IP over DWDM

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Abstract:

This paper deals with the concept of transmitting raw IP packets over an optical layer, which employs DWDM for increasing its bandwidth demand. It also gives a brief introduction to DWDM systems. The requirements for creating an all optical networks and the issues pertaining such an evolution have been discussed here. The protocol architecture based on multiprotocol lambda switching has also been discussed. This paper shall serve as a guide to the optical transport networks.

See Also: IP over DWDM (Lecture by Prof. Jain) | Optical DWDM Networks (Lecture by Prof. Jain) | Optical Networking And Dense Wavelength Division Multiplexing (DWDM) | References on Optical DWDM Networks | Books on Optical DWDM Networks | Terabit Switches and Routers
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1. INTRODUCTION

Dense Wavelength Division Multiplexing (DWDM) is the process of multiplexing signal of different wavelength onto a single fiber. Through this operation, it creates many virtual fibers each capable of carrying a different signal. At its simplest, DWDM system can be viewed as a parallel set of optical channels, each using a slightly different light wavelength, but all sharing a single transmission medium. This new technical solution can increase the capacity of existing networks without the need for expensive re-cabling and can tremendously reduce the cost of network upgrades.

'Internet Protocol (IP) over DWDM' is the concept of sending data packets over an optical layer using DWDM for its capacity and other operations. In the modern day world, the optical layer has been supplemented with more functionality, which were once in the higher layers. This creates a vision of an all-optical network where all management is carried out in the photonic layer. The optical network is proposed to provide end-to-end services completely in the optical domain, without having to convert the signal to the electrical domain during transit.

Transmitting IP directly over DWDM has become a reality and is able to support bit-rates of OC-192. As we can clearly see, it holds the key to the bandwidth glut and opens the frontier of terabit Internets too.

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2. DENSE WAVELENGTH DIVISION MULTIPLEXING

DWDM performed on an optical fiber serves as the underlying carrier for the optical network. The narrow channel spacing of about 1nm characterizes the system. Fig.1 depicts the general structure of the DWDM system. The Erbium doped Fiber Amplifier (EDFA), Multiplexer and the Demultiplexer form the vital blocks of the system.
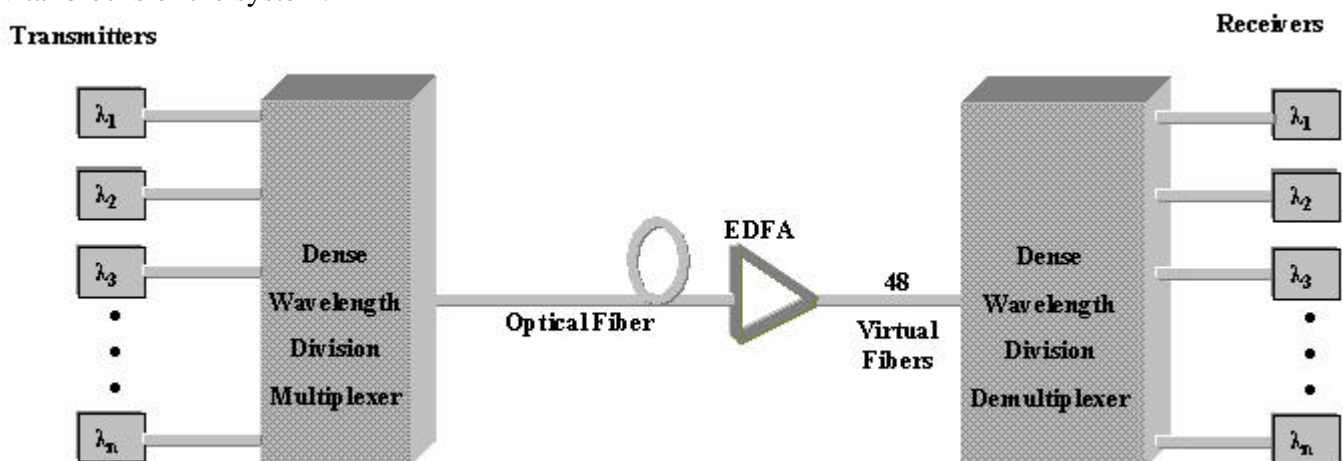
Fig.1 Block Diagram of a DWDM System

The concepts of optical fiber transmission, loss control, packet switching, network topology and synchronization play a major role in deciding the throughput of the network. These factors have been discussed briefly in this chapter. More detailed explanations refer to [Refi99]

2.1. Optical Transmission

The DWDM system has an important photonic layer, which is responsible for transmission of the optical data through the network. Transmission refers to the conversion of electronic data (bits) to information in the form of light waves and sending it through the fiber. In the case of IP over DWDM, raw packets are converted into light and sent over photons. This layer is governed by various parameters.

- **Channel Spacing**
  The minimum frequency separation between two different signals multiplexed in known as the Channel spacing. Since the wavelength of operation is inversely proportional to the frequency, a corresponding difference is introduced in the wavelength of each signal.

