IP over All-Optical Networks - Issues

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Abstract - **IP over Optical is being envisioned as one of the most attractive architectures for the new Internet. There have been various proposals in IETF and other international standards organizations regarding the interaction of IP routers and Optical core networks. This paper describes the architectural alternatives for the integration of IP and DWDM networks using Multiprotocol Lambda Switching (MPLambdaS). The paper also addresses the issues of routing, signaling, control and survivability in an all-optical network.**

I. INTRODUCTION

Challenges presented by the growing need for intercommunication have resulted in the intense demand for broadband services in the Internet. With the recent developments in dense wavelength-division multiplexing (DWDM) technology, all-optical networks offer an almost unlimited potential for bandwidth. Research is ongoing to introduce more intelligence in the control plane of the optical transport systems, which will make them more survivable, flexible, controllable and open for traffic engineering. Some of the essential desirable attributes of optical transport networks include real-time provisioning of lightpaths, enhanced network survivability, interoperability functionality between vendor-specific optical sub-networks, and enabling operational protection and restoration capabilities. The research efforts now are focusing on the efficient internetworking of higher layers, primarily IP with WDM layer.

One approach for sending IP traffic on WDM networks would use a multi-layered architecture comprising of IP/MPLS layer over ATM over SONET over WDM. This architecture has 4 management layers. Similarly 3 management layers is also possible. The two-layer model, IP over WDM, aims at a tighter integration between IP and optical layers, and offers a series of important advantages over the current multi-layer architecture. One of the main goals of the integrated architecture is to separate control plane from data plane. Other benefits include: more flexibility in handling higher capacity networks, better network scalability, more efficient operations and better use of traffic engineering.

The multi-layered protocols architecture can complicate the timely flow of the possibly large amount of topological and resource information. Another problem is with respect to *survivability*. There are various proposals stating that the optical layer itself should provide restoration/protection capabilities of some form. This will require careful coordination with the mechanisms of the higher layers such as the SONET Automatic Protection Switching (APS) and the IP re-routing strategies. Hold-off timers have been proposed to inhibit higher layers backup mechanisms. In certain cases, there could even be a flooding of fault alarms.

A much closer IP/WDM integration is required. Multi-Protocol Label Switching (MPLS) for IP packets is believed to be the best integrating structure between IP and WDM. MPLS brings two main advantages. First, it can be used as a powerful instrument for traffic engineering. Second, it fits naturally to WDM when wavelengths are used as labels. This extension of the MPLS is called the Multi-protocol lambda switching. There is general consensus on adopting this protocol for optical networking [1].

The discussions, henceforth in this document, shall be of the lambda switching architecture. There exist, clouds of IP networks and clouds of WDM networks. Transfer of packets from a source IP router to a destination is required. How the combination does signaling to find an optimal path, route the packet, ensure survivability and eventually providing seamless transport of data are the main topics of discussion. The following section deals with the architectural alternatives available while designing an optical Internet. Routing approaches and other procedures are discussed in Section 3. Section 4 describes signaling and control of lightpath establishment. The last section gives a gist of the restoration mechanism in the optical network.

II. IP OVER WDM ARCHITECTURAL ALTERNATIVES

The optical network model considered in this paper consists of multiple Optical Crossconnects (OXCs) interconnected by optical links in a general topology (referred to as an "optical mesh network"). Each OXC is assumed to be capable of switching a data stream from a given input port to a given output port. This switching function is controlled by appropriately configuring a crossconnect table. Lightpaths are assumed to be bi-directional, i.e., the return path from the egress port to the ingress port follows the same path as the forward path. The optical core network is assumed to consist of multi-vendor optical sub-networks and are incapable of processing IP packets. In this network model, a switched lightpath has to be established between a pair of IP routers for their communication. The lightpath might have to traverse multiple optical sub-networks and be subject to different provisioning and restoration procedures in each sub-network. There are various alternatives to adopt for the implementation. Fig.1 illustrates one such network architecture. The node at the edge of the optical subnetwork is termed as the *Boundary OXC* (or *edge switch*).

