AN HIGH PERFORMANCE TRAFFIC ENGINEERING MODEL FOR ALL-OPTICAL NETWORKS
Evolutionary GMPLS control plane services in all-optical cross-connects

Francesco Palmieri
Centro Servizi Didatico Scientifico, Federico II University, Via Cinthia 45, Napoli, Italy

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Abstract: One of the major issues in the networking industry today is the tremendous demand for more and more bandwidth. With the development of all-optical networks and the use of Dense Wavelength Division Multiplexing (DWDM) technology, a new and probably very crucial milestone is being reached in network evolution. In this scenario, carriers need powerful, commercially viable and scalable tools that can be used to balance the traffic load on the various fiber links/wavelengths and optical switches in the network so that none of these components is over utilized or underutilized. Generalized Multi-Protocol Label Switching (GMPLS) is actually the most promising technology, which will play a key role in future IP pure optical networks by providing the necessary bridges between the IP and optical layers to deliver effective traffic engineering features and allow for interoperable and scalable parallel growth in the IP and photonic dimension. This paper propose an integrated control plane approach that will combine existing GMPLS control plane techniques with the point-and-click provisioning capabilities of photonic switches to set up optical channel trails and to distribute optical transport network topology state information. The GMPLS control plane will support various traffic engineering functions, and enable a variety of protection and restoration capabilities, while simplifying the integration of photonic switches and label switching routers.

1 INTRODUCTION

With the development of an information-oriented society, the explosive growth of the Internet and the emerging demand for integrated network-based applications, the needs of network capacity have increased dramatically, requiring a substantially higher bandwidth than that offered by current networks based on Electronic Time Division Multiplexing (ETDM) technology. For this reason, all-optical networks, based on the concepts of Wavelength Division Multiplexing (WDM) and wavelength routing, promising data transmission rates several orders of magnitude higher than current networks, are considered as the transport networks for the future (Mukherjee, B., 1997). In such networks, two adjacent nodes are connected by one or multiple fibers each carrying multiple wavelengths/channels. Each node consists of a dynamically configurable optical cross-connect (OXC) which supports fiber switching and wavelength switching, that is, the data on a specified input fiber and wavelength can be switched to a specified output fiber on the same wavelength (Mokhtarm A. et al., 1998). In order to transfer data between source–destination node pairs, a lightpath needs to be established by allocating the same wavelength throughout the route of the transmitted data. Benefiting from the development of all-optical amplifiers, lightpaths may span more than one fiber link and remain entirely optical from end to end. It has been demonstrated that the introduction of wavelength-routed networks not only offers the advantages of higher transmission capacity and better switching throughput, but also satisfies the growing demand for protocol transparency and simplified operation and management (Karasan, E., 1998). In this scenario, OXCs are likely to emerge as the preferred option for switching multi-gigabit or even terabit data streams, since the slow electronic per-packet processing is avoided. The most interesting and desirable function of an OXC is to dynamically reconfigure the network at the wavelength level for restoration or to dynamically accommodate changes in bandwidth demand. OXC systems are expected to be the cornerstone of the photonic layer providing carriers more dynamic and flexible options in building network topologies with enhanced survivability.

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The process of adaptively mapping traffic flows onto the physical topology of a network and allocating resources to these flows, usually referred to as *traffic engineering*, is one of the most difficult tasks facing service providers today. In this way, they can exploit some economies on the bandwidth that has been provisioned across the entire network and increase their revenues by fully supporting the needs of time or/and mission critical applications. Traffic engineering (TE) should be viewed as assistance to the routing/switching infrastructure that provides additional information used in forwarding traffic along alternate paths across the network, trying to optimize service delivery throughout the network by improving the network utilization and avoiding congestion caused by uneven traffic distribution. Traditionally, all provisioning and engineering in optical networks has required manual planning and configuration, resulting in setup times of days or even weeks and a marked reluctance amongst network managers to deprovision resources, when it implies impacts on other services. Where control and traffic management protocols have been deployed to provision optical networks they have been proprietary and have suffered from interoperability problems. Recently, a new paradigm for the design of control planes for OXCs intended for automatically switched optical transport networks was proposed in (Banerjee, A. et al., 2001). This new paradigm is termed GMPLS and exploits recent advances in MPLS control plane technology to foster the expedited development and deployment of a new class of versatile OXCs that specifically address the optical transport needs of the Internet. The GMPLS control plane has been shown to be an extensible general purpose control plane technology, supporting flexible traffic engineering, for a variety of high performance network elements. This paper propose an integrated GMPLS-based framework built on the strengths of MPLS for fine grain traffic load balancing and optical layer reconfiguration for providing effective TE in all-optical networks. It is modeled according to the principle of providing a single control plane, directly suitable for OXC, for the transport and service management layers and using widely available IP traffic engineering and management tools to greatly simplify and scale network operations. Beyond eliminating proprietary vendor “islands of deployment”, this common control plane, based on a single set of semantics, enables independent innovation curves within each product class and faster service deployment with end-to end provisioning in the whole optical network.