  There exists a bound on the channel spacing. The optical amplifier's operational bandwidth & the receiver's capability to identify two close wavelengths are major factors introducing the bound. They restrict the number of unique wavelengths passing through the amplifier. Taking into consideration the above two factors, the international bodies have established a spacing of 100GHz to be the worldwide standard for DWDM. This means that the frequency of each signal is different than the rest by atleast 0.1THz. The frequency is converted appropriately before multiplexing, based on the channel vacancy in the DWDM system.

- **Signal Direction**
  An optical fiber helps transmit signal in both directions. Based on this feature, a DWDM system can be implemented in two ways - Unidirectional, Bi-directional. The choice is made based on the availability of fiber and the required bandwidth. The former brings in the need for a secondary fiber line and the latter reduces the capacity of the system.

2.2 System Components

The DWDM system comprises of units like the Optical Amplifiers, Wavelength Converters, Wavelength Add/Drop Multiplexers and Optical Cross Connects for its operation. The concept of the optical transport network implies that the service provider should have optical access to traffic at various nodes in the network (like the SONET layer for SONET traffic). All these components ensure that by not requiring any other electrical accessory.

- **Optical Amplifiers**
  Optical Amplifiers (OA) are devices used to amplify a weak, distorted signal with the aim of generating a good signal. It operates in the optical domain, without converting the signal into electrical pulses. It is usually found in the long haul networks, where the cumulative loss is huge. The amplification property is attained by doping a small strand of fiber with an earth metal (like Erbium - Er_{68}). The Noise Figure, Automatic gain control, Bandwidth and Gain Flatness characterize the optical amplifier used in a system. Erbium Doped Fiber Amplifier (EDFA) is a

common amplifier found in most networks.

The performance of the optical amplifier has improved tremendously over the past few years. Current amplifier systems provide very low noise and flatter gain, which proved advantageous to the DWDM system. The amplifier throughput has steadily increased onto nearly +20db, which is many a time powerful than the primitive model. The recently developed *Silica Erbium fiber-based Dual-band fiber amplifier (DBFA)* solves that problem by widening the bandwidth to 75 nm (1528 - 1610 nm wavelength range).

- **Wavelength Converters**
  A wavelength converter's function is to convert data on an input wavelength onto a possibly different output wavelength within the operation bandwidth of the system. This component is used in the routing devices when the wavelength, which marks the route to be followed, is to be changed. An ideal wavelength converter should be transparent to bit-rates and signal formats. It has many other physical requirements governing its operation - like fast setup time, large signal-to-noise ratio, moderate input power levels, insensitivity to input signal polarization etc. Wavelength conversion can be opto-electronic (or) all-optical, based on the strategy employed. Usage of a particular scheme depends on the requirements of the system. Nevertheless the all-optical wavelength conversion is more future oriented and advantageous.

- **Wavelength Add/Drop Multiplexer**
  This is the optical sub-system that facilitates the evolution of the single wavelength point-to-point optical network to the wavelength division multiplexed networks. It is responsible for managing the WDM traffic in the fiber. The WADM serves as the entry point to the optical layer in many other aspects. The practical utilization of the fiber bandwidth is achieved by being able to selectively remove and reinsert individual channels, without having to regenerate the all of the WDM channels.

  A WADM is characterized in terms of the total number of input, through, drop and add channels (virtual fibers). The system maintains each connection as sequential ports and performs manipulations on them. The channels to be added/dropped can either be pre-assigned or reconfigured automatically based on the type of implementation. The former is called as Fixed WADM and the latter is known as Reconfigurable WADM.[Giles99]

- **Optical Cross Connect**
  The OXC is a DWDM system component that provides crossconnect functionality between N input ports and N output ports, each handling a bundle of multiplexed single-wavelength signals. The bandwidth management flexibility is obtained with the introduction of an Optical Cross Connect (OXC).

  An OXC will support network reconfiguration and will allow network providers to transport and manage wavelengths efficiently at the optical layer. An OXC is most efficient when it contains a bit-rate & format independent optical switch. These attributes help the OXC cross connect over multiple bit-rates - such as OC-3, OC-12, OC-48 and OC-192 and other formats like SONET, ATM. [Jackman99]

  This block is also required to perform network management in the optical layer. The OXC, owing to its architecture, can easily perform Signal Monitoring, Provisioning and grooming, Restoration at the photonic layer itself.

- **Optical Gateways**
  The optical gateway is a common transport structure that must groom and provision traffic entering the optical layer. These blocks are essential for maintaining protocol transparency and for a maximum bandwidth capacity. The emerging basic format for high-speed transparent transport is ATM, and optical gateways will allow a mix of standard SONET and ATM services. By providing a link between the variety of electrical protocols and allowing flexible deployment of any mix of them, optical gateways provide networks the maximum benefits of optical networks. The optical gateway will be the key element to allow smooth transition to optical networks.

2.3 Reducing losses

Fiber dispersion and non-linearities attribute to most of the losses in the optical channel. Some strategies have been designed to cure them in the least time possible. A few of the methods are mentioned below. [Wilner99]

- **Dynamic compensation**
  The accumulation of dispersion in a high-speed optical channel can be compensated either by using a Dispersion Compensating Fiber (DCF) or a linearly chirped fiber Bragg grating. But, the dispersion thus accumulated is capable of changing with time. This calls in for tuning the compensating element. The tuning characteristics of a novel *non-linearly chirped fiber Bragg grating* is used for achieving this task.