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A. Service Models

Based on the interaction between the two domains, IP and optical, the services offered by the system are categorized as [2]:

Domain Service Model - In this model interface A is different from interface B as shown in the Fig.1. The interaction between the client IP network and the optical network is termed as User-to-Network Interface (UNI) and the interaction within the Optical Network is termed ad the Network-to-Network Interface (NNI). Furthermore the NNI interface inside the domain could be different from the NNI interface between domains and the later ones could be trusted or untrusted [15]. Under this model the optical network primarily provides a set of high bandwidth pipes to the IP clients. Signaling extensions need to be added to allow clients to register, deregister and query other clients for an optical-networked administered address so that lightpaths can be established with other clients across the optical network. In this service model the routing protocols inside the optical network are proprietary. Only a minimal set of messages need to be defined between the IP router and the optical network.

Unified Service Model - In this Service Model, IP and optical networks are treated as a single network and there is no distinction between optical switches and IP routers as far as the control plane goes. MPLS would be the preferred method for control and routing. There is no distinction between the UNI (Interface A in Fig.1), NNI (Interface B in Fig.1) or any other router-router interface. Under this model, optical network services are provisioned using MPLS signaling.

B. Optical Interaction Models

The previous section presented possible service models for IP over optical networks. The models differ in the way routing is implemented. It is important to examine the architectural alternatives for routing information exchange between IP routers and optical switches. The goal is to allow service discovery, automated establishment and seamless integration with minimal intervention.

Based on the perspective of the various nodes involved in a lightpath, different interaction models have been proposed [2]. The key consideration, in deciding the model, is whether there is a single/separate monolithic routing and signaling protocol spanning the IP and the Optical domains. If there are separate instances of routing protocols in each domain, then an interface is defined between the two protocol instances at the UNI and policies are applied regarding provisioning of the lightpaths across the optical domain between edge routers.

Fig.1. Optical Internet scenario

defined between the two protocol instances at the UNI. Policies are applied regarding provisioning of the lightpaths across the optical domain between edge routers.

Overlay Model - Under this model, IP is more or less independent of the optical sub-network. That is IP acts as a client to the Optical domain. In this scenario, the optical network provides point to point connection to the IP domain. The IP/MPLS routing protocols are independent of the routing and signaling protocols of the optical layer. The overlay model may be statically provisioned using a Network Management System or may be dynamically provisioned.

Peer Model - In the peer model the optical routers and optical switches act as peers and there is only one instance of a routing protocol running in the optical domain and in the IP domain. A common Interior gateway protocol (IGP) like OSPF or IS-IS may be used to exchange topology information. The assumption in this model is that all the optical switches and the routers have a common addressing scheme.

Augmented Model - In the augmented model, there are actually separate routing instances in the IP and optical domains, but information from one routing instance is leaked into the other routing instance. For example IP addresses could be assigned to optical network elements and carried by optical routing protocols to allow reachability information to be shared with the IP domain to support some degree of automated discovery. This is a hybrid of the peer and the overlay models proposed earlier.

Clearly the future lies in the peer model implementation since it improves scalability and ease of interoperability. But, the cost for the adoption is unreasonable at this moment. Thereby forcing current implementation and research proposals to focus more on the overlay model. This paper deals predominantly with the overlay model wherein a domain based routing is adopted though most of the proposals are applicable to peer models as well.

C. Generalized MPLS (GMPLS)

The Multi Protocol Lambda Switching architecture has recently been extended to include routers whose forwarding plane recognizes neither packet, nor cell boundaries, and therefore, can't forward data based on the information carried in either packet or cell headers. Specifically, such routers include devices where the forwarding decision is based on time slots, wavelengths, or physical ports. GMPLS differs from traditional MPLS in that it supports multiple types of switching, i.e., the addition support for TDM, lambda, and fiber (port) switching. The support for the additional types of switching has driven generalized MPLS to extend certain base functions of traditional MPLS such as the establishment of bi-directional paths. Other features supported by generalized MPLS are: rapid failure notification and termination of an path on a specific egress port [3].

