lightpath in a manner so as to reduce the network blocking probability when a connection request arrives.

In earlier work, the SLE problem has been formulated as an integer linear program, which is NP-Complete. In [1], a multi-commodity formulation combined with randomized rounding is introduced to calculate the routes for lightpaths. Wavelength assignments are performed based on graph-coloring techniques. The work in [14] develops an integer linear programming (ILP) formulation of the RWA problem, from which it derives a generic RWA algorithm's performance bounds — an upper bound on the carried traffic, or equivalently, a lower bound on the lightpath blocking probability. Today's voice-optimized metro and backbone transport networks are designed mainly for the highly predictable voice data and leased line traffic. Provisioning in such networks can be implemented by solving SLE problem when the networks are built up.

However, the next-generation optical core is designed as an IP predominant network, where IP-based traffic is difficult to predict and model. So, the RWA problem in such an IP-centric data transport network cannot be formulated as a SLE problem. Instead, the DLE problem has to be solved to achieve automatic lightpath establishment for the purpose of a fair network performance. For this reason, recently more attention has been paid for developing heuristics to solve the DLE problem. Due to lack of knowledge about the network traffic matrix, the DLE problem is harder than the SLE problem, which is already NP-Complete. If distributed connection management is employed in the next-generation optical core, another problem arises: how much information does each node in optical networks need to know in order to solve the RWA problem? Maintaining a global knowledge of the network resources has the potential to achieve better network performance, but may result in reduced scalability and increased overhead.

To establish a lightpath, an optical network normally requires a common wavelength to be assigned on all the links on the route. This requirement is known as the wavelength-continuity constraint and such a network is called wavelength-continuous network. The wavelength-continuity constraint is eliminated, if the data arriving on a wavelength at an input port can be transferred on another wavelength at the output port at an OXC node. Such a technique is referred to as wavelength conversion [19] and wavelength converters are the devices to operate wavelength conversions. Optical switches embedded with wavelength converters can provide wavelength conversion capability to a network [19]. Such a network is called a wavelength-convertible network.

3.1.2 Heuristics for DLE

Essentially, heuristics divide RWA problem into two independent sub-problems: routing and wavelength assignment. The routing schemes are classified into three classes: fixed routing, fixed-alternate routing, and adaptive routing [15]. In the fixed routing, the route for each lightpath is fixed and computed before connection requests arrive. The fixed-alternate routing keeps a set of pre-selected alternative routes for each lightpath. In case a lightpath establishment fails on one route, another route may be chosen from the set of alternative routes. The adaptive routing dynamically selects a route for each lightpath when a connection request arrives. Given a route for a lightpath in a wavelength-convertible network, the wavelength assignment becomes straightforward by allocating any one of available wavelengths on the link to the lightpath. So, wavelength assignment algorithms are mainly referred to as schemes proceeding under the wavelength continuity constraint.

Numerous wavelength assignment algorithms and their variants exist in the literature, such as First-Fit (FF), Random, Least-Used (LU), Most-Used (MU), Least-Loaded (LL), Max-SUM (MS), and Relative Capacity Loss (RCL). The work in [15] showed that RCL has the best performance among them and FF is the simplest one to implement with network performance close to RCL. In FF, all the wavelengths are indexed with consecutive integer numbers and the wavelength with the lowest index among all the available wavelengths is selected for the lightpath establishment. The MAX_SUM algorithm was first proposed in [17] for WDM ring and tori networks. In [16], MAX_SUM is slightly changed to become RCL. Both MAX-SUM and RCL are designed for assigning wavelengths under fixed or fixed-alternate routing schemes. As an improvement to RCL, the distributed RCL (DRCL) is proposed for adaptive routing in [15] and found to have the best performance among those previously proposed. The better performance of DRCL is originated from its adaptive routing, which considers network load when selecting a route. For a better understanding of these heuristics, please refer to [15–17].

The simulation experiments in [18] showed that the heuristic simultaneously considering both routing and wavelength assignment is better (in terms of network utilization) than the one separately solving them when computing lightpaths. This requires a global knowledge of wavelength usage in the whole network. By flooding link state advertisement (LSA) in the network, each node can keep the same picture of the complete network resources. This method can yield a fair network performance and obtaining global knowledge of the network resources in an optical network appears to be feasible by extended Internet interior gateway protocols (e.g. OSPF or IS-IS). As a result, some new distributed adaptive routing and wavelength assignment heuristics, based on global knowledge of the network, have been proposed in the recent literature [18,21,22].