- **Bit pattern mis-alignment for Crosstalk**
  Wavelength multiplexers and demultiplexers are not ideal and allow unwanted crosstalk of any input wavelength to be integrated with other normal input signals. This coherent crosstalk can be potentially reduced by the deliberate misalignment of bit patters in the main signal and its crosstalk replicas. Having varied fiber lengths for all the signals introduces 1 bit length misaligning. This makes the crosstalk differ from the original signal at approximately 50% of the bit locations. This reduces the interference of the crosstalk with the main signal, thereby reducing the non-linearity.

2.4 Packet Switching

DWDM systems are capable of performing switching in the optical domain without having to convert the signal onto the electrical domain. This reduces the delay at the switches and increases system throughput. Switching involves reading in a header from the signal and altering the path of the signal (or packet) appropriately. In the course of altering, the switch might have to edit either a part or whole of the header. If DWDM systems are capable of doing that, then switching can be done safely in the optical domain itself.

All optical header replacement is the key to updating information in the wavelength-based packets (For example: Modifying routing information). In the case of a same-wavelength header, this is achieved by using a continuous wave (CW) tag attached at the beginning of the packet as carrier for the new header. This continuous wave tag does reduce the throughput of the network, but it had the advantage of maintaining spectral accuracy in the packet.

When the header is wavelength independent, replacement can be done at 1 Gbps, without using the static continuous wave tag that precedes the packet. The new header is created by optically modulating a

continuous wave region generated from the data packet's own flag. This ensures the same wavelength for the new header, as in the original packet. This continuous wave tag generation adds certain complexities to the packet, but the overall packet structure is maintained.

2.5 Network Topology

A network can be physically structured in the form of a ring or a mesh based on the connection between the various nodes. A connected network of arbitrary topology, in which the node degree is typically more than two, is regarded as a Mesh. Although the physical topology of a DWDM system might be that of a ring, the logical traffic distribution topology can be arbitrary. This is done through the use of different wavelengths to interconnect each node. The Optical Cross Connect (OXC) helps pass on traffic between each of the rings.

There exists the concept of a virtual topology that indicates the lightpaths from one node to another. This arises from a logical view all connections in the network (and not the physical structure). The virtual topology will comprise N x N connection. Hence, determining a light path constitutes an N^2-scaling problem. An efficient algorithm needs to be devised to calculate an optimal virtual topology based on the traffic pattern. There exist many algorithms for dynamically reconfiguring the virtual topology of the system. In most cases, knowing the physical structure would help reducing overheads, by keeping the number of fiber links traversed to a minimum.

A ring topology may be preferable in most cases, owing to many of its capabilities. Unlike a mesh network, the expense of laying out the links is reduced in the ring, because the number of links increases only as a linear progression. The ring topology besides serving as a standby link helps share the load. The working segment (Refer to Fig.2) and the protection segment of the fiber together handle the large data burst of the computer network. This reduces the load on the router and removes the need for buffering. Nonetheless, mesh networks provide a faster restoration in the system.
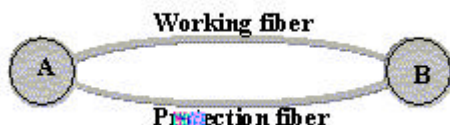

Fig.2 Ring Topology Connecting Nodes A & B

2.6 Synchronization

The SONET networks currently support the multiplexing of lower Time Division Multiplexing (TDM) rates onto higher rates. The Add/Drop Multiplexers (ADM) and transponder en route provide the much-needed synchronization. This ensures the quality and guarantees proper delivery of data. But, since DWDM systems support the multiplexing of different wavelengths, no timing relation exists for the system. The need for a clocking system, similar to one used in SONET, is absent.

Nevertheless, synchronization may still be used for assuring good transmission quality. The numerous regenerators / transponder and other devices in the path of an optical signal introduces jitter. Synchronization can be used to ensure quality by cleaning up the signals transmitted at each node. SONET terminals and ADMs have a special timing output port, which provides timing to customers. It is sometimes referred to as the *Derived DS1*. It is a true DS1 signal, but carries no traffic. All data bits are set to logic 1 to minimize timing jitter. A clock distribution amplifier may be used to split the Derived

DS1 signal, to synchronize many network elements. In a network, each distribution amplifier output may be routed to a different network element.

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3. UNIFYING OPTICAL LAYER

This chapter discusses the different approaches to increasing the network bandwidth and analyses them. The trend of deploying IP over DWDM systems has been justified and compared with the existing SONET architectures.