The widening scope of MPLS into the optical and time domain, requires several new forms of "label", collectively referred to as "generalized label". A generalized label contains enough information to allow the receiving node to program its crossconnect. Since the nodes sending and receiving the new form of label know what kinds of link they are using, the generalized label does not contain a type field, instead the nodes are expected to know from the context what type of label to expect. Currently, label formats supported by GMPLS are the Generalized Label, the Waveband Switching Label (which apparently uses the same Generalized Label format), the Suggested Label and the Label Set.

III. OPTICAL ROUTING

Routing in the optical domain involves switching data to the appropriate optical ports at the crossconnect level. It involves computing the path subject to various network constraints (both physical & service level). The protocol used for the resource discovery and other preprocessing depends on the network architecture adopted, since each patronizes a different approach towards routing [2].

A Routing Approaches

Integrated Routing - This routing model is used for the peer model described above. Under this approach there is only one instance of the routing protocol running in the IP and Optical domain. An IGP like Open Shortest Path First (OSPF) or Intermediate System – Intermediate System (IS-IS) with suitable optical extensions is used to exchange topology information. These optical extensions will capture the unique optical link parameters. The OXCs and the routers maintain the same link state database. The routers can then compute end to end paths to other routers across the OXCs. This lighpath is always a tunnel across the optical network between edge routers. The routing protocol defines forwarding adjacencies which represent and replace the link state advertisements.

Domain Specific Routing - This routing model supports the augmented routing model. In this model the routing between the optical and the IP domains is separated with a specific routing protocol running between the domains. The focus is on the routing information to be exchanged at the IP optical interface. IGP concept-based protocols as OSPF or BGP can help in route discovery and collecting reachability information. Determination of paths and setting up of the Lambda Switched Paths (LSP) is a traffic engineering decision. Interdomain routing protocols like Border Gateway Protocol (BGP) may be used to exchange information between the IP and optical domain. OSPF areas may also be used to exchange routing information across the UNI. BGP will allow IP networks to advertise IP addresses within its network to external optical networks while receiving external IP prefixes from the optical network. Specific mechanisms to propagate the BGP egress addresses are yet to be determined. OSPF supports the concept of hierarchical routing using OSPF areas. Information across a UNI can be exchanged using this concept of a hierarchy. Routing within each area is flat. Routers attached to more than one areas are called Area Border Routers (ABR). An ABR propagates IP addressing information from one area to another using a summary LSA. Domain specific routing can be done within each area. IP client networks can be running OSPF with TE extensions.

B. Constraints on Routing

The constraints highlighted here apply to any circuit switched networks but differences with an optical network are explained where applicable.

One of the main services that should be provided by a transport network is *restoration*. Restoration introduces the constraint of physically diverse routing. Restoration can be provided by pre-computed paths or computing the backup path in real time. The backup path has to be diverse from the primary path at least in the failed link or completely physically diverse. A logical attribute like the Shared Risk Link Group (SRLG) attribute is abstracted by the operators from various physical attributes like trench ID and destructive areas. Such an attribute may be needed to be considered when selecting the path a network. Two links which share a SRLG cannot be the backup for one another because they both may go down at the same time. Another restoration mechanism is restoration in a shared mesh architecture wherein backup bandwidth may be shared among circuits. The case where two link disjoint paths share a backup path in the network. This may be possible because a single failure scenario is assumed. Another constraint of interest is the concept of node, link, LSP inclusion or exclusion, propagation delay, wavelength convertibility and connection bandwidth among other things. It may happen in a service providers network that the service provider may want to exclude a set of nodes due to the geographic location of the nodes. An example would be nodes lying in an area which is earthquake prone. Propagation delay may be another constraint for a large global network. Traffic from the US to Europe, shouldn't be routed over links across the Pacific ocean but instead should use links over the Atlantic ocean since propagation delay in this case would be much less.

