Internet Protocol over DWDM – Recent Developments, Trends and Issues

a report by

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The trends and events that have led to the recent development of the Internet Protocol (IP) over dense wavelength division multiplexing (DWDM) architectures are presented in this article. The need for such architectures arises from the overlapping functionalities that are provided in the current layered architectures. The issues encountered in such architectures and the proposed solutions in the standard committees to solve them are discussed. The issues that require further research attention are also identified.

Trends in Carrier Networks

Introduction

There are number of recent trends that have led to the current evolution and need for IP over DWDM networks. Some of these trends are as follows.

Trend – Super-exponential Growth in Internet Traffic

The number of Internet hosts and the amount of Internet traffic is growing super-exponentially. The growth is said to be super-exponential to imply that the growth itself is growing exponentially. This is due to an increase in the number of hosts on the Internet and in the traffic per host resulting from the high-speed access such as cable modems and asynchronous digital subscriber line (ADSL). UUNET, one of the largest Internet service providers in the US, claimed that its traffic was doubling every four months and now every 100 days.

The Moore's law for processor development has predicted doubling the processor speed every 18 months.[1] However, looking at the rate of the increase in the traffic growth, it is clear that the traffic growth in the Internet will out-pace the end-system development. This growth has challenged continually the architectures that are used for the Internet.

Trend – Data Traffic is Exceeding Voice Traffic

The amount of data traffic on carrier networks now exceeds that of voice traffic. The cross-over happened for many carriers in 1998. This shift in traffic patterns in carrier networks has lead to a change in the way that networks need to be organised.

In the past, the amount of data traffic on carrier networks was small compared with voice traffic. Therefore, as shown in *Figure 1*, the carrier networks were designed mainly for voice. The data networks were on the edges. Data could be carried on the core networks in ways mimicking the voice traffic. For example, data clients would use lease constant bit rate lines to carry data traffic over voice networks. As the amount of data traffic has now surpassed that of voice traffic, the data domain has become a lucrative market for the voice network providers. In addition, the voice revenue traffic has continued to decline due to market competition. These two effects are leading to a trend where the core networks will be designed primarily for data and where voice networks would be on the edges. The voice can be carried in the core networks using 'voice over IP' or similar paradigms. Such architectures have resulted in the need for richer quality of service (QoS), protection and availability guarantees in IP networks.

Issue – Access Network Bottleneck

The networking equipment market is classified generally into five areas: desktop, enterprise, access, metro and core as shown in *Figure 2*. Today, most desktop computers have 10/100Mb per second Ethernet while the enterprise backbones use Gigabit Ethernet links. Charges for access into the carrier networks are so high that many small businesses use only 64Kb/s to 384Kb/s Frame Relay connections to the Internet. Large corporations have T-3 (45Mb/s) or optical carrier level three (OC-3) (155Mb/s) access. Metro networks use OC-48 (2.5Gb/s) links typically, while the core networks

1. *The observation made in 1965 by Gordon Moore, co-founder of Intel, that the number of transistors per square inch on integrated circuits had doubled every 18 months since the integrated circuit was invented. Mr Moore predicted that this trend would continue for the foreseeable future.*

use OC-192 (10Gb/s) links. *Figure 2* shows these typical link speeds in various market segments. Access links are the bottleneck. One would assume that improving the access should be the highest priority. However, the deployment of access bandwidth has been limited by business reasons in spite of the technological advancements. High-speed access technologies have been around for some time in the form of digital subscriber lines (DSLs) and cable modems. Deploying faster access does not translate into a corresponding increase in revenues for the carriers. Existing carriers have therefore resisted the rapid deployment of high-speed access technologies.

New CLECs, on the other hand, are racing ahead to introduce high-speed access at costs that are lower significantly. In some cases, a price reduction of as much as 100:1 is being claimed. For example, if the carriers charge US$1,000 per month for a 1.5Mb/s T-1 line, these new CLECs are announcing 100Mb/s Ethernet service for the same price.

Given that the network traffic is doubling every 100 to 120 days, the traffic is expected to grow at a rate of 10 times per year. In five years, the traffic demands will grow by a factor of 105. Assuming a conservative growth of 103 times in five years, it can be argued that the desktop market segment will require approximately 10Gb/s or 100Gb/s, enterprise backbones may use 1Tb/s to 10Tb/s, access speeds may go up to 64Mb/s, and Metro and Core link speeds may grow from 2.5Tb/s to 10Tb/s, respectively. This prediction, although simplistic, verifies the need for high-speed DWDM in the core and metro markets. Such needs can be met cost-effectively with optical networks.

Trends Enabling IP over DWDM

Trend – The Number of Wavelengths, Bandwidth per Wavelength and Distances between Regeneration are Increasing

In recent years, DWDM has moved from the research laboratories to field deployment. The three factors that affect the cost of transport (bandwidth) are the number of wavelengths per fibre, bandwidth per wavelength and distance between regeneration. Due to non-linear effects, the relationship between the three factors is not necessarily multiplicative. For example, technology that takes 10Gb/s to 1,000km may not be able to carry 20Gb/s to 500kms. *Table 1* shows some of the recent records. Each of these records improves one of the three factors over other records. A good place to find these records is the Optical Fiber Conference (OFC) that is organised annually by the Optical Society of America (OSA).