Although these heuristics can achieve a fair network performance, they have scalability problems due to the requirement of global knowledge of network state. In a WDM optical network employing hundreds of fibers with tens of wavelengths on each fiber, it is a great burden for each node to maintain large amounts of information of wavelength availability (and probably a routing table for each wavelength). Furthermore, the requirement of large overhead capacity and relatively long routing convergence time will cause the network performance to be lower than expected. Link bundling is a proposed solution to deal with this scalability problem in the next-generation optical core. The aggregation due to link bundling may cause information loss at the lower level link status. Link management protocol (LMP) has been proposed to solve this problem. The relevant discussion of link bundling and LMP is provided in the later sections (see Section 3.4 and Section 3.5)

3.2 Physical layer impairment constraint

The RWA problem as discussed above remains at a theoretical level without considering optical layer impairments. However, physical layer impairment is a critical constraint for designing an automatic switched optical network in reality. To support high-speed end-to-end data communication in a large-scale WDM optical network, a lightpath may traverse a long distance using wavelength switching. The quality of the signal degrades as it travels through several fiber spans and optical components. The optical amplifiers, e.g. erbium-doped fiber amplifiers (EDFAs), may compensate for some loss, but introduce noise at the same time. Furthermore, the OXC introduces crosstalk, which may interfere with a particular channel. The accumulated impairments without regeneration will result in a high bit error rate (BER), which in turn increases the network blocking probability. If the BER of the signal in a lightpath at destination node is higher than a pre-defined threshold, the lightpath may be blocked. In an opaque optical network, the regenerators on each node conduct optic-electronic-optic (O-E-O) conversion and 3R regeneration (regeneration, reshaping, and retiming) to clean up the signals carried on the fiber. However, the expensive regenerators increase the cost of the network and the O-E-O conversion becomes a bottleneck, which limits the network data rate. In a transparent optical network, lightpaths bypass the expensive electronic signal processing at intermediate nodes. However, transparent optical networks are difficult to be practically deployed on a large scale due to the impairments.

Authors in [23] studied the impact of transmission impairments on the routing in the optical layer. The linear and nonlinear impairments were investigated. The limitation of transparent fiber length is calculated by considering the polarization mode dispersion (PMD), and the maximum number of spans between optical amplifiers is calculated from the problem formulation of amplified spontaneous emission (ASE). PMD and ASE are linear impairments. It is more complex for routing to deal with the nonlinear impairment, such as crosstalk. One of the solutions to conquer the impairments is to divide networks into sub-domains with regenerators deployed at each edge node, such that the scale of each domain is small enough to limit impairments in an acceptable level. Regeneration only happens at each edge node when the lightpath exits or enters a sub-domain. In such a network, the signal quality is ensured so that dynamic routing does not need to consider impairment constraints. The impairment analysis in [23] offers some insight into designing such networks from a routing perspective.

Another solution relies on the concept of the recently proposed translucent network [24]. In a translucent optical network, a signal is made to traverse in optical layer as long as possible before its quality falls below a threshold value. Because the signal is regenerated only if necessary, we need only sparse regeneration deployment in the network. Authors in [24] described the architecture of a translucent optical network and proposed several algorithms to allocate the regeneration resources in the network. In a typical WDM optical network, most intermediate nodes are attached to access nodes. Each access node inherently has a regenerator, which can be reused to conduct regeneration on a bypass lightpath when it is idle. The authors of [25] propose two dynamic routing heuristics (MRHBC and MBRHC) fitted into a GMPLS-based framework, taking into consideration regenerator's location and availability, signal bit error rate (BER), and lightpath distance. In order to implement these two heuristics, a logical network topology is generated based on the knowledge of available regenerators' location and wavelength availability. Lightpaths are calculated on the logical topology with the objective of minimizing both regenerator hops and BER. A lower network cost is achieved by dynamically using the idle regenerators inherited from the access nodes, which are attached to the OXC nodes. In order to implement dynamic routing in translucent networks, additional information, such as location of available regenerators, needs to be added into the GMPLS routing protocols. However, a problem may arise if there are no additional regenerators in the network. An OXC cannot drop a signal to the access nodes attached to it, when all regenerators on this OXC are occupied by bypass lightpaths. Further study is needed to investigate this problem.