3.1 Need for IP over DWDM

SONET (Synchronous Optical Network) is a standard for connecting fiber-optic transmission systems. It defines interface standards at the physical layer of the OSI model. It takes care of scheduling the packets to be transported by way of time division multiplexing. It also handles rate multiplexing, traffic grooming, error monitoring and restoration. SONET establishes Optical Carrier (OC) levels from 51.8 Mbps (about the same as a T-3 line) to 2.48 Gbps. But SONET was primarily designed for voice only systems. The standard protocol stack used for the SONET system is depicted in Fig.3. The SONET layer can be further divided into four layers (Path, Line, Section and Photonic).
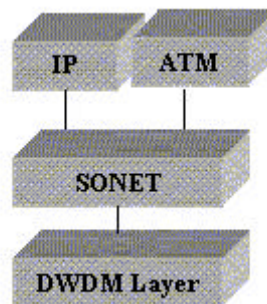
Fig.3 Primitive Protocol Stack for SONET over DWDM

This multi-layer stack is required to maintain a division of labor. The ATM layer is used as an access technology and might be limited to a speed of OC-12. The IP layer acts as the data plane in this case and operates at less that OC-3 speeds. The system performs all important tasks like signal monitoring, provisioning and grooming, restoration.

The multi-layer stack has more problems than advantages. Functional overlap is one such problem. Each layer tries to perform restoration in the event of a failure, thereby creating more havoc in the system. The SONET interface is advantageous for constant bit rate traffic, but not for bursty traffics found in the Internet. Presence of high capacity in the system obviates the need for time division multiplexing and traffic grooming. Thus a multi-layer stack introduces undesired latency. The SONET system does not provide fast provisioning. It provides protection in the form of redundancy. (One more fiber cable in the form of a ring). All these problems have made it necessary to redesign the system without having too

many layers.

The other proposed solution for transmitting IP packets reliably over a fiber optic network is to adopt an IP over DWDM system. The transport layer is all-optical and thereby maintains a high data rate. This is more favorable because it avoids the cost of the SONET / ATM equipment. SONET does not work very well with bursty traffic. The need for SONET's multiplexing is no more present.

The need for the IP directly over DWDM system has set in to increase the bandwidth and to reduce the latency. The system performs satisfactorily at high speeds of OC-192. The overheads because of the SONET & ATM layers have been eliminated. The new architecture facilitates for faster restoration, provisioning & path determination. It seems to have much potential as the architecture of the future.

3.2 Optical Internet

The fundamental properties of the DWDM system are exploited to form an all optical layer. Bit rate and protocol transparency enables transport of native enterprise data traffic like Gigabit Ethernet, ATM, SONET, IP etc. on different channels. It also brings in more flexibility so that the system can be connected directly to any signal format without extra equipment.

The optical transport architecture will employ both transport networking and enhanced service layers, working together in a complementary and interoperable fashion. The functionality in the optical layer can be split as given in Table1. The two layers perform the functions of the four SONET layers. The transport layer acts like the lower physical layer, while the service layer acts like a higher layer.

Table 1. DWDM Network model

Transport Layer	Service Layer
Bandwidth, Reliability, Wavelength level traffic-control	Access speed, Usage rates, Security, VoIP services etc

The two layers together achieve the granularity needed by all the services (like traffic engineering). In this model, the SONET gives way to the optical transport, which tries to achieve reliability and performance as provided by the standard SONET architecture. Having an intelligent optical layer that performs fast restoration can appease the bandwidth demand. Restoration happens in the optical layer rapidly and does not overlap with the service layer's mechanisms. Switching & bandwidth is furnished at the granularity of the wavelength. The ATM's virtual path becomes equivalent to a wavelength. Furthermore, the Multiprotocol Label Switching (MPLS) protocol divides the traffic engineering requirements between the IP layer and the Optical transport layer. Thus a DWDM layer with required functionality is molded to form the all-optical network.

Achieving the benchmark set by SONET leads to many complex expectations. When a connection is established, the DWDM layer has to provide both reliable optical path and traffic engineering. An automated provisioning of end-to-end wavelength path should happen in a virtually less amount of time. In case of a physical failure, the wavelength routing protocol will have to restore the transcontinental paths across many routers within a maximum of 50 ms. These expectations bring about a vagueness in the extent to which some functionality should be pushed down to the optical layer.