Table 1: Recent Advances in the DWDM Records

# of λs wavelengths	Bit rate (in Gb/s)	Distance (km)	Comments
32	5	9,300	Achieved in 1998
64	5	7,200	By Lucent in 1997
100	10	400	By Lucent in 1997
16	10	6,000	Achieved in 1998
132	20	120	By NEC in 1996
70	20	600	By NTT in 1997
128	40	300	By Alcatel in 2000
1,022	Not specified	Not specified	By Lucent in 2000 (Lab trials)

Trend – Switching is the Bottleneck in the Current Networks

Switching and transport costs are two key parts of the carriers' costs. Some advances have reduced the cost of switching while the others have reduced the cost of transport. Historically, such advances have been alternating as shown in *Figure 3*.

In the beginning, switching (by manual operators) was more expensive than transport (on copper wires). The invention of automatic mechanical switches removed the need for operators. The focus then shifted to transport.

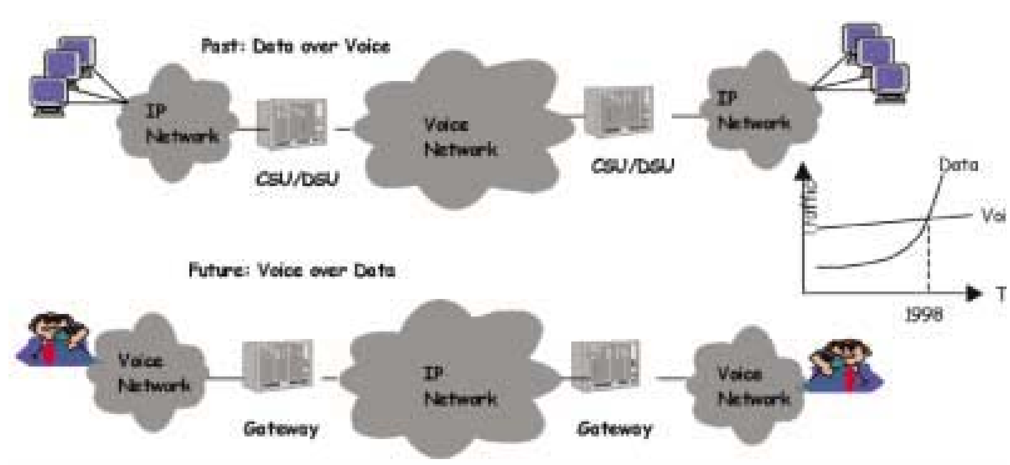
Numerous frequency and time division multiplexing (TDM) techniques to carry multiple conversations on copper wires were discovered. This brought the focus back to switching. Large electronic switches were developed to handle the increased volume of traffic. At this point, transport again became the bottleneck, so microwave and satellite communication were used. Finally, the introduction of optical fibre and DWDM has brought significant reductions in the cost of transport. In 2001, DWDM is in wide deployment. Carriers have deployed DWDM equipment that allows each fibre to carry 32 to 64 wavelengths at 2.5Gb/s to 10Gb/s. Therefore, each fibre can carry as much as 640Gb/s and more. With these improvements in transport, the bottleneck has now shifted back to switching.

Trend – All-optical Switching

A number of vendors have developed cross-connects that can switch bit streams among various DWDM fibres. Currently, most of such cross-connects are optical-to-electrical-to-optical (OEO) equipment, as shown in *Figure 4* on the left side. One problem with electronic switching is that, after a certain capacity, the increase in capacity – bit rate and number of ports – is obtained by parallelism and so the cost, power and space requirements increase linearly with capacity.

The solution is to develop all-optical switches – optical-to-optical-to-optical (OOO). In OOO

Figure 1: The Paradigm Shift of Moving Data over Voice to Voice over Data



switches, the optical signal is not converted to electronic form. Rather, it is switched optically from one port to another. Optical switching has the advantage of being cost-effective, and consumes less space and power. The OOO technology is also independent of the data rates, for example, OC-48, OC-192, OC-768 or OC-1536, etc., and the payload format, for example, asynchronous transfer mode (ATM), Synchronous Optical Network (SONET) or IP/Point-to-Point Protocol (PPP), etc. These newer devices are being designed to be very intelligent with auto provisioning, routing and signalling. As a result, these devices are being called 'switches' as distinguished from 'cross-connects' that do not understand signalling.

Trend – Long-haul Transport

While the switch manufacturers are working on faster switches, the transport manufacturers are developing devices that allow long-haul (LH) transmission. Normally, the optical signal in the fibre has to be amplified every 60km and regenerated every 600km. The regenerators re-amplify, reshape and retime (3Rs) the signal. LH transport equipment raises the distance to 4,000km and greater between regenerations. This results in considerable cost saving due to the elimination of numerous amplifiers and regenerators.