3.3 Wavelength conversion capability

An OXC embedded with wavelength converters provides wavelength conversion capability, which may result in an improved network blocking performance [19]. Authors in [20] give an extensive review on the importance of wavelength converters in dynamically reconfigurable WDM optical networks. The opaque networks inherently have wavelength conversion capability at each intermediate node due to the O-E-O operation. In translucent networks, nodes with available regenerators have wavelength conversion capacity. However, in all-optical transparent networks, wavelength conversion capability depends on the function of optical switches. By sparsely deploying wavelength conversion nodes, the network performance of transparent networks can be dramatically increased [18]. In this case for RWA computation, each node should know the location of the nodes with wavelength conversion capability either through manual configuration or by flooding routing messages. The latter method needs an extension to the routing protocol.

3.4 Scalability and link bundling

In a DWDM optical network, two adjacent OXCs may be connected by hundreds of fibers, each of which may have tens of wavelengths transmitted together. The traditional LSA update method for these network resources results in a large volume of control message overhead. It also causes scalability problems to interior gateway protocols, such as OSPF and IS-IS. Link bundling [30] is proposed by IETF working group to improve network scalability by abstracting information on traffic engineering (TE) links. The routing messages are dramatically reduced by disseminating abstracted link information, rather than exchanging the status for all the links. The resources between two adjacent OXCs are identified by tuples in the form of <Bundled Link ID, Component Link ID, Label>. As defined in [31], a bundled link (or TE link) is a logical construct that represents a way to group/map the information about certain physical resources and their properties. Link bundling abstracts the resources between two label-switched routers (LSRs) into disjoint sets of component links. Each bundled link may contain a set of component links. A combination of <Bundled Link ID, Component Link ID, Label> unambiguously identifies the appropriate resources. Component links will not be disseminated in routing messages into the network. Determining a component link is a matter for the local LSR. The rules for bundling must be consistent across all the LSRs in the same domain.

Now, we take a closer look at link bundling in WDM optical networks using an example. In Figure 2, each OXC connects to its neighboring OXCs with five fibers, represented by {F1, F2, F3, F4, F5}. Each fiber can simultaneously transmit 40 wavelengths, represented by $\{\lambda_i \mid 1 \leq i \leq 40\}$. The link bundling can be implemented according to the following rules: every group of 5 fibers, which are linked to the same neighboring OXCs, is mapped to a bundled link (TE link); each fiber is mapped to a component link; every wavelength is mapped to a label. In this way, network resources, i.e., wavelengths, can be identified unambiguously. For instance, the λ_{30} at fiber 4 from OXC B to OXC A can be represented as <BA, 4, 30>. After link bundling is finished, the status of a bundled link is defined as:

- alive – if any one of the component links is alive;
- dead – if all the component links are not alive.

In this example, if a conduit cut causes all the fibers to go down between B and A, only one update message, instead of five messages, is flooded into the network to inform other nodes that link BA is down.

Another example is used to show that the selection decision on a component link occurs at local OXCs. When OXC D wants to set up a connection to OXC A, the following steps happen (only steps in the forward direction are detailed):

- OXC D calculates a path and wavelength, e.g. D-B-A and λ_{30}, according to its RWA algorithm.
- OXC D reserves wavelength <DB, 130> according to wavelength availability on each fiber in a local database and sends a signaling message to B (identifier in signaling message uses <bundled link ID, label>, e.g. <BA, 30>).
- OXC B reserves <BA, 4, 30> and sends a signaling message to A.
- OXC A configures related equipment and sends a confirmation message back to D.

When several changes on wavelength usage at a bundled link occur simultaneously, one LSA update message, carrying the wavelength usage information of the bundled link, will be sent out. Without link bundling, more than one LSA update message will be flooded into the network. So, link bundling potentially reduces the overhead caused by the additional messages. Corresponding change in routing and signaling protocols is needed for using link bundling in a GMPLS-based optical network. For a detailed explanation of link bundling, please refer to [30].