3.3 IP/DWDM Architecture

The DWDM layer has been designed in compliance with industry wide standards. This is the key for ensuring protocol and format transparency in the network. These quest for a standard brought-in two different approaches: SONET-centric and generic (or Closed & Open as it is widely known).
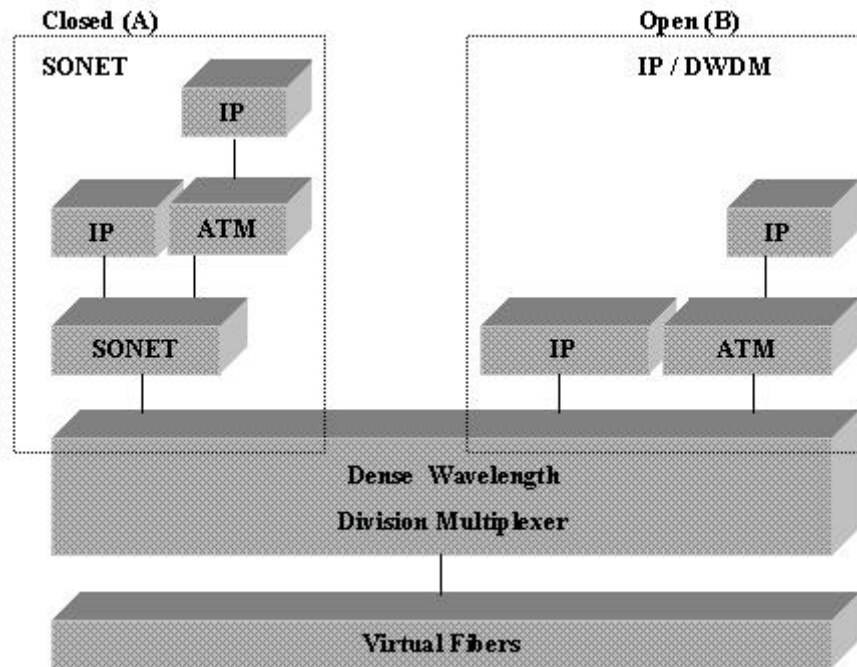

Fig 4: DWDM Network Architecture

The closed architecture was designed to serve the SONET systems better. It increases the capacity in the SONET system, by utilizing the necessary components and the technology of DWDM in the standard SONET terminal. It is dependent on the higher SONET layers or any other TDM system for its other functionalities (like Network management). The segment A in Fig.4 denotes such a system. Here, the carrier gets stuck with the vendor's proprietary technology.

IP/DWDM systems adopted the alternative approach, which yields a whole new transport layer, called the Open architecture. It is open in the sense that it is not tied with SONET or other TDM systems. This case reflects protocol transparency and exhibits all the properties of the all-optical network. For optical networking to realize its full potential there must be a standard interface to the optical layer. The segment B in Fig.4 denotes the open system. The customer is responsible for providing the actual interface to the end user and for all the protection work. The IP bits enter the DWDM system and then are transported "*as is*" over the high-speed connection.

The IP/DWDM system can adopt a variety of architectures based on what the payload is and what the underlying transport network is. [Doshi98]. They can be grouped as:

- ***Optical mesh transport***

OXCs and multiplexers are used to provide wavelength management and restoration. In case of a physical failure, the signal is rerouted through a different physical path. Meshes provide the fastest way for restoration. Systems, which take care of the management functions, are also available at this time.
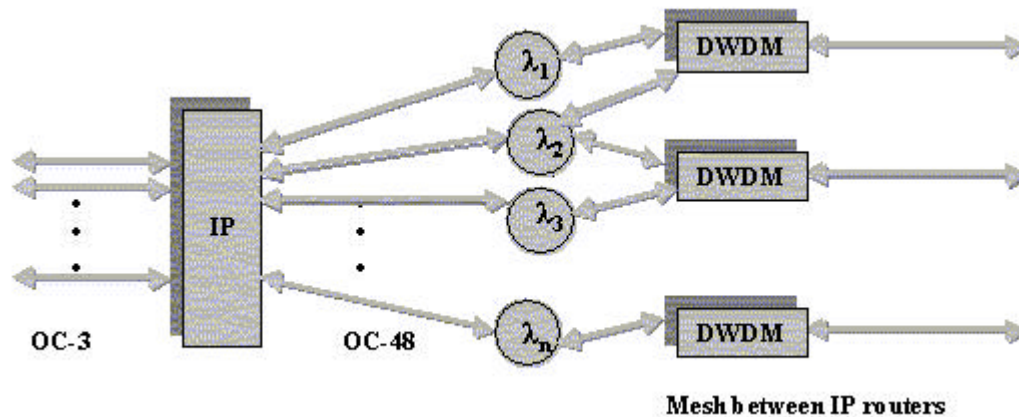

Fig.5 Wavelength transport network

- *Wavelength transport network* (Refer to Fig.5)
  IP and ATM connect directly over the wavelength links. It is devoid of the OXCs. The detection of failure and restoration is done at the service layer. This has inherent advantages over the previous architecture in that one layer of equipment is avoided and restoration is at a different level. Lack of multiplexing layer between the service & the transport layer brings in added complexities.

Thus, an open case with the wavelength transport network would be a practical implementation for an IP over DWDM system. However, the onset of higher expectations from the IP/DWDM system makes it essential to adopt the optical mesh transport instead, because OXCs helps ensure Quality of Service (QoS).

3.4 SONET vs. IP/DWDM

The DWDM system builds in some advantages in both the systems. The increase in the bandwidth capability of the fiber is the foremost influence of DWDM. It also brings in the property of virtual fibers where each wavelength can be considered as a dedicated connection. But, the infrastructure and usage of this DWDM layer is different in both the networks.

SONET serves two basic functions: multiplexing and network restoration. If the network survivability of the DWDM system improves, then SONET will become obsolete. SONET's reliability represents wastage by setting aside a large portion of its resources. But, it is the cheapest solution available for incorporating reliability in the circuit-based system. This it does by supporting a four-layer architecture. Moreover, SONET solutions are very much vendor specific. The advent of gigabit routers makes the need for SONETs even less because the increased capacity seems more than sufficient.