2 THE GMPLS PARADIGM

GMPLS has been proposed shortly after MPLS. With the success of MPLS in TE and resource management of packet switched IP networks, optical network providers have driven a process to generalize the applicability of MPLS to cover all-optical networks as well. In GMPLS the idea of a label can be generalized to be anything that is sufficient to identify a traffic flow. GMPLS mainly focuses on the control plane that performs connection management for the data plane, by creating label switched paths (LSPs) on both packet-switched and non-packet-switched (i.e. lambda-switched) interfaces. In detail, it realizes four basic functions as follows:

- *Routing control*: It provides the routing capability, TE and topology discovery.
- *Resource discovery*: It provides a mechanism to keep track of the system resource availability such as bandwidth, multiplexing capability, and ports.
- *Connection management*: It provides end-to-end service provisioning for different services. This includes connection creation, modification, query, and deletion.
- *Connection restoration*: It provides an additional level of protection to the networks.

GMPLS encompasses control plane signaling for multiple interface types: Packet Switch Capable (PSC), Time Division Multiplexing Capable (TDM), Lambda Switch Capable (LSC) and Fiber Switch Capable (FSC). Each of them can be considered as a lower level LSP endpoint nested within a higher-level LSP one. In this sense the extension of MPLS for supporting different types of LSP is the generalization of the stacking functionality. The diversity of controlling not only switched packets and cells, but also TDM network traffic and optical network components makes GMPLS flexible enough to position itself in the direct migration path from electronic to all-optical network switching. In order for these interface types and link bundles to be handled accordingly, GMPLS needed a method to manage the links between adjacent nodes. The Link Management Protocol (LMP) was developed to address several link specific problems that surfaced when generalizing the MPLS protocol across different interface types. LMP provides control channel management, link connectivity verification, link property correlation, and fault isolation. Control channel management establishes and maintains connectivity between adjacent nodes using a keep-alive protocol. Link verification verifies the physical connectivity between nodes, thereby detecting loss of connections and misrouting of cable connections. Fault isolation pinpoints failures in both electronic and optical links without regard to the data format traversing the link.

3 TE IN PHOTONIC NETWORKS

If a TE application implements the right set of features, it should provide precise control over the placement of traffic flows within a routing and switching domain gaining better network utilization and realizing a more manageable network.

3.1 Fundamental TE requirements

A traffic engineering solution suitable for pure optical networks will always consist of a number of basic functional components, as described below:

- *Traffic monitoring, analysis and aggregation*: is responsible for collecting traffic statistics from the network elements, e.g. the OXCs. Then the statistics are analyzed and/or aggregated to prepare for the traffic engineering and network reconfiguration related decision-making.
- *Bandwidth demand projection*: projects the bandwidth requirements in the near future based on past and present measurements and the characteristics of the traffic arrival processes. The bandwidth projections are used for subsequent bandwidth allocation.
- *Reconfiguration trigger*: consists of a set of policies that decide when a network level reconfiguration is performed. This is based on traffic measurements, bandwidth predictions, and on operational issues, e.g., to suppress influence of transitional factors and reserve adequate time for network to converge.
- *Topology design*: provides a network topology based on the traffic measurements and predictions. Conceptually this can be considered as optimizing a graph (i.e. OXC connected by light paths in the WDM layer) for specific objectives (e.g. maximizing throughput), subject to certain constraints (e.g. nodal degree, interface capacity), for a given load matrix (i.e. traffic load applied to the network.) This is in general a NP-hard problem. Since reconfiguration is regularly triggered by continually changing traffic patterns, an optimized solution may not be stable. It may be more practical to develop heuristics that emphasize more on factors like fast convergence, and less impacts on ongoing traffic, than on optimality.
- *Topology migration*: consists of algorithms to coordinate the network migration from an old topology to a new topology. As WDM reconfiguration deals with large-capacity channels, changing allocation of channel resources in this coarse granularity has significant effects on a large number of end user flows. Traffic flows have to adapt to the light path changes at and after each migration step. These effects can potentially spread over the routing pattern of the network, which in turn may affect more user flows.