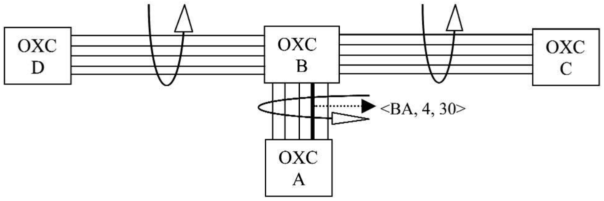

Figure 2: An example of link bundling.

3.5 Link management protocol (LMP)

The aggregation of network resources by link bundling results in loss of some of the link information, such as the status of component links, since link bundling abstracts the network resource to only two levels, i.e., bundled link and label. Link management protocol (LMP) is designed to support maintaining a detailed level of network resources [35]. The connectivity of fibers (component links) between a pair of adjacent OXCs and their port configuration at each side may be maintained by exchanging LMP messages between two adjacent OXCs. The difference between LMP and other routing/signaling protocols is that LMP is a protocol for two adjacent OXC, but routing and signaling protocols apply to all the nodes in the network. A key function of LMP is to test the health of the data-bearing channels (wavelengths). Because the control channel and data channels in an all-optical transport network are very likely to be separate, the status of the control channel is not the same as that of data channels. So, sending *hello* messages periodically on the control channel can only obtain the status of the control channel, but not the status of the data channels. One of the key concerns of LMP is for testing the health of each data channel that is not in use. The core procedures of LMP include [35]:

- Control Channel Management
  It uses a *Config* message and a fast keep-alive mechanism over the control channel between adjacent nodes.
- Link Property Correlation
  The link property correlation of LMP is designed to aggregate multiple data channels (ports or component links) into bundled links and to synchronize the properties of the bundled links.
- Link Connectivity
  The link connectivity verification is used to verify the physical connectivity of the data-bearing links between the nodes and to exchange the interface IDs. In-band *Test* messages are sent over data-bearing channels and *TestStatus* messages are transmitted over the control channel.
- Fault management
  Fault management of LMP is used to exchange status of data-bearing channels and to detect and locate faults. It relies on physical layer mechanisms to detect faults.

All of the LMP messages for the above functionality, except for *Test* message of link connectivity, are sent over control channels. In order to carry the *Test* message over data-bearing channels, each OXC node should be able to send and receive messages over any data link. This is an additional requirement for all-optical switches. After the control channel has been established between two nodes, the data link connectivity can be verified by exchanging *Test* messages over each data channel specified in the bundled link. The verification is done initially when bringing up a link and can be periodically conducted on the idle data channels between two OXC nodes.

When considering LMP in the design of wavelength state transition diagram, an additional wavelength status needs to be added into the wavelength status pool. The current status pool of wavelength state transition function contains: idle, reserved, active, and down. A new status, *under verification*, needs to be added into the status pool. How the OXC acts when a reservation request arrives to reserve the channel under verification becomes a problem. This is not addressed in the existing IETF drafts. Two solutions may exist:

- The OXC node holds the reservation message until the verification ends.
  This increases the reservation time and thus reduces the network utilization.
- The OXC ends the verification by sending an *EndVerify* message and then reserves the channel immediately.
  This assumes that the link connectivity configuration is not changed since last verification. So, the channel connectivity may be out-of-date.

No matter what decision is made to deal with this situation, corresponding changes should be made on the wavelength state transition diagram.

3.6 Bi-directional lightpath establishment

A lightpath tends to be bi-directional in the optical transport networks. A bi-directional path consists of two associated lightpaths in opposite directions routed over the same set of nodes. The bi-directional lightpath establishment operates under the risk of race conditions, in which the end nodes may assign two associated lightpaths to different requests simultaneously. There are essentially two ways to solve this problem. The first one is to give up the lightpath establishment procedure if the race condition happens. The second way is to set up some rules of lightpath establishment for both end nodes to follow during the lightpath establishment procedure. For example, the higher addressed node always preempts the lower addressed request when race condition occurs.

3.7 Crankback routing

In a distributed routing environment, the resource information used to compute a constraint-based path may be out-of-date. This implies that a connection setup request may be blocked because a link or node along the selected path has insufficient resources. When a setup failure occurs, a notification is returned to the setup initiator (ingress LSR). In the current CR-LDP, the ingress LSR receiving the notification has to terminate the message and give up the LSP establishment. If the ingress or intermediate gateway LSR knows the location of the blocked link or node, the LSR can designate an alternate path and then reissue the setup request, which can be achieved by the mechanism known as crankback routing [36]. Crankback routing requires notifying an upstream LSR of the location of the blocked link or node. So, a corresponding extension of signaling protocol is necessary to support crankback routing [36].