Wavelength convertibility is a problem encountered in waveband networks. It refers to ability to crossconnect two different wavelengths. The wavelengths may be completely different or slightly different. Since wavelength convertibility involves cost & latency, conversion vendors may selectively deploy these converters inside the network. Therein lies the problem of routing a circuit over a network using the same wavelength. This requires that the path selection algorithm know the availability of each wavelength on each link along the route. There are optimizations that obviate the global knowledge. Bandwidth availability is another consideration in routing. This is simplified in a wavelength optical network since requests are end to end. However in a TDM transport network such as a SONET/SDH network requests can be variable bandwidth. Routing needs to ensure that sufficient capacity is available end to end. Detailed resource information on local resource availability is only used for routing decisions.

The route computation, after receiving all network parameters in the form of link state packets, reduces to a mathematical problem. It involves solving a problem of Routing and Wavelength Assignment (RWA) for the new connection. The problem is simplified if there exists a wavelength converter at every hop in the optical network. But, current technology invalidates such an assumption. Suitable solutions already exist to the RWA problem which makes optical routing a practical possibility [4].

IV. SIGNALING & CONTROL

Signaling refers to messages used to communicate characteristics of services requested or provided. This section discusses a few of the signaling procedures. It is assumed that there exists some default communication mechanism between routers prior to using any of the routing and signaling mechanisms.

A. Control Plane

In IP-centric distributed optical interworking systems, each entity should have a control plane for a coordinated operation [1]. One alternative is to have centralized control plane. That is within an optical sub-network the control functions are centralized to one OXC. In this case there is no intra-domain NNI signaling between OXCs belonging to the same optical sub-domain. For a more scalable solution, a control plane is incorporated at each node. In this case within an optical sub-network intra-domain NNI is established between OXCs [2]. A single control plane would be able to span both routers and OXCs. In such an environment, a lambda switched path could traverse an intermix of routers and OXCs, or could span just routers, or just OXCs. This offers the potential for real bandwidth-on-demand networking, in which an IP router may dynamically request bandwidth services from the optical transport network. To bootstrap the system, OXCs must be able to exchange control information. One way to support this is to pre-configure a dedicated control wavelength (out-of-band) between each pair of adjacent OXCs, or between an OXC and a router, and to use this wavelength as a supervisory channel for exchange of control traffic. Another possibility would be to use in-band or out-of-network channels, in the later case by constructing a dedicated IP network for the distribution of control traffic.

A candidate system architecture for an OXC equipped with an MPLS control plane model is shown in Fig 2. The salient feature of the network architecture is that every node in the network consists of an IP routing module and a reconfigurable OLXC. The IP router is responsible for all non-local management functions, including the management of optical resources, configuration and capacity management, addressing, routing, traffic engineering, topology discovery, exception handling and restoration. In general, the router may be traffic bearing, or it may function purely as a controller for the optical network and carry no IP data traffic. The IP router implements the necessary IP protocols and uses IP for signaling to establish lightpaths. Between each pair of neighbors in the network, one pre-routed communication channel exists that allows router to router connectivity over the channel. These signaling channels reflect the physical topology. As long as the link between two neighbors is functional, there is a signaling channel between those neighbors [5].

The IP router communicates with the OLXC device through a logical interface. The interface defines a set of basic primitives to configure the OLXC, and to enable the OLXC to convey information to the router. Fig 2 illustrates this implementation. For all of the interfaces, the end of the connection can also be a drop port.

B. Node Addressing

As per the requirements of the IP control plane, every network addressable element must have an IP address [6]. Typically these elements include each node and every optical link and IP router port. When it is desirable to have the ability to address individual optical channels those are assigned IP addresses as well. The IP addresses must be globally unique if the element is globally addressable. Otherwise domain unique addresses suffice. A client must also have an IP address by which it is identified. However, optical lightpaths could potentially be established between devices that do not support IP (i.e., are not IP aware), and consequently do not have IP addresses. Whether or not a client is IP aware can be discovered by the network using traditional IP mechanisms.