3.2 TE in current overlay networks

Today's carrier-class data services network typically consists of five layers (Fig. 1): a local access layer connecting enterprise networks to the carrier network, IP for carrying data applications, ATM for traffic engineering, SDH/SONET for transport, and wavelength division multiplexing (WDM) for capacity. IP supports the wide variety of data and multimedia applications dominating traffic growth in the networks. ATM supplies the QoS and service guarantees for reliability and provides the means for engineering the flows of traffic. SDH/SONET networks, grooming optical channels onto light paths, are pervasive in their ability to distribute traffic reliably within the Metropolitan (MAN) and Wide Area Network (WAN). Carriers implement WDM extensively to augment the capacity of their installed base of fiber by combining multiple optical paths onto a single fiber optic link.

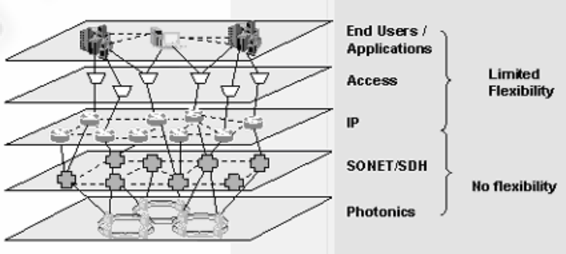

Figure 1: Multi-layered Network Architecture

Carriers manage each layer separately and use each layer to perform one function as well as possible. Each layer relies on a different control and data plane technology and has its own network management system. The SDH/SONET and WDM layers are static network layers that must be manually provisioned. The IP layer gives the carrier some automation in traffic distribution and service provisioning but provides little in the TE control or QoS guarantees. Consequently, carriers must use manual provisioning to implement TE policies and to address performance deficiencies. Thus, the layered network design leads to frequent manual reconfigurations of the SDH/SONET and WDM layers for IP-related services. The static nature of the current carrier network architecture left many carriers unprepared for provisioning large amounts of fiber and optical wavelengths to meet the needs of enterprise IP networks, ISPs, VPNs, and other data-centric services. Manual provisioning left the carriers with a complex collage of multiplexers, OXCs, and fiber patch panels. Customers want rapid provisioning and flexible deployment of services, but the multilayer control structure of carrier networks built during the last decade could not cope with the rapidly growing and changing service demands. Carriers need new methods for provisioning optical bandwidths and for automatically provisioning shared-bandwidth across their networks. They need to support IP data traffic effectively, provide QoS guarantees for customer service level agreements (SLAs), and utilize core network bandwidth efficiently. Much of the current carrier network architecture lacks the ability to satisfy the needs of a growing variety of IP applications. In order to bypass the tradeoffs due to excessive layering in traffic control the basic and necessary TE functions must move directly to the OXCs and WDMs. At the end, this results in a simpler, more cost-efficient network that will transport a wide range of data streams and very large volumes of traffic. Recently, an innovative TE framework (Banerjee, A. et al., 2001) built on the strengths of MPLS for fine grain traffic load balancing, and optical layer re-configuration has been proposed. Moreover, there is an approach to the design of control planes for optical cross-connects which leverage existing control plane techniques developed for MPLS TE. This approach combines recent advances in MPLS traffic engineering control plane constructs with optical cross-connect technology to provide a framework for real-time provisioning of optical channels, foster development and deployment of a new class of optical cross-connects, and allow the use of uniform semantics for network management and operations control in networks consisting of IP addressable and TE-capable optical cross-connects.