In contrast, the IP over DWDM system has inherent advantages because of the absence of many layers, thereby cutting down on the cost part. The signals need not be converted onto an electrical domain for performing control operations on it. Hence, the latency in the IP/DWDM system is less compared to that encountered in the SONET system. The absence of a vendor specific component makes the system service transparent.

The result of this combat between SONET & IP/DWDM ends in a tie. The primary reason being that the current implementation of IP over photons does not exist without a SONET interface. Many carriers and vendors predict that SONET will still be around for a while. Many others predict that the features of SONET shall soon be burnt into the IP/DWDM system, leading to the end of SONET.

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4. IP OVER DWDM ISSUES

IP over DWDM can become a reality only when all the end-to-end services are offered optically. Hence, the optical network to be complete requires implementing the features like Error detection & correction, fault tolerance, network management, routing, switching etc. in the DWDM layer itself (Usually referred to as Layer1). These features supported by the all-optical network are explained in this section. The implementation in the DWDM layer is also put out in some detail. Most of the implementation uses a SONET interface for its functioning.Refer to [Wei99] for applications in practical cases.

4.1 Error Detection

SONET has the capability of detecting signal errors through the overhead in the frame. The overhead enables monitoring network faults also. This feature can be carried down to the DWDM system when SONET is used as the higher layer. This error checking can be accomplished at any of the SONET equipment - DWDM transponder, SONET regenerator, or other interface card supporting SONET framing system.

In the case of the other non-SONET data, the system becomes a bit more complex. Transporting signals over the DWDM layer directly enhance protocol transparency. But, it hampers bit-error checking. Therefore, fault detection is hindered and the maximum distance traversed without possibility of a bit-error reduces.

Forward Error Correction

Forward error correction (FEC) is performed in the all-optical DWDM systems. It can be categorized into two types. The first way is to put in the FEC data onto the unused portion of the SONET overhead. The performance is limited by the fact that SONET frame has a restricted amount of space available in its frame. This is also known as the *in-band FEC*. The other alternative is to have the FEC data encoded and transmitted on the line separately. This method, also known as the *out-band FEC,* increases the line rate and hence, provides significant system improvement.

4.2 Fault Tolerance

In addition to wavelength provisioning/ routing flexibility, a backbone must support optical network survivability schemes, including protection switching and restoration. The establishment of the all-optical network brings in the opportunity to provide optical layer network protection. 1+1 optical multiplex section protection (MSP) is the strategy currently supported by the WDM system. It is similar to the 1+1 multiplex section protection in SDH. The WADMs can accommodate more advanced optical layer protection switching.
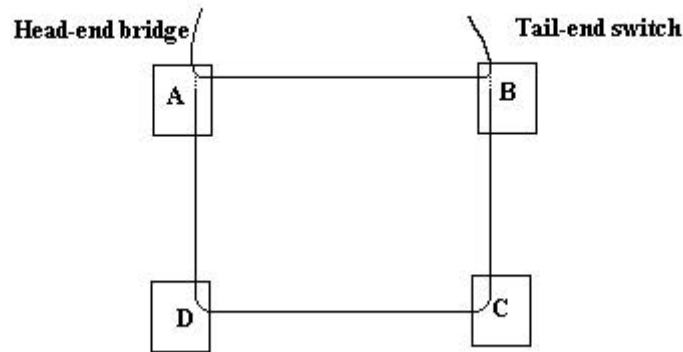

Fig.6: 1+1 protection by OXC

Optical Cross Connects (OXC) can be used as an integral part of this protection architecture. It can provide a 1+1-protection scheme via a head-end bridge, while the tail-end OXC can be provisioned to flexibly switch between two receive optical ports, based on signal quality. This 1+1 optical layer protection switch guards against fiber cuts at the highest possible level, which is architecturally the most appropriate solution. Fig.6 depicts the topology consideration during restoration.

The strategies for network restoration and survivability will undergo significant advances in the years to come. MPLS holds out good scope for such advancement, by allowing optical networks to carry out the restoral and path protection switching at the IP layer, rather than at the photonic layer. Furthermore, Optical networking will, in time, support powerful self-healing capabilities consistent with those of SONET/ SDH needed in a comprehensive optical layer.

4.3 Wavelength Routing

A unique property of the all-optical network is to perform wavelength routing. The wavelength and origin of the signal, as well as the states of the network switches and wavelength changers en route, decide the path of the signal through a network.

WADM can interconnect the IP routers, making it possible to establish a light path between the two. (A *light path* is the path an optical signal traverses to reach the destination beginning from the unique source. During transit, it may pass through wavelength converters. But, a *wavelength path* is the light path devoid of wavelength changers). The routers essentially reduce to neighbors thereby changing the network topology perceived by all the participating IP routers. This type of flexibility implies that the topology assumed by the IP routing protocols, could be changed as traffic conditions vary.