Trend – All-optical Transport

While all-optical switches reduce the cost of switching compared with OEO switches, for high-speed or a large number of ports particularly, the OEO conversion in the transport equipment is still required unless the transport equipment also becomes OOO. Making both switches and transport OOO would make the network truly all-optical. However, this transformation raises several new issues that must be resolved.

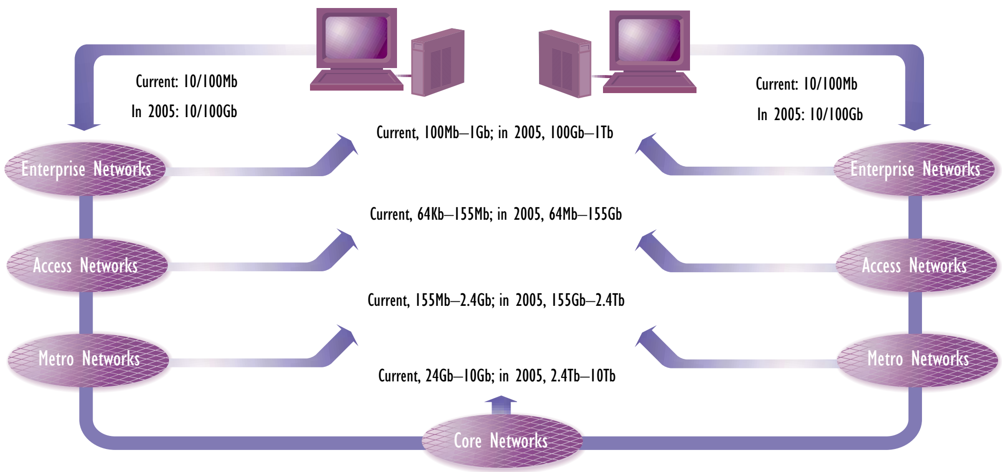
The first issue is the issue of 3Rs. The optical signal that is generated by the end devices – electronic routers with optical interfaces – is not powerful enough generally to travel long distances. Most DWDM transport equipment also requires the signal to be regenerated at 600km or so. This limitation can be resolved by having LH transport equipment as described earlier.

The second problem is that of wavelength conversion. In an all-optical network, two lightpaths cannot go on to the same fibre if they have the same wavelength and, therefore, require wavelength conversion. In general, wavelength conversion is done electronically, which reduces some of the cost advantage of all-optical approaches. Without wavelength conversion, there is the problem of routing lightpaths so that wavelength collision does not occur. This is known as a routing and wavelength assignment (RWA) problem.

Trend – IP over DWDM

A few years ago, the only way to send IP packets over a DWDM fibre was to connect the IP routers to ATM switches and then send ATM cells over SONET devices that were connected to a DWDM transport system. This results in a five-layer protocol architecture as shown in *Figure 5*. ATM switches were required for multi-service integration (integrating voice and data). In addition, routers were limited generally in speed compared with ATM switches. SONET was required for aggregation – combining 155Mb/s ATM streams to OC-48 SONET streams – and protection. Over the years, IP routers have become faster significantly. With the introduction of quality of service (QoS) in IP, the need for ATM was reduced. Beginning in 1996, packet over SONET or IP over PPP over SONET started becoming a popular approach. In 1999, several router manufacturers announced fast OC-192 interfaces

Figure 2: Bandwidth Requirements at Different Places in End-to-End Networks



and therefore the need for traffic aggregation using SONET is now being questioned.

Some of the problems that arise with the multi-layered architecture are as follows.

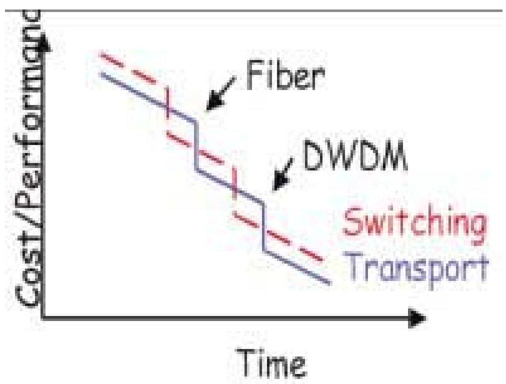
- Functional overlap:
  - *Multiplexing* – For different purposes, the multi-plexing of connections happens in many places in the layered architecture. A DWDM equipment multiplexes many λs, each λ contains many SONET virtual tributaries (VTs), each VT may group many ATM virtual circuits (VCs), in each of the VCs there may be many IP flows and each IP flow contains many IP packets.
  - Routing – To achieve different goals, multiple layers perform routing of the circuits or packets. For example, optical routing (at the circuit-level) is performed on DWDM switches, VC routing is performed in the ATM cloud using private node-to-network interface (PNNI), and IP routing is performed in the forwarding of connectionless IP packets.
  - Addressing – Different layers provide different addressing schemes, which need to be translated during the transition between these layers. For example, ATM has an E.164 ATM end system address (AESA) scheme against an IPv4 or IPv6 addressing scheme.
  - QoS/integration – Similarly to the other issues that have already been discussed, QoS that is provided by different layers overlap with each other. Transmission technologies provide circuit-level guarantees for the restoration, which can be called QoS, etc., and switching technologies, such as ATM and IP, have their own packet-level (or flow-level) guarantees.
- Failure affects multiple layers:
  - For example, each fibre carries 64 λs, which in turn carries 1,000 OC-3 channels that can carry an aggregate of 105 VCs, which can host an aggregate up to 108 IP flows. In such a scenario, a fibre failure will affect multiple layers at an increasing magnitude. To compensate for this rippling effect, each of the layers has its own restoration mechanisms, which implies another functional overlap.
- Connection set-up time:
  - Since SONET does not have any signalling mechanisms, provisioning an end-to-end SONET connection takes a very long time – in some cases, months. This may be unacceptable for the data networks.