4 INTEGRATING GMPLS CONTROL PLANE IN OXCS

All of the above observations suggest, therefore, that the GMPLS Traffic Engineering control plane would be, with some minor extensions, very suitable as the control plane for OXCs. This concept originated from the observation that from the perspective of control semantics, an OXC with an GMPLS Traffic Engineering-enabled control plane would resemble a Label Switching Router, subsuming and spanning LSRs and OXCs functionalities in a single integrated control plane, with some restriction due to the peculiarity of the OXC data plane. In fact, the adaptation of MPLS control plane ant TE concepts to OXCs, which results in OXC-LSRs, needs to consider and reflect the domain specific peculiarities of the OXC data plane. From a data plane perspective, an LSR switches packets according to the label that it carries. An OXC uses a switching matrix to connect an optical wavelength/signal from an input fiber to an output fiber. From a control plane perspective, an LSR bases its functionality on a table that maintains relations between incoming label/port and outgoing label/port. It must be pointed that in the case of the OXC, the table that maintains the relations is not a software entity but it is implemented in a more straightforward way, e.g. by appropriately configuring the micro-mirrors of an optical switching fabric. There are several constraints in re-using the GMPLS control plane. These constraints arise from the fact that LSRs and OXCs use different data technologies. More specifically, LSRs manipulate packets that bear an explicit label and OXCs manipulate wavelengths that bear the label implicitly. That is, since the analogue of a label in the OXC is a wavelength or an optical channel there are no equivalent concepts of label merging nor label push and pop operations in the optical domain. The transparency and multi-protocol properties of the MPLS Control Plane approach would allow an OXC to route optical channel trails carrying various types of digital payloads (including IP, ATM, SDH, etc) in a coherent and uniform way. The distribution of topology state information, establishment of optical channel trails, all-optical network Traffic Engineering functions, and protection and restoration capabilities would be facilitated by the GMPLS control plane. An out-of-band IP communications system can be used to carry and distribute control traffic between the control planes of different connected OXCs, perhaps through dedicated supervisory channels, using dedicated wavelengths or channels, or an independent out-of-band IP network. An OXC that uses the GMPLS control plane would effectively become an IP addressable device. Thus, this proposition also solves the problem of addressing for OXCs. In this environment, SNMP, or some other network management technology, could be used for element management. A reasonable architectural model for an OXC equipped with an integrated GMPLS control plane (OXC-LSR) consists of two components: the *data forwarding plane* and the *GMPLS control plane*. A simple schema, consistent with IETF GMPLS standard draft, is represented in Fig. 2 below:

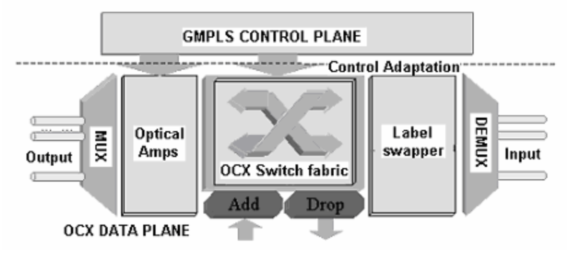

Figure 2: OXC with GMPLS control plane architecture

4.1 The OXC-LSR data plane

The data/forwarding plane performs data routing to the appropriate ports, channel add/drop to external legacy networks (using the edge interfaces) and label/lambda swapping through an array of demultiplexers, wavelength converters, optical cross-connects, optical amplifiers and multiplexers. A simple and linear architectural model for the data/forwarding plane of an all-optical OXC supporting a GMPLS-based control plane is shown in Fig. 3 below:

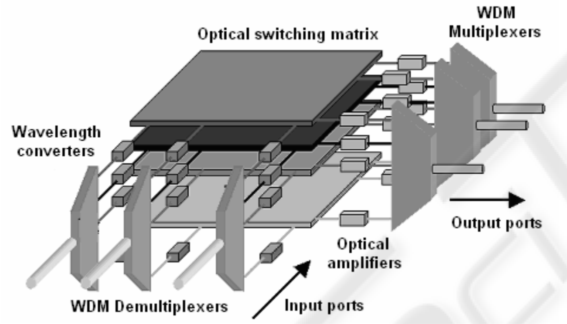

Figure 3: All-optical OCX data plane architecture

Here, the WDM *Demultiplexers* separate incoming wavelengths (*N* grouped lambdas) from input ports into individual lambdas. The *wavelength converters* will perform, if necessary, wavelength conversion (that is swapping the optical label in the GMPLS control plane) based on the instruction from the control plane. A sufficiently large low-loss connectivity and compact design all optical switching fabric can be realized by using the reflection of light and micro-electromechanical systems (MEMS) technology, now widely available on the market. This MEMS-based multi-layer *optical switching fabric* driven by a micro-machined electrical MEMS actuator redirects, according to the GMPLS control plane instructions, each wavelength into appropriate output ports passing through *optical amplifiers,* typically Erbium doped Fiber Amplifiers (EDFA) or Silica Erbium based Dual band Fiber (BDFA) amplifiers, which boost the signal power inline without the need for any optoelectronic conversion to cope with the effects of polarization mode dispersion and attenuation on long distances. The WDM *Multiplexer* then groups the wavelengths from the above multiple layers of cross connects. There may be a special input/output port that adds and drops from the edge of the all-optical network acting as the “interface” between the OXC-LSR and external legacy networks such as ATM, SONET/SDH and Gigabit Ethernet. The channels that can be added/dropped can be configured automatically. By definition, the resulting Optical Cross Connect architecture is strictly non-blocking and transparent to bit-rate and data format, due to its all-optical implementation. It is also link modular since the addition of new input/output fibers just requires the addition of new elements without changing the OXC overall structure. On the other hand the OXC architecture is not wavelength modular, since the adding of a new channel changes all the used MUXes, DEMUXes, MEMS fabric and wavelength converters.