C. Path provisioning

This section describes a protocol proposed for setting up an end-to-end lightpath for a channel. A complete path might contain the two endpoints and an array of intermediate OXCs for transport across the optical network. Provisioning an end-to-end optical path across multiple sub-networks involves the establishment of path segments in each sub-network sequentially. Inside the optical domain, a path segment is established from the source OXC to a border OXC in the source sub-network. From this border OXC, signaling across the NNI is performed to establish a path segment to a border OXC in the next sub-network. Provisioning continues this way until the destination OXC is reached.

The link state information is used to compute the routes for the needed lightpaths. It is assumed that a request to establish a lightpath may originate from an IP router (over the UNI), a border node (over the NNI), or a management system.

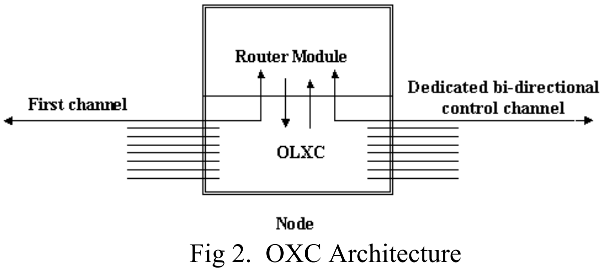

Fig 2. OXC Architecture

This request carries all required parameters. After computing the route, the actual path establishment commences. However, once path setup is complete the data transfer happens passively and is straightforward without much intervention from the control plane. The connection needs to be maintained as per the service level agreements.

The handshake has been divided into UNI setup and NNI setup. To automate all these processes, there are certain initiation procedures like resource discovery and route computation which help determine the route for each segment (viz. IP host – IP border router, IP border router - border OXC, between border OXCs). These procedures are enveloped inside a routing protocol. Routing within the optical network relies on knowledge of network topology and resource availability. Topology information is distributed and maintained using standard routing algorithms, e.g., OSPF and IS-IS. On boot, each network node goes through neighbor discovery. By combining neighbor discovery with local configuration, each node creates an inventory of local resources and resource hierarchies, namely: channels, channel capacity, wavelengths, and links. This information is used to compute a route between various nodes in accord with the RWA problem.

UNI Path Provisioning - The real handshake between the client network and the optical backbone happens after performing the initial service & neighbor discovery. The continued operation of the system requires that client systems constantly register with the optical network. The registration procedure aids in verifying local port connectivity between the optical and client devices, and allows each device to learn the IP address of the other to establish a UNI control channel. The following procedures may be made available over the UNI [7]: a) Client Registrationand b) Client De-Registration

The optical network primarily offers discrete capacity, high bandwidth connectivity in the form of lightpaths. The properties of the lightpaths are defined by the attributes specified during lightpath establishment or via acceptable modification requests. To ensure operation of the domain services model, the following actions need to be supported at the UNI so as to offer all essential lightpath services. The UNI signaling messages are structured as *requests* and *responses* for [7]: 1) Lightpath creation, 2) Lightpath deletion, 3) Lightpath modification, 4) Lightpath status enquiry, and 5) Client Notification.

Thus, the above actions provision both edges of the overall connection, while NNI provisioning builds the backbone of the setup

NNI Path Provisioning - The model for provisioning an optical path across optical sub-networks is as follows. A provisioning request may be received by a source OXC from the client border IP router (or from a management system), specifying the source and destination end-points. The source end-point is implicit and the destination endpoint is identified by the IP address. In both cases, the routing of an optical path inside the optical backbone is done as follows [8]:

The source OXC looks up its routing information corresponding to the specified destination IP address. If the destination is an OXC in the source sub-network, a path maybe directly computed to it. If the destination is an external address, the routing information will indicate a border OXC that would terminate the path in the source sub-network. A path is computed to the border OXC.