As a conclusion, multiple layers give an "intersection of features and union of problems". Due to the increase in the bandwidth to the desktop, the number of connections to be aggregated by the core is reducing, leading to the collapse of the layers, as shown in *Figure 6*.

The five-layer IP/ATM/SONET/DWDM/Fibre architecture in 1993 was reduced to IP/PPP/SONET/DWDM/Fibre by 1996. Running IP/PPP on SONET boxes eliminated the ATM boxes. In 1999, the need for SONET add-drop multiplexers (ADMs) were questioned. Routers with SONET interfaces that can fill an entire wavelength have started appearing.

The protection and restoration function that is provided by SONET ADMs can be subdivided between IP and DWDM equipment. In 2000, Ethernet framing seems to be gaining a foothold with the evolution of 10 Gigabit Ethernet. Some are predicting that eventually, SONET will not be

Figure 3: Developments in the Switching Technology and Transport Technology



needed and Ethernet will be running end-to-end. Regardless of what datalink layer framing (SONET/PPP/Ethernet) is used, the reduced architecture is called IP over DWDM and IP and DWDM are the only two layers that are required.

IP is used as the revenue generator for data traffic and possibly for other traffic in the future. It provides multiplexing, routing, traffic engineering and restoration mechanisms. DWDM, on the other hand, is used as the cheap bandwidth facilitator. It provides optical layer provisioning, protection and restoration. Therefore, putting IP and DWDM together is a winning combination. The IP/DWDM combination captures all of the required features for end-to-end application support, thereby eliminating the expensive SONET and ATM equipment. In such a combination, a co-ordinated effort should still be implemented for the restoration and path determination mechanisms in the IP level and the optical level.

IP over DWDM – Issues and Solutions

Beginning with the November 1999 meeting of the Internet Engineering Task Force (IETF), IP over DWDM issues are receiving industry-wide attention. It was realised that lightpaths and label-switched paths (LSPs) used in multiprotocol label switching (MPLS) have several common routing and signalling requirements. In MPLS, all packets with the same label are sent on an LSP. If the wavelength of the packet is used as the label – instead of the label field in the packet header – all packets with the same wavelength will follow one LSP. This leads to a variant of MPLS called multiprotocol lambda switching (MPλS).[2] A unified view of MPLS and MPλS was then developed to include packet switching capable devices, for example, routers, TDM-capable devices, for example, SONET ADMs, wavelength switching-capable devices, for example, OEO and OOO switches and fibre switching-capable devices. This work is being performed under the name generalised multiprotocol label switching (GMPLS) at IETF.[3,4]

As shown in *Figure 6*, an optical domain consisting of IP/DWDM equipment can provide transparent services for all traffic including SONET, ATM and IP. It is important to note that different providers may own the optical and the electronic networks. An optical domain customer, such as an Internet Service Provider (ISP), CLEC or incumbent local exchange carrier (ILEC), purchase services from the optical domain providers to interconnect their networks. In such a configuration, it is essential to remember that the topology transparency between the customer and the provider domains is essential. This transparency is achieved by hiding each other's topology information and by defining a standard interface between the customer and the provider. This is called a user-to-network interface (UNI). The definition of UNI has led to several issues including the following:

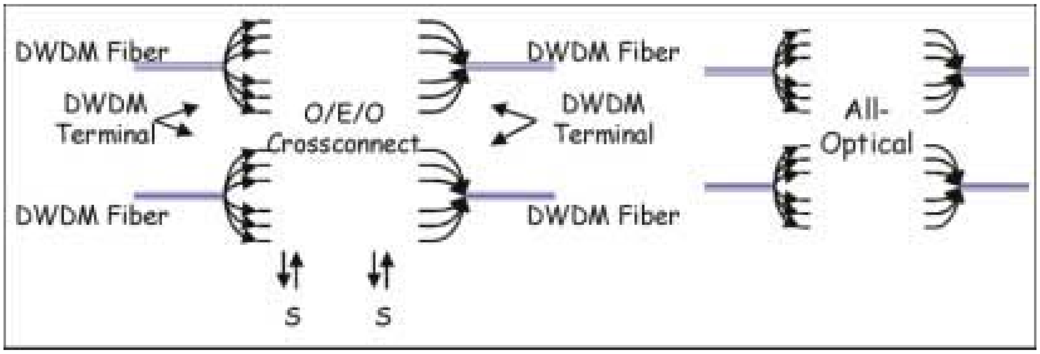
- uniformly addressing client end-systems;
- data and control plane separation among optical devices;
- signalling models between the client and optical domains;
- integrated protection mechanisms between layers; and
- circuit-based provisioning in optical devices.

Addressing Issues

Almost all standards bodies and industry forums including Optical Domain Service Interconnect (ODSI), the Optical Internetworking Forum (OIF) and IETF have decided to use IP control plane and, therefore, IP addressing in all connection set-up messages. This decision reduces the reworking of signalling (GMPLS) protocols for non-IP clients. In the scope of addressing, two issues need to be resolved by the standards communities as follows:

2. *Daniel O Awduche, et al., "Multi-Protocol Lambda Switching: Combining MPLS Traffic Engineering Control With Optical Crossconnects," draft-awduche-mpls-te-optical-03.txt,* IETF working group draft, *2001.*
3. *Peter Ashwood-Smith, et al., "Generalised Multi-Protocol Label Switching (GMPLS) Architecture," draft-many-gmpls-architecture-00.txt,* IETF working group draft, *2001.*
4. *Ayan Banerjee, et al., "Generalised Multiprotocol Label Switching: An Overview of Routing and Management Enhancements",* IEEE Communications Magazine, *January 2001.*

Figure 4: Evolution of All-optical Switching Devices



- the way in which to reduce the addresses consumed by the optical cross-connect (OXC) boxes; and
- the way in which to map the client device addresses to the OXC addresses for the address resolution.

The first issue on the reduction of the IP address consumption is handled by allocating one IP address per the OXC and identifying the end-points by their port identifiers. This connect is similar to the unnumbered interfaces in IP routers. As shown in *Figure 6*, if an IP address is allocated to each port in switch 1 (S1), many IP addresses will be consumed. Therefore, a link or port is identified by the IP address of the OXC and the corresponding port number. For example, the port to which router A is attached on S1 is identified by S1's IP address – port 1's ID. Similarly, the link 1 on S1 is identified by S1's IP address – Link 1's ID.

The second issue of address mapping between client and OXC address spaces is handled by creating a mapping between the address spaces.[5]

This mapping will be in the following format – client end-point identifier (client node address – client end-point identifier) – optical end-point identifier (OXC IP address – optical end-point identifier). The client address can be in formats that are used commonly in carrier networks, such as E.164, IPpv4, IPpv6 or ATM. The registration between these addresses should be performed to do the address resolution look-up during connection set-up. This address-mapping database can be centralised or distributed via routing protocols.

Control Channel and Data Channel Separation

In a conventional electrical data-networking world, both the control protocol, such as routing information and signalling data, information and the application protocol information (user data) share the same communication channel. In such a case, the number of routing adjacencies and the physical adjacencies are the same. Whereas, in the OOO networks, since it is not preferable to decipher the regular data, an option to separate the control channel from the data channel is advised. This separation also helps in increasing the number of data channels between the OXCs. As shown *Figure 6*, a control channel can represent a group of data channels. These data channels can be allocated at the discretion of the client equipment, based on the requests that they make to the optical domain.

Such a scenario creates the following issues:

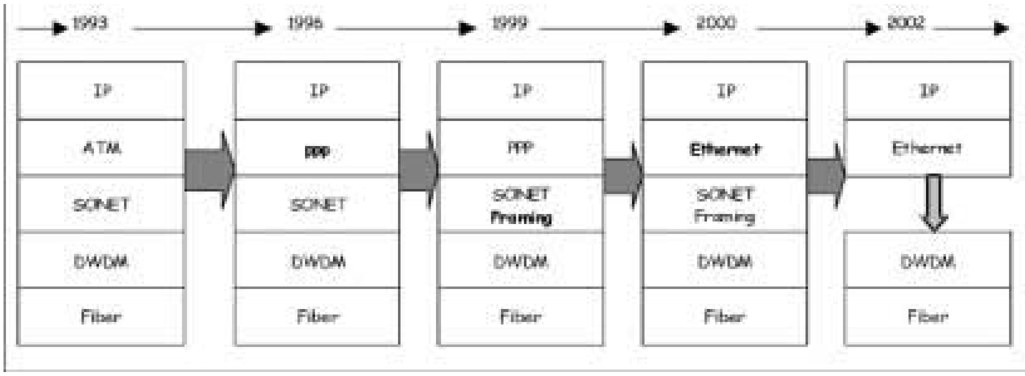
- the way in which to communicate the control information between the adjacent OXCs;
- the way in which the failure of the control channel is recovered without disrupting the data channels;
- the way in which the status of the adjacent data channels is detected; and
- the way in which to reduce the number of routing adjacencies that are defined between the OXCs.