3.8 Inter-domain routing and signaling

As addressed above, the next-generation GMPLS-based optical transport network may use routing protocols to broadcast and maintain network resource status, based on which the RWA algorithm can dynamically calculate a route and corresponding wavelengths for each lightpath. Once a lightpath request arrives at the network, a signaling protocol is initiated to reserve the network resources assigned to this lightpath by the RWA algorithm. However, these processes are suited for use in a single domain, which employs the same routing and signaling protocols. The issues in inter-domain routing and signaling appear to be more complex and need a careful consideration for the purpose of automatic lightpath establishment in a global environment. The need for inter-domain routing and signaling may be triggered by several reasons, such as existence of administrative boundaries, requirement on scalability of routing and signaling, security and reliability concern, and topology difference in different areas.

In today's Internet, BGP or OSPF Areas are used for inter-domain routing. The summary of reachability information is exchanged among edge routers in the Autonomous Systems (ASs). The Internet IP forwarding is designed on the hop-by-hop basis, i.e. only the next-hop for the destination is provided at each node. But, optical circuit switching may require computing explicit constraint-based routes at source nodes. MPLS's loose routing allows a source node to specify a route for a lightpath in terms of a sequence of optical domain numbers. In loose routing, an abstract node represents a group of nodes whose internal topology is opaque to the ingress node of the LSP. Using this concept of abstraction, an explicitly routed LSP can be specified as a sequence of IP prefixes or a sequence of ASs [37].

Authors in [32] proposed two solutions, based on OSPF, for sub-network routing information exchange within the optical network owned and managed by a single carrier. Both of them can support loose routing at source node. Each node maintains a complete network state information of its own domain and summary information of other domains. So, a lightpath spanning several domains is decided as follows:

- The source node decides a route and corresponding wavelengths in its domain and border nodes in other domains.
- The border nodes, selected in the first step, will make RWA decisions in their own domains.

In most of the current work, signaling is assumed to happen only in a single domain. Further research is necessary to study the signaling schemes across several administrative domains, in which different signaling protocols may be employed. Network to network interface (NNI) defines the communication interface between border OXCs in different domains. Optical NNI interface and signaling requirements can be found in [33] and [34]. To date, how to set up a lightpath crossing several domains (inter-domain signaling), has not been addressed in detail in the literature. In summary, how to interoperate with different administrative domains, which may employ different routing and signaling protocols, remains a topic of further research on automatic provisioning in next-generation optical networks.

4 Network Survivability

Another key concern in WDM optical transport networks is network survivability, which is referred to as the capability of continuous data transmission upon occurrence of failure. In the context of a WDM optical transport network, a duct cut implies loss of data at terabits per second. Due to its paramount importance, substantial efforts have been made to find efficient methods to achieve optical network survivability in the literature [40-48]. Protection and restoration are two schemes for survivable networks. In both cases, data transmission is switched from a working channel to a backup channel upon occurrence of failure. A protection mechanism reserves some spare capacity before the occurrence of failure. A restoration scheme searches for backup resources after failure happens, and thus has a longer restoration time than the protection scheme. In a WDM optical network, there is no clear boundary between these two schemes. We will use protection and restoration interchangeably in this paper. Path-based protection/restoration refers to the schemes that use a backup path, which is link-disjoint with the working path, to recover the traffic from failure. Link-based protection/restoration recovers from a link failure by routing the data on a detour between the two end nodes on the link disrupted. Compared with a path-based scheme, link-based scheme has a faster restoration speed, but at the expense of more spare capacity. We can also classify the protection/restoration schemes as 1+1, 1:1, and 1:N. 1+1 path-based protection uses dedicated network resource on both the working and backup paths to transfer data simultaneously. The destination node will choose one of them based on the signal quality. 1:1 scheme pre-selects spare capacity, but allows lower priority users to occupy it under normal conditions. Upon a failure, it will preempt the network resources from the low priority user and switch the transmission to backup channels. 1:N scheme allows N users share a backup resource. In case of failure, only one of the users can obtain the backup resources. Both 1:1 and 1:N schemes need additional signaling effort to configure network resources upon a failure.