The computed path is signaled from the source to the destination OXC within the source sub-network. The destination OXC in the source sub-network determines if it is the ultimate destination of the path. If it is, then it completes the path set-up process. Otherwise, it determines the address of a border OXC in an adjacent sub-network that leads to the final destination. The path set-up is signaled to this OXC using NNI signaling. The next OXC then acts as the source for the path and the same steps are repeated.

Thus, NNI provisioning involves looking up in the routing table computed by various schemes mentioned previously and performing path setup within an optical sub-network. Techniques for link provisioning within the optical sub-network depends upon whether the OXCs do or do not have wavelength conversion. In the case of a network with Wavelength Converters, the route computation gets simpler. The upstream node just has to intimate the downstream node about a connection underway. It does not need to make decisions about wavelength at each hop. In the case where Wavelength converters are absent, the source node has to decide the wavelength to use by sending out a vector and getting feedback on channel availability. Note that the lightpath is established over the links traversed by the lightpath setup packet. After a channel has been allocated at a node, the router communicates with the OLXC to reconfigure the OLXC to provide the desired connectivity.

D. Signaling Protocols

The OXCs in the optical network are responsible for switching streams based on the labels present. The MPLS architecture for IP networks defines protocols for associating labels to individual paths. The signaling protocols are used to provision such paths in the optical networks. There are two options for MPLS-based signaling protocols – *Resource reSerVation Protocol (RSVP)* or *Constraint Routed Label Distribution Protocol (CR-LDP)*, with appropriate extensions to handle the optical parameters.

There are some basic differences between the two protocols, but both essentially allow hop-by-hop signaling from a source to a destination node and in the reverse direction. Each of these protocols is capable of providing quality of service (QoS) and traffic engineering. Certain new features must be introduced in these protocols for lightpath provisioning, including support for bi-directional paths, support for switches without wavelength conversion, support for establishing shared backup paths, and fault tolerance.

Automated establishment of lightpaths involves setting up the crossconnect table entries in the appropriate OLXCs in a coordinated manner such that the desired physical path is realized. The request to establish a lightpath should identify the ingress and the egress OXC as endpoints of the lightpath. The connection request may include bandwidth parameters and channel type, reliability parameters, restoration options, setup and holding priorities for the path etc. On receipt of the request, the ingress node computes a suitable route for the requested path, following applicable policies and constraints. Once the route has been computed, the ingress node invokes RSVP/CR-LDP to set up the path.

Label Distribution Protocol (LDP) is defined for distribution of labels inside one MPLS domain. CR-LDP is the constraint-based extension of LDP. One of the most important services that may be offered using MPLS in general and CR-LDP in particular is support for constraint-based routing of lightpaths across the routed network. Constraint-based routing offers the opportunity to extend the information used to setup paths beyond what is available for the routing protocol. For instance, a lambda switched path can be setup based on explicit route constraints, QoS constraints, and other constraints. Constraint-based routing (CR) is a mechanism used to meet traffic-engineering requirements that have been proposed.

Resource reSerVation Protocol (RSVP) is a unicast and multicast signaling protocol designed to install and maintain reservation state information at each routing engine along a path. The key characteristics of RSVP are that it is simplex, receiver-oriented and soft. It makes reservations for unidirectional data flows. The receiver of a data flow generally initiates and maintains the resource reservation used for that flow. It maintains "soft" state in routing engines. The "*path*" messages are propagated from the source towards potential recipients. The receivers interested in communicating with the source send the "*Resv*" messages.

Another alternative could be the case when the OXC are controlled remotely by control messages from a centralized Traffic Engineering (TE) manager [16]. The TE manager could base its decitions on the network status such as link bandwidth utilization.

VI. CONCLUSIONS

The network seems to be migrating towards an all-optical dynamically provisioned system. The scalability and transparency of the optical networks are the primary concern when choosing the network architecture. Generalized MPLS is gradually being accepted as a unifying protocol for deploying IP over WDM networks. Management of the networks remains rudimentary while signaling protocols are being enhanced for better services. Restoration in the MPLS layer, using rapid signaling of faults, will be a key feature of the future optical networks. This paper described the important proposals towards implementing the all-optical networks.

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