The control information between the adjacent OXCs can be propagated using an out-of-band channel, such as via Ethernet, etc., a dedicated in-band channel, such as using a dedicated wavelength, or by using in-band control information, such as SONET overhead bytes.

By using a separate control channel from the data channels, the failure of either of them does not mean that the other channel(s) has/have failed. On the other hand, failure of one control channel can prevent further set-up and restoration of many of the data channel adjacencies. Therefore, solutions are proposed to have a standby control channel in case the primary control channel fails.

5. *D Papadimitirou, J Jones, S Ansorge, Y Cao and R Jain, "Address Resolution Proposal," OIF2000.261,* OIF working group draft.

Figure 5: Evolution of Layer Merging/Modifications over the Last Few Years



Another interesting by-product of the control and data channel separation is that the status change of the data channel is not known to the control channel as-a-matter-of-fact, which was the case for the integrated control and data channels.

Therefore, in order to detect the status changes of the data channel, management protocols, such as Link Management Protocol (LMP)[6], have been developed or the control channel should depend on the manual configuration.

If each of the data channels is defined as an Open Shortest Path First (OSPF) adjacency, the number of links that are advertised will be numerous and, therefore, the protocol traffic and the processing overhead will increase. Such a solution will not scale to larger networks. Therefore, a logical grouping of these data channels has been proposed in the standards under the term 'link bundling'.[7]

A group of links between IP neighbours with similar characteristics is advertised as an IGP adjacency. The similarity could be in sharing the same encoding schemes and similar capacity, etc.

Signalling Model Choice

Many of the carrier transport networks are slow in provisioning. To overcome this bottleneck, GMPLS has been proposed for use in the optical transport domain. This raises the following issues.

- The extent to which information can be trusted between the optical domain and the client domain.
- The way in which the existing signalling protocols change.

In order to solve the problem of the amount of information exchange between the domains, two main schools of thought have arisen. In one solution, the optical domain information and the client domain information are isolated completely. That is, the client networks do not know the optical domain topology. The communication is provided between these domain(s) for their registration – for address resolution and service discovery – and request for services. This model is called the 'overlay model' or 'cloud model'. Here, the client networks register their end-point information with the optical domain initially and then, as a second step, the client networks request for the services across the optical domain using the optical user-to-network interface (O-UNI) signalling mechanism. O-UNI is defined by OIF to be a simple request-response-oriented protocol to create, destroy and modify the lightpaths between the client end-points via the optical domain.

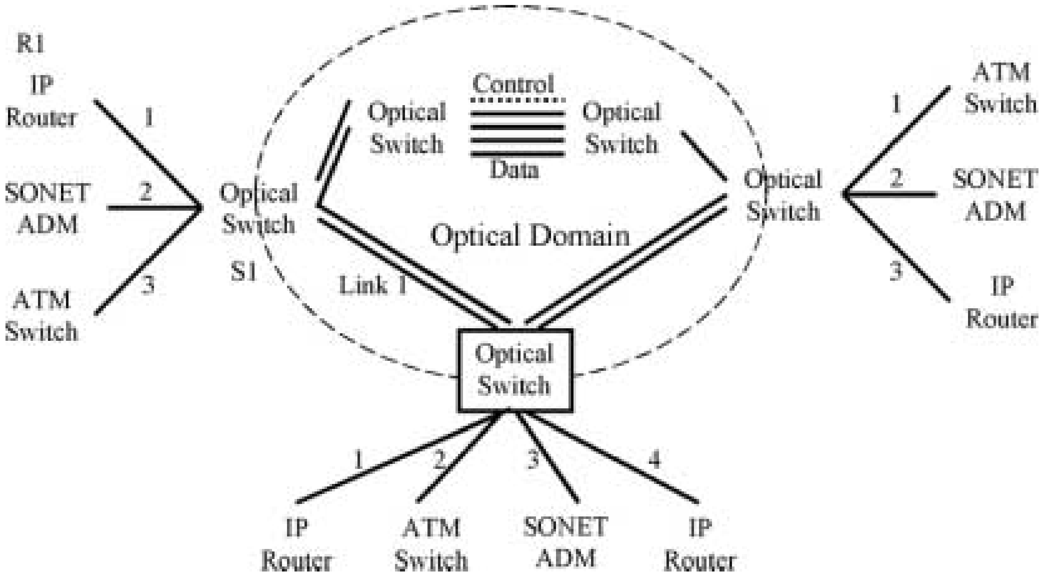
The other school of thought is to consider both the optical domain and the client domain as peers to each other. This implies that both the domains exchange their topology information with each other and therefore the client can choose the path between the optical domain end-points as it does now for inside an autonomous system (AS). This model is known commonly as the 'peer-to-peer model'. This approach has two fundamental roadblocks, which are as follows:

- the optical and the client domains are operated by two providers normally and therefore they may not be willing to exchange their topology information; and
- the service transparency cannot be achieved easily in this model.