The above discussion can be found in most of the papers related to optical network survivability in the literature [40-48]. Actually, some of these approaches were originally developed for ATM or SONET networks, where a survivable network is also called a self-healing networks. These concepts can be applied directly to optical networks, because the survivable network design appears to be a logical problem. However, the unique properties of an all-optical core network require additional effort and impose challenges when leveraging existing schemes. Challenges include the difficulties in real-time fault detection at the optical layer, the requirements for physically diverse lightpath computation, the difficulty in achieving fast restoration speed, etc. In Section 4.1, we give a brief introduction to the distributed restoration schemes in self-healing networks and indicate the possibility for them to be used in GMPLS-based optical networks. The sections following Section 4.1 reviews some challenges in designing survivable all-optical networks.

4.1 Self-healing network

Two key concerns in designing a self-healing network are: (i) Efficient control with fast restoration procedure; (ii) Economic spare capacity assignment. Given the traffic matrix, the latter one can be formulated as a linear programming problem, where the objective is to minimize the total spare capacity under a set of constraints [49–51]. This can be implemented off-line at a central controller. But, the centralized restoration experiences a restoration speed of minutes and is not suitable for a network with unpredictable traffic [56]. Distributed restoration algorithm (DRA), which can be classified into path-DRA and link-DRA, has been studied for many years [52,53,56]. As indicated by its name, the spare capacity is found by distributed messages sent by the end node upon a failure. The simulation results in [52] showed that path-DRA can restore failure within two seconds and achieve a near optimal spare assignment. However, 2-second restoration still may not satisfy the fast restoration requirement for optical domain. The idea of distributed preplanning is to preplan the spare capacity for expected failure, whose working procedure is similar to DRA, except that it is executed before the occurrence of any failure [56]. Distributed preplanning with fast restoration signaling protocol provides a solution for efficient network restoration, in which the spare capacity is effectively found by flooding messages in the whole network before any failure and using a fast restoration protocol to implement notification and switching upon a failure. By this way, a fast restoration is implemented, because the relatively slow planning phase has finished before failure happens. However, the unpredictability is not a desirable property of DRA for transport carriers.

p-Cycle, which is a link-based restoration technique in mesh networks, is proposed to solve both capacity and speed problems in restoration [54]. It is shown to have a mesh-like capacity and ring-like restoration speed. In the p-Cycle scheme, a number of cycles are prepared for recovering from every link failure in the network. Optimal p-Cycle coverage discovery is an integer-programming problem. Distributed Cycle PreConfiguration (DCPC) [54] has been introduced as an approach to implement a self-organizing p-Cycle, where p-Cycle coverage is preplanned in a distributed manner automatically. DCPC works as follows [54]: A cycler node is chosen in a round-robin fashion among all the nodes in the network and other nodes are regarded as Tandem nodes; The cycler node floods out messages to all the Tandem nodes; Tandem nodes will keep broadcasting messages until they return to the cycler node, forming several cycles on the cycler; Some rules are applied to ensure that only simple cycles are formed; Based on the metrics of each cycle collected by the flooding messages, the cycler node can make a local decision to choose the best cycle to serve as the p-Cycle; After each node serves as a cycler node, the last cycler node will initiate a global construction of best p-Cycle coverage; The concept of DCPC is similar to DRA preplanning, but the objective is to find optimal cycle coverage; The simulation results in [54] showed that DCPC can have a mesh-like efficiency in terms of spare capacity assignment and a ring-like restoration speed (50-150 ms).

All the schemes discussed above are mainly designed in the context of SONET/SDH networks, where in-band signaling is easy to implement in the overhead bytes. It is possible to map the concepts into WDM optical networks if the control channel is terminated at the intelligent OXCs (However, the wavelength continuity constraint will bring complication to the distributed resource assignment in optical networks). GMPLS routing protocols may be extended to support DRA or DCPC. The challenges in mapping these schemes into optical networks are addressed in the following sections.