There are two solutions to the routing problem [Anderson99]:

- The *separate routing solution* for the IP/DWDM network comprises the individual solutions of two subproblems - the routing assignment, the wavelength assignment. The routing problem in DWDM networks is commonly referred to as the Routing and Wavelength Assignment (RWA) problem. This problem is divided into two subproblems and solved individually using well-known approximation techniques. The complexity of the routing & wavelength assignment problem depends on whether a particular node possesses a wavelength converter and whether it is a single fiber / multi fiber network.

- The *integrated routing solution* employs an integrated solution for determining the virtual topology, routing assignment & wavelength assignment. The problem needs to be split into four sub-problem and combining their individual solutions. Two of the subproblems arise because of the present of the optical network and the other two subproblems are equivalent to a data network's optimal routing problem.

The future holds some changes for wavelength routing too. Successful adoption of MPLS removes the necessity of propagating routing updates through the network, in the event of a node/ segment failure. Thereby reducing routing to an IP layer problem. This simplifies the system to a maximum extent. Moreover, inclusion of QoS measure to the IP routing problem is under research.

4.4 Network Control & Management

The evolution towards an optical network brings further challenges to integrate network management fundamentals, which constitute a major step in the network evolution, with the existing architecture. The requirements pertaining to fault, configuration, performance management, speed, latency and robustness are brought into the IP/DWDM system. The modified system reduces the complexity of controlling and managing a gigabit IP backbone. For present-day systems, this process of managing can be accomplished by enabling IP backbone routers to interface directly with the SONET or DWDM equipment.

Some of the issues that must be faced to deploy IP gigabit backbones are:

1. Outlining the specification and dimension of the network and network elements
2. Evaluating the impact of customer bandwidth on network architectures
3. Using network design and operation principles.
4. Evaluating the role of all-optical end-to-end paths
5. Evaluating the role in the routing and wavelength assignment problem
6. Design the wavelength pool and performing wavelength reuse.
7. Introducing integrated network management for the backbone access.

These are yet to be incorporated satisfactorily in a IP/DWDM system. Many products achieve this by providing a separate network management system that has full control over the complete optical network.

4.5 Service Transparency

Service transparency can be defined as a feature where-in the network transporting the signal does not need any extra information about it. The future transport infrastructure calls in for a high degree of transparency. This is required in order to treat all types of client in a unified manner. The assumption is

made that the first and last node, which accepts the signal, will handle all the client-specific information.

Bit rate independence is a necessary condition for being service transparent. The optoelectronic processing in a network can introduce minor jitter. To remove the jitter and to regenerate a good quality signal, certain timing relations need to be used. This hampers the bit-rate independence. This dilemma can be resolved by using a bit-rate independent optoelectronic regenerator with re-timing functionality. [Alferness99]

The protocol transparent and bit-rate independence together establish the service transparency, which is essential for developing an all-optical network and a complete optical transport layer.

4.6 Interoperability

The application of any new technology requires that standards be developed to facilitate multi-vendor internetworking. The key methodology is to completely define the information that is associated with the optical node. (For example: The format of the supervisory channels that carry optical add/drop multiplexer data between the network elements). The physical properties of the optical signal also need to be specified unambiguously. Internetworking can occur only when the specifications of the optical layer overhead and the optical supervisory channel exists.

According to a Juniper press release, the interoperability between the Juniper Networks M40 Internet backbone router and CIENA's MultiWave Sentry^{TM} DWDM optical-networking system has been successfully tested. This announcement demonstrates the direct connectivity of Juniper Networks' and CIENA's equipment and indicates the availability of an integrated IP over DWDM solution that simplifies IP packet transmission via an optical core.

4.7 Quality of Service

Work is underway to add QoS measures to IP routing protocols like OSPF. i.e, the protocols carry not only the topology information, but also the loading information such as maximum availability of bandwidths on links. Hence the route has to be calculated taking into account the bandwidth parameters and the topology metrics.

The above consideration requires analysing as to what benifits are reaped by performing traffic management at the optical layer (instead of at the IP layer). Moreover some thought has to be given in determing whether those functions can be implemented effectively in the optical layer. In most cases, the IP layer can be modified to take care of the routing based on the loading conditions and the optimal path. This avoids functional overlap and thereby improves the system performance. An analytical study is hence needed to decide between a QoS based distributed routing scheme in the IP layer and an optimal routing algorithm undertaking the IP/DWDM routing.

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5. MULTIPROTOCOL LAMBDA SWITCHING

Multiprotocol Label Switching (MPLS) is a switching protocol that uses a set of labels for forwarding the packet. The switches are assumed to be capable of doing only label lookup and replacement. The stack of labels present in the packet decides the forwarding path. No other information is used during switching. This protocol also tries to satisfy the QoS requirements for a connection.

IP/DWDM system tries to merge into one layer the functionalities of the ATM switch, SONET Mux / Demux and IP routing. This feature of the optical layer has brought in the concept of a Multiprotocol Lambda Switching protocol, which will perform those operations. The protocol shall try to implement routing protocols, enforce QoS & perform protection. This section discusses the features & architecture of the protocol adopted. [Awduche99] describes much of the work in this area.