4.2 The OXC-LSR control plane

The OXC-LSR GMPLS control plane has to perform the following functions in order to set up the G-LSP routing and resource table:

- Wavelength Assignment and Routing Management at each link.
- Resource management and Traffic Engineering to set up the generalized LSPs (or G-LSPs)
- Link Management between OXC-LSRs (with the LMP protocol)

Routing Management and wavelength assignment: In order to transfer data between source–destination node pairs, a lightpath needs to be established by allocating the same wavelength throughout the route of the transmitted data. As In general, if there are multiple feasible wavelengths between a source node and a destination node, then a wavelength assignment algorithm is required to select a wavelength for a given lightpath. The wavelength selection may be performed either after a route has been determined, or in parallel with finding a route. Since the same wavelength must be used on all links in a lightpath, it is important that wavelengths are chosen in a way which attempts to reduce blocking for subsequent connections. When lightpaths are established and taken down dynamically, routing and wavelength assignment decisions must be made as connection requests arrive to the network. It is possible that, for a given connection request, there may be insufficient network resources to set up a lightpath, in which case the connection request will be blocked. The connection may also be blocked if there is no common wavelength available on all of the links along the chosen route. Thus, the objective in the dynamic situation is to choose a route and a wavelength which maximizes the probability of setting up a given connection, while at the same time attempting to minimize the blocking for future connections.

Resource management and Traffic Engineering: In order to set up a lightpath, a signaling protocol is required to exchange control information among nodes, to distribute labels and to reserve resources along the path. In our case, the signaling protocol is closely integrated with the routing and wavelength assignment protocols. Suitable GMPLS signaling protocols for our model include RSVP and CR-LDP. Each of them can be used to instantiate the optical channel trails. With the RSVP extensions, for example, the wavelength information or optical channel information implicitly referring to the label concept, will be used to control and reconfigure the OXCs. Furthermore, each node maintains a representation of the state of each link in the network. The link state includes the total number of active channels, the number of allocated channels, and the number of channels reserved for lightpath restoration. Additional parameters may be associated with allocated channels, for example, some lightpaths may be preemptable or have associated hold priorities. Once the local inventory is constructed, the node engages in a routing protocol to distribute and maintain the topology and resource information. Standard IP routing protocols, such as Open Shortest Path Forwarding (OSPF) or Intermediate System-Intermediate System (IS-IS) with GMPLS TE extensions, may be used to reliably propagate the information. Furthermore, the OXC will maintain a WFIB (Wavelength Forwarding Information Base) per interface (or per fiber). This is because lambdas and/or channels (labels) are specific to a particular interface (fiber), and the same lambda and/or channel (label) could be used concurrently on multiple interfaces (fibers).

Link Management between OXC-LSR: Although LMP assumes the messages are IP encoded, it does not dictate the actual transport mechanism used for the control channel. However, the control channel must terminate on the same two nodes that the bearer channels span. As such, this protocol can be implemented on any OXC, regardless of the internal switching fabric. A requirement for LMP is that each link has an associated bi-directional control channel and that free bearer channels must be opaque (i.e., able to be terminated); however, once a bearer channel is allocated, it may become transparent. Note that this requirement is trivial for optical cross-connects with electronic switching planes, but is an added restriction for photonic switches.

5 CONCLUSIONS

In this paper the key aspects related to Traffic Engineering in new generation all-optical network infrastructure are reviewed investigating how the MPLS Traffic Engineering-enabled control plane could be adapted and reused as the control plane for optical cross-connects. Such a control plane would be used to distribute optical transport network topology state information and to setup optical channel trails. Such a control plane would support various traffic engineering functions in the optical domain, and enable a variety of protection and restoration capabilities. Furthermore, such a control plane technology would expedite the development and deployment of a new class of versatile IP-addressable OXCs. We envision a horizontal network where all network elements work as peers to dynamically establish optical paths through the network. This new photonic internetwork will make it possible to provision high bandwidth in tenths of seconds, enable new revenue-generating services, and dramatic cost savings for the service provider.

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