4.2 Restoration speed at the optical layer

The optical layer is located at the bottom in a network from a layered perspective. It serves as the medium for the data transfer from upper layers. If the restoration speed is not fast enough at the optical layer, all the upper layers will be affected by the disruption at the optical layer. As stated in [57], a 2-second outage will cause all the circuit-switched connection, private-line, and dial-up services to be disconnected. So, two seconds becomes the connection-dropping threshold. Besides, some real-time services ask for a more critical restoration speed on the order of tens of milliseconds. On the other hand, the layers above the optical level may have their own restoration schemes. Contention for network resources may happen when the optical level restoration is not fast enough to avoid failure detection at the upper layer. Escalation is proposed as the solution for multi-layer efficient restoration, which will bring more complex design for the all-optical network [39]. The simplest and most efficient solution is to provide fast restoration at the optical layer. Since SONET automatic switching protection (ASP) provides 50 ms restoration speed and has been proven to have a good effect in practice, network designers aim at SONET-competitive survivability at the optical level.

DRA is shown to have a restoration speed of less than two seconds in mesh networks, but it is far greater than the requirement of fast restoration (<50 ms) at the optical layer. Pre-configured p-Cycle has a fast restoration speed (50-150 ms), but DCPC needs a sampling period of about 1/3 second as stated in [54]. As a result, the convergence time for DCPC may be on the order of seconds. If lightpath connection requests arrive frequently, which is very likely to happen in the IP-over-WDM context, the speed of DCPC in calculating new p-Cycles is not fast enough to achieve real-time provisioning. The same problem also remains for the DRA preplanning schemes.

Emulation experiments in fast restoration using GMPLS have been conducted on the GMPLS prototype control plane at AT&T labs [55]. The experimental results showed a worst-case restoration speed under 200ms using path-based restoration, in which backup lightpaths are preplaned and RSVP signaling is used to reserve wavelength and configure OXCs upon detection of failure. Although a link-based restoration is faster than a path-based scheme, it is not practical in an all-optical network due to the difficulty in detecting failure at intermediate nodes. We will discuss fault detection in the next section.

4.3 Fault detection

A SONET network uses in-band overhead information to implement performance monitoring electrically at intermediate nodes. In all-optical networks, fault detection becomes a challenge for bypass lightpaths at intermediate nodes without electrical processing. So, link-based restoration is not practical until a solution for fast fault detection at intermediate nodes in the optical domain comes out. Measuring bit error rate (BER) is a popular method for performance monitoring in the electrical domain, while the power measurement and optical spectrum analysis are candidates for optical fault detection in optical domain. We list some optical performance monitoring techniques [38] and corresponding challenges for their deployment in an all-optical network:

- Power Detection
  Power detection measures the power against an expected value over a wide band. However, it will take a relatively long time to detect a slight decrease in power. In addition, power detection is insensitive to any power reduction, which is uniformly distributed over all bits.
- Optical Spectrum Analysis (OSA)
  The OSA scheme relies on the analysis of the optical spectrum. Spectrum filters are used to isolate the spectrum of signal and noise. As a result, optical signal-to-noise ratio (OSNR) can be measured and used as the threshold to detect fault conditions. However, OSA is a slow procedure mainly used by operators. Additional programming effort is needed in order to implement a fast and automated OSA procedure.
- Pilot tones [58]
  Pilot tones are signals, which travel along the same wavelengths (channels) and nodes as the payload, but are distinguishable from payload. This is achieved by modulating a low-frequency pilot tone (KHz) onto each wavelength of ongoing lightpaths. The frequencies of the tones and the low-speed digital information carried by them can easily be monitored at various points in the network using optical taps and inexpensive low-speed detectors followed by narrow-band electrical filters [59]. The introduction of a pilot control system introduces a new design criterion. The tone frequencies must be low enough so that they will not affect high-frequency payload, and must be high enough to not be affected by slow gain dynamics in the EDFA. In a dynamic environment, each pilot tone monitoring point must know the pilot tone frequency on each channel, since different frequencies may be used for pilot tones on each wavelength. Thus, the pilot tone frequency for each wavelength should be carried in the signaling messages before a lightpath is established.

4.4 Physically diverse lightpath computation

A backup lightpath is required to be physically diverse from its working lightpath. Two lightpaths are physically diverse if they are not subject to a single point of failure. The physical diversity ensures that the working and backup paths will not be affected under a common failure, such as a conduit cut. A simple assumption is that the network is only protected from a single link failure at the physical layer. So, the failure of one of the physically diverse paths will not affect the other. Since lightpath computation happens at the OXC layer, knowledge of the underlying fiber configuration is required at the OXC layer.