The current signalling protocols that are used for MPLS are also used for GMPLS. These protocols, namely Constraint-routed Label Distribution Protocol (CR-LDP) and Resource Reservation Protocol for Traffic Engineering (RSVP-TE)[8,9] have been modified to assist in the lightpath

6. J P Lang, et al., "Link Management Protocol (LMP)," *draft-ietf-mpls-lmp-02.txt,* IETF Internet Draft.
7. K Kompella, "Link Bundling in MPLS Traffic Engineering," *draft-kompella-mpls-bundle-04.txt,* IETF Internet Draft.

Figure 6: A Typical Usage of the Optical Domain to Transport IP, ATM and SONET Traffic



provisioning. O-UNI triggers the request for a lightpath across the optical domain, which is provisioned by the signalling protocol of choice. These signalling protocols are enhanced to carry the lightpath-related attributes such as framing attributes, bandwidth attributes, transparency attributes, propagation delay attributes and service-level attributes.[10]

Protection Issues

Historically, transmission equipment vendors excelled in protection mechanisms – to bind the restoration time to 50msec – with circuit-level multiplexing. IP networks, on the other hand, paid more attention to higher (packet-level) multiplexing and longer restoration times. With the advent of IP/DWDM equipment, the problem definition becomes supporting transmission network-like protection (50msec) for IP-like traffic, which is multiplexing millions of connections. This is one of the classic examples of the union of the problems that surface with such a cross-technology integration. Here, some of the issues that are encountered include the following:

- Identifying the layer that is to be used for protection.
- Identifying the mechanisms that are to be used for protection.

Protection can be provided at the transmission layer[11-13] or at the protocol layer as in GMPLS. The granularity of protection is selected based on the priority of the connections.

The SONET-like protection mechanisms, such as point-to-point, mesh (path and line) and ring (two wire and four wire) are being extended to the optical transmission equipment. In the protocol layer, the choice between pre-provisioned paths for fail-over *versus* restoring the failed paths is considered. The back-up path in both the mechanisms is selected such that it does not share the same fibre, cable, trench or central office as the primary path. To automate the protection path selection, a concept of shared risk link group (SRLG)[7] is defined. This concept groups all of the entities, such as wavelengths and links, etc., that are affected by a single failure. For example, in *Figure 6*,

8. *Peter Ashwood-Smith, et al., "Generalised MPLS Signaling – CR-LDP Extensions", draft-ietf-mpls-generalised-cr-ldp-03.txt,* IETF working group draft, *2001.*
9. *Peter Ashwood-Smith, et al., "Generalised MPLS Signaling – RSVP-TE Extensions", "draft-ietf-mpls-generalised-rsvp-te-03.txt,* RSVP IETF Internet Draft, *2001.*
10. *Osama S Aboul-Magd, et al., "Signaling Requirements at the Optical UNI", draft-bala-mpls-optical-uni-signaling-00.txt,* IETF Internet Draft.
11. *Thomas E Stern and Krishna Bala,* Multiwavelength Optical Networks – A Layered Approach, *Addison-Wesley Publications.*
12. *K Vinodkrishnan, A Durresi, N Chandhok, R Jain, R Jagannathan and S Seetharaman, "Survivability in IP over DWDM Networks: A Survey,, submitted to* Journal on High Speed Networking Special Issue on Survivability, *12 July 2000.*
13. *Ornan Gerstel and Rajiv Ramaswamy, "Optical Layer Survivability: A Services Perspective",* IEEE Communications Magazine, *March 2000.*

if link 1, link 9 and link 8 share a common trench, they have a common SRLG number.

Provisioning Issues

Integration of the transmission equipment and the data equipment lead to new transmission services such as provisioned bandwidth service (PBS), bandwidth on demand service (BODS) and optical VPN service (OVPN).[14] These evolving services put new requirements on the network management systems, the policy management systems and the traffic engineering tools. The issues that arise in optical provisioning are as follows.

- The way in which rapid service provisioning needs to be done.
- The way in which the circuit-based networks differ from packet-based networks, from a provisioning perspective.

Traditional carrier (SONET and SDH-based) networks are known for their slow provisioning services. Since the integration of such equipment with the data networks, the demand for improving the provisioning response time has increased. With the advent of new market services, the needs for on-demand service provisioning techniques are evolving. These encompass point-and-click provisioning tools and signalled provisioning mechanisms. In addition to the provisioning, the need for decision-making, such as on the user groups and on network resources, has evolved, which is leading to policy-based provisioning. In addition, since the number of circuits is limited in an optical domain, the need for efficient resource management (traffic engineering tools) is becoming apparent.