5.1 Multiprotocol Lambda Switching over DWDM

This is the switching protocol using in the Optical layer. The optical channel layer network supports end-to-end networking of optical channel trails between access points. In data networks, all crucial functions are performed by the MPLS traffic engineering control plane. Similarly, the Optical Channel layer network provides the following functions: routing, monitoring, grooming, and protection and restoration of optical channels. In this situation, programmable OXCs, with rearrangeable switch fabrics and relatively smart control planes, will be critical to the realization of the optical layer functions (esp. in mesh optical networks).

A DWDM network is analogical to an ATM network in the aspects of switching. ATM networks perform packet switching based on the virtual circuit number, while the optical channel layer performs switching based on the wavelength of the signal (or packet). Hence the name "Lambda Switching" is applied to the optical network.

An Optical Channel trail is the complete sequence of wavelengths assumed by the Ip packet in transit. This sequence is similar to the stack of labels in MPLS. If the node did not contain a wavelength converter, then the circuit identifier (in this case a wavelength bound by the operational bandwidth) has global significance. Cross connects contain different ports each characterized by a unique wavelength. It is reponsible for switching the packets appropriately.

The Mulitprotocol Lambda Switching currently has many limitations. It does not support TDM. There exists no buffering of packets. Hence no scheduling algorithm is required. The packets are sent as and when they arrive. The large capacity of the fiber facilitates such an operation. The implementation of the Lambda switching, currently, is vendor specific. Thereby hindering interoperability between the systems.

5.2 MPLS Control Plane

The MPLS traffic engineering control plane comprises the requirements of the cross connects and other components of the system. It arises from the synthesis of new concepts in IP traffic engineering (enabled by Label Switching) and the traditional IP layer control plane. This establishes the framework for the MPLS traffic engineering control plane model. The model includes:

- Resource Discovery by protocols like Interior Gateway Protocol
- Network State (Topology, resource availability data) information exchange

- Path computation for deciding the route for explicit routing.
- Route management which performs activities like path relocation, maintenance, placement and label distribution

Having such independent modules enhances overall system performance. The MPLS control plane is to be implemented using the efficient modules performing the above set of operations.

The real implementation should have an integrated control plane. Each component (like OXC, Label Switching Routers) should not have different control plane. The drawback in IP over ATM, where both IP and ATM has distinct control planes, shows us that such a control plane is disadvantageous. The components shall have an uniform control plane. The MPLS traffic engineering control plane would be suitable for that of OXCs. The OXC using that control plane will be an IP addressable device. Thus a new architecture for the MPLS control plane is born.

5.3 Future Network Architecture

The MPLS based network architecture has been found to be favorable for the IP/DWDM system. It shall host features like:

- MPLS control plane will handle costraints like Data rate, Attentuation, Dispersion, Length, Delay.
- Using Next hop forwarding label entry (NHFLE) for determining the output port (or path) of a packet.
- The control plane shall be enforced by network management by having a dedicated supervisory channel
- Each OXC shall be an IP addressable device.
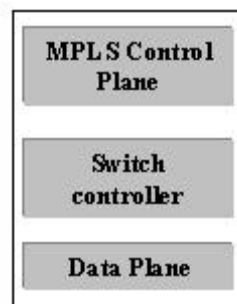- The subnets will acts as a single abstract node performing restorations within itself

Fig.7 Network Architecture of the future

The required protocol stack, for achieving those goals, would be as shown in Fig.7. The MPLS control plane shall regulate all the connections. The switch fabric would perform packet switching based on the wavelengths. The data plane shall be responsible for transmitting the packets. The switch shall maintain mapping between the wavelength + port at input and the wavelength + port at output. The table ensures that the packets reach the proper destination eventually. This is similar to how wavelength routing is done.

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SUMMARY

This paper has been instrumental in discussing several issues arising in an all-optical network. The basic concepts underlying an IP over DWDM system - like Network Management, Fault Tolerance, Service Transparency, Optical Switching - were discussed in quite some detail. The IP/DWDM systems shall support the Open architecture & provide complete service transparency. It shall host a MPLS control plane in the OXCs for providing much of the services.

The future holds many a challenges to the all-optical networks. But, the commercial implementations for IP over DWDM are not far away. It opens the pathway to Terabit networking and unleashes the enormous bandwidth potential of the silica fiber. The trend of IP/DWDM solutions over the last few years seems to have taken an exponential growth. DWDM acts as the stepping stone towards a true optical networking era.

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LIST OF ACRONYMS

ADM	Add/Drop Multiplexer
DS	Digital Signal
DWDM	Dense Wavelength Division Multiplexing
FEC	Forward error correction
IP	Internet Protocol
ITU	International Telecommunications Union
MPLS	Multiprotocol Label Switching
OA	Optical Amplifiers
OC	Optical Carrier
OXC	Optical Cross Connect
QoS	Quality of Service
SDH	Synchronous Digital Hierarchy
SONET	Synchronous Optical Network
TDM	Time Division Multiplexing
WADM	Wavelength Add/Drop Multiplexer
WDM	Wavelength Division Multiplexing

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Note: This paper is available on-line at
http://www.cis.ohio-state.edu/~jain/cis788-99/ip_dwdm/index.html