An optical transport system may be connected by a sequence of fiber cables, which are placed in a sequence of conduits. The layer containing conduits is called the fiber span layer. Two lightpaths, which are disjoint at the OXC layer, may be placed in the same conduit and thus are not physically disjoint. Conduits are buried underground along a right of way (ROW), which is normally obtained from companies operating railroad, pipeline, etc. So, even if two fibers are located in different conduits, they may be buried in the same pipeline, causing a single point of failure.

An example of physically diverse lightpath computation is shown in Figure 3. At the OXC layer, for the lightpath from node A to node E, there exist three choices for the route: A-D-E, A-B-E, and A-C-E. Those three lightpaths are node-disjoint from OXC layer perspective. However, A-D-E and A-B-E share a common fiber span a-g, whose failure will cause both A-D-E and A-B-E to fail. So, A-D-E and A-B-E are not physically diverse paths. A-D-E and A-C-E are a pair of physically diverse paths, which can be used as working and backup paths for the connection from A to E.

For the purpose of increasing network utilization, the lightpath computation is aimed at finding a pair of the shortest physically disjoint paths, whose cost is defined as the sum of the cost on all the links of the two paths.

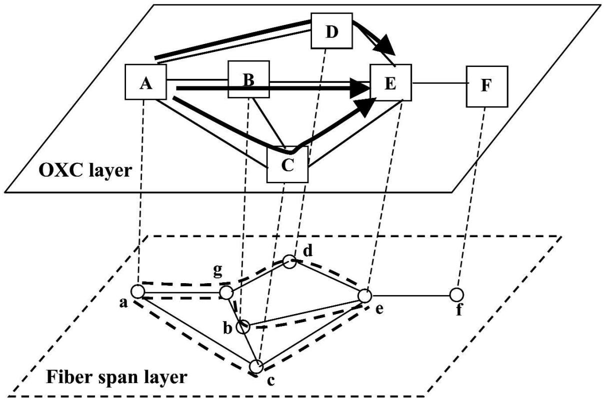

Figure 3: Fiber span and OXC layers in an optical transport network.

Given a directed graph, Suurballe's algorithm [26,27] can be used to find a pair of shortest link/node-disjoint paths. However, a pair of disjoint paths at the OXC layer does not imply that they are also physically disjoint. The work in [28] showed how to change Suurballe's algorithm slightly to find a pair of physically disjoint paths in the network with three kinds of fiber span configurations, including fork, express, and standard configurations. The fiber span topology is then limited to these three configuration types in order to use the algorithm; however the types of fiber span configuration in reality may be different.

A capacity-efficient distributed routing scheme has been proposed in [60]. It tries to extend the current OSPF protocol to implement a distributed method for finding link-disjoint lightpaths and achieving an efficient spare capacity assignment at the same time. However, the scheme only finds the link-disjoint lightpaths at the OXC layer. Further studies are necessary to design a distributed restoration scheme, which can find a physically diverse backup lightpath taking into consideration the spare capacity assignment, wavelength usage, routing convergence time, and flooding message size [61].

The concept of Shared Risk Link Group (SRLG) was proposed to deal with the diverse routing problem [29]. Each link in the network is mapped to a set of SRLGs, each of which represents an instance of possible failure at the optical fiber span layer. Two lightpaths that do not share SRLGs are regarded as SRLG diverse paths and can be used as a pair of working and backup paths. The definition of SRLGs in a network is determined at the installation time and will not change often. How to define SRLGs in a network to achieve a fair survivability and network utilization remains a topic of further study.

5 Conclusion

GMPLS appears to be a promising technology paving the way toward an intelligent optical core. Some relevant topics, such as RWA problem, routing and signaling, and network restoration, have been studied for many years. However, solutions for those problems remain at the theoretical level. More effort is needed to find practical solutions, taking into account the unique characteristics of all-optical networks. We have discussed the issues and challenges in implementing an optical core network from the automatic provisioning and the fast restoration perspectives. Although most of the issues are logical problems, some challenges, such as the fault detection in optical domain, still await a good solution from the lower level (e.g., hardware devices). For carriers, the cost is a key concern for upgrading today's transport network into an intelligent optical core. Besides technical issues, whether or not the solution can bring increased revenue becomes a very important criterion. We believe that all the challenges presented in this paper, plus the cost issue, need to be addressed in the design of the next-generation GMPLS-based optical core.

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