In the packet-level provisioning mechanisms, in addition to the path set-up, the queuing, marking and scheduling information is considered in the core. The circuit-level provisioning, on the other hand, works at the granularity of the wavelength and considers circuit-level priorities for set-up, holding and restoration. The more challenging portion of the provisioning in IP/DWDM architectures is mapping the operator-created physical topology into the end-to-end provisioned (or signalled) path.

Current Trends and Research Issues

In this section, developments that are not related directly to IP over DWDM, but are somewhat related, are presented. In addition, research problems that have resulted from IP over DWDM architectures are also discussed.

Trend – Local Area Network -Wide Area Network Convergence

In the past, shared media technology was common in the local area network (LAN) environment, which is similar to the point-to-point technology in the wide are network (WAN) environment. This trend is changing to point-to-point technology both in the WAN and in the LAN environments. This is due mainly to the 'high-bandwidth to the workstation' concept.

This trend leads to the interesting concept of using LAN technologies in the WAN environment. In the conventional shared LANs, due to the operation of medium-access control (MAC) protocols, such as collisions due to multiple nodes transmitting at the same time, the end-to-end span of the LAN was bounded. In the shared LAN environment, the distance limitation is not due to the physical layer. Therefore, once the point-to-point environment is moved to, the distance limitation due to MAC protocols will be eliminated.

These arguments lead to the possibility of using Ethernet-like LAN protocols in the WAN environment. Using 10 Gigabit Ethernet in up to 40km spans[15], without repeaters, is possible. Access rates as low as US$1,000/month for a 100Mb/s service as compared with US$1,000/month for a 1.5Mb/s T-1 line have been promised by some of the upcoming vendors.

Trend – Ethernet versus SONET

SONET uses extensive mechanisms to maintain the timing information and provide synchronous transmission of the data. In addition, SONET provides solutions for grooming (virtual tributaries/containers), protection (line or path, 1+1 or 1:1) and restoration – 50ms using bi-directional line switched rings (BLSRs)/unidirectional path switched rings (UPSRs). Although these are very useful mechanisms, they increase the cost of the SONET equipment, such as ADMs.

Ethernet, on the other hand, operates in an asynchronous mode, which does not require the extensive timing-related functionalities as in SONET. This feature with the current trends in extending LAN technologies to WAN distances makes Ethernet a favourable choice over SONET.

14. *OIF Architecture and Signaling working group, "Carrier Optical Services Framework and Associated Requirements for UNI", OIF2000.155,* OIF working group draft.
15. *10 Gigabit Ethernet Alliance,* 10 Gigabit Ethernet – An Introduction, *http://www.10gea.org/Tech-whitepapers.htm*

A current trend is evolving to use only SONET framing initially to transport 10 Gigabit Ethernet frames over WAN and later, to use Ethernet with its native framing on top of a wavelength end-to-end. Such a development needs protection and restoration from the optical layer.

Research Topics – Network Layer

The integration of the IP layer above DWDM equipment has many newer research issues, which need further detailed attention. Some of them include the following.

- Networks that are connected highly – In the current IP/DWDM networks, multiple λs connect adjacent nodes. This leads to the discussion on the way in which to advertise them in the control plane (routing protocols) and the way in which to use them effectively in the data plane. A concept that is evolving in trying to solve this problem is 'link bundling'.

- Dynamic topology – Due to multiple λs between adjacent nodes, the availability and unavailability of the λs need to be detected and propagated promptly into the topological information.

- Adaptive networks – Unlike in end-to-end SONET equipment, where the provisioning takes a long time, the simplistic nature of the IP/DWDM architecture prompts the need for new on-demand services. Such services lead to the issues on automated service provisioning and therefore make networks more adaptive.

- Risk avoidance and protection – the newer IP/DWDM architectures simplify or avoid the SONET layer and also integrate a large number of connections end-to-end in the optical domain. In order to avoid high data losses, the control plane protocols should enhance their capabilities to reduce the risks of failures by developing better optical protection and restoration mechanisms. A concept of SRLG is devised to identify the risks. Many optical restoration mechanisms are under study to achieve SONET-like protection.

- QoS/traffic engineering – By moving from the packet-centric designs in the router world to circuit-centric designs in the IP/DWDM equipment, all of the concepts on the QoS and traffic engineering takes on a new meaning. This area needs further attention in the standards bodies and in the research community.

Conclusions

In this article, the way in which the advent of DWDM transmission technologies led to a bottleneck in switching technology, which led to the development of OOO switches, was discussed. In such networks, the number of protocol layers between IP and DWDM is minimised. This architecture led to a new set of problems such as the data and the control plane separation, protection mechanism integration and thinking in terms of circuit-switched data traffic.

The extensions to the current IP networks to provide address translation, signalling exchange in the optical domain, routing modifications and protection for lightpaths were also discussed. Finally, the trend of LAN-WAN convergence, which leads to new technical problems, was presented. ■

Additional References

Kireeti Kompella, "Link Bundling in MPLS Traffic Engineering," draft-kompella-mpls-bundle-05.txt, IETF Internet Draft, 2